Thermonuclear Supernova
A Successful Failure

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*Paths to Exploding Stars: Accretion and Eruption*
KITP, UCSB
March 2007
Outline

- Why do we care?
- The explosive ZOO
- Simulation technology: Mueller’s eye opener
- Forgotten tale of the ICs
- Close but no cigar: pure deflagrations
- Detonating Failed Deflagrations
- DFD model validation
- Summary
Why Do We Care?

- SN Ia are crucial for galactic chemical evolution.
- Probes allowing study of expansion and geometry ($\Omega_M, \Omega_\Lambda$) of the Universe
- Offer constraints on the nature of dark matter
- Provide astrophysical setting for basic combustion problems.
**SN Ia Theory Cosmic Timescale**

**1960s**
- WD explosion proposed for Type Ia (Hoyle & Fowler)
- 1D detonation model (Arnett)

**1970s**
- Detonation models (several groups)
- Deflagration models (Nomoto)

**1980s**
- Improved 1D deflagration models (Nomoto’s group)
- First 2D deflagration model (Mueller & Arnett)

**1990s**
- 2D and 3D deflagration models, DDT (Khokhlov)
- Non-standard models 2D He detonations (Livne & Arnett)
- Small scale flame turbulence (Niemeyer & Hillebrandt)

**2000s**
- 3D deflagration models (NRL, MPA, Barcelona, Chicago)
- 3D DDT models (NRL)
### The Explosive Zoo: The D-rich Family

<table>
<thead>
<tr>
<th>DET</th>
<th>DEF</th>
<th>subCh</th>
<th>DD</th>
<th>PDD</th>
<th>TDD</th>
<th>LDET</th>
<th>GCD</th>
<th>PRD</th>
<th>DFD</th>
<th>WDM</th>
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<td>Ivanova et al. (1974), Khokhlov (1991) (pulsating)</td>
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<td>Khokhlov (1991; tampered, common envelope)</td>
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<td>Bravo &amp; Garcia-Senz (2006)</td>
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<td>DFD</td>
<td>P2007, PK2007</td>
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<td>Iben &amp; Tutukov/Webbink (1984), Hachisu et al. (1986)</td>
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<td>Benz (1990), Guerrero et al. (2004)</td>
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</tbody>
</table>

1. a. trans. To assume falsely the appearance or signs of (anything); to feign, pretend, counterfeit, imitate; to profess or suggest (anything) falsely.

Ex.: 1874 L. STEPHEN Hours Libr. (1892) I. i. 9

*These [...] show the pleasure which he took in simulating truth.*
**Simulation Aspects Worth Remembering**

The initial conditions (push) may predetermine the outcome (alpha-group RTI)

Memory of the initial conditions may survive for long

Numerical transients can be important (Zhang/flame)

Insight often comes from different application (Rosner/nova)

Simulations have a potential of producing arbitrarily complex unverifiable results

Computer models are becoming more realistic – they are NOT realistic!!
**Example: GCD - The Real Story**

Robust procedure: the outcome insensitive to small perturbations.

Różyczka: What happens if the perturbations are random?

Kritsuk, Böhringer, & Müller (1998)
GCD - The Real Story

Robust procedure: the outcome insensitive to small perturbations.

Kritsuk, Plewa, & Müller (2001)

Large scale core convection…
**Simplifying Scenario Warning**

Problem of (over)simplification will reappear later in this talk.

-Kuhlen, Woosley, & Glatzmaier (2005)
Larson’s Reflection

Numerical methods utilizing finite space and time steps have been applied in many areas of science over the past half-century, and they have expanded enormously our ability to model and understand natural phenomena. Detailed numerical simulations have allowed many new problems to be solved and many old ones to be advanced to a higher level of understanding. But perhaps the most important contribution of numerical techniques to science has been that they have often discovered new phenomena or revealed unexpected results whose importance had not previously been recognized. In doing so, they have greatly expanded our ideas about what can happen in complex systems for which no analytic solutions exist and the laws of physics may allow many outcomes; in effect, they have provided a powerful exploratory tool that can supplement our limited imaginations and provide new insights into how nature works. In astronomy, a classic and elegant example of how numerical techniques can reveal an unexpected richness of phenomena was provided by the work of Toomre and Toomre (1972), who used numerical integration of the restricted three-body problem (two massive bodies and one massless one) to model tidal interactions between galaxies; the results were dramatic and showed immediately that many strikingly peculiar galaxies could be understood as gravitationally interacting systems. This work launched the whole new field of study of galaxy interactions, a phenomenon whose importance had not previously been realized.

Even systems governed by simple laws can quickly develop a level of complexity that surpasses our ability to form a simple mental picture or model, and in such cases computer simulations can often be used to gain understanding. A common way in which complexity can emerge is via the chaotic behavior that characterizes many natural phenomena and makes them unpredictable, even in principle, over extended periods of time. An example is provided by the three-body problem, in which the extreme sensitivity of the orbits to the initial conditions can cause them to diverge exponentially and make them impossible to predict over indefinite periods of time. A three-body system generally decays eventually into a binary system and an
We often think that when we have completed our study of one we know all about two, because "two" is "one and one." We forget that we still have to make a study of "and."

Sir Arthur Eddington

We need to study and understand separate components.

We also need exploratory integrated simulations to learn about connections.

However, we do not even understand one’s!!
**Some of the One’s**

Channels for progenitors
- Binary evolution
- Population synthesis

**Initial conditions**
- State of the stellar core
- Metallicity
- Rotation profile
- Magnetic fields

**Basic physics**
- Flame on intermediate scales
- Unsteadiness
- DDT

**Numerics**
- Multiphysics coupling
- Nucleosynthesis
  postprocessing
one cannot speak of individual blobs but must consider a dense pack of flame born with and maintaining roughly spherical symmetry, the net buoyancy is reduced. For hot matter to flow out, cool matter must also flow in. Perhaps this circulation is impeded. But then the fault may not lie in the stars, but in our codes. Do the codes have sufficient resolution and sufficiently low shear numerical viscosity to allow small blobs to detach from the flame pack and float away? Have they obscured the nature of the solution by starting with unrealistically simple conditions—a central point flame?

Garcia-Senz & Woosley (1995)

Kuhlen, Woosley, & Glatzmeier (2005)

Höflich & Stein (2002)
**Single Bubble, Three Different Methods...**

2.5D

![Graph showing a 2.5D model](image)

Niemeyer, Hillebrandt, & Woosley (1996)

2.5D

![Graph showing a 2.5D model](image)

Livne, Asida, & Höflich (2005)

3D

![Graph showing a 3D model](image)

Calder et al. (2004)

...and virtually the same result!

This is followed by...
Lots of Waiting...
Initial Conditions So Far

Based on analytic, semi-analytic, and numerical models, the most likely outcome of a mild ignition is the off-center deflagration.

Garcia-Senz & Woosley (1995)
Niemeyer, Hillebrandt, & Woosley (1995)
Höflich & Stein (2002)
Calder et al. (2004)
Livne, Asida, & Höflich (2005)
Kuhlen, Woosley, & Glatzmeier (2005)
Major Sins of Classic Central Deflagrations

Context: Branch-normal las

1. Uniformly mixed ejecta, unburned low-velocity carbon

2. Explosion energies too low, need ~50% more burning

3. Initial conditions either too idealized or defined ad hoc

4. Large Ni-rich structures visible at maximum light

5. Insufficient production of intermediate mass elements
Some Recent Evidence

Garcia-Senz et al. (2007)
- difficult to produce > 0.2 M☉ of IME
- MIME correlates with MRIE
- difficult to explain low energy explosion events

Wang et al. (2006): SN 2004dt (VLT)
- highly aspherical high-velocity burned regions
- globally asymmetric residual fuel

Fesen et al. (2006): SNR 1885 (HST)
- neutronized central region: high-density burn
- free of IME
- degree of mixing smaller than in deflagrations

Gerardy et al. (2007): SN 2003hv, SN 2005df (MIR, Spitzer)
- chemically stratified ejecta
- Ar and Ni shifted in velocity in respect to Co

- flat-topped NIR lines: burning at high densities
- line center shift: asymmetric, off-center explosion
Ejecta Composition: Pure Deflagrations

Röpke et al. (2005)

Gamezo et al. (2003)

Reinecke et al. (2002)

Stratification, Energy: Speculative DDT

3-D pure deflagration

3-D speculative DDT

Gamezo et al. (2003)
Preferred SN Ia Scenario

10^{2/4-7} cm
10^{10} seconds
deeper subsonic, Ma ~ 10^{-4}

mild ignition

10^{-3/5-8} cm
few seconds
subsonic: Ma ~ 0.3

deflagration

10^{1/5-8} cm
0.5 second
compressible: Ma ~ 2

detonation
What is DFD

DFD is a delayed detonation model: deflagration followed by a detonation

Detonation is inertially (and not gravitationally) confined (mea culpa!)

Transition density understood in terms of amount of preexpansion

Controlled by physics of both deflagration and detonation (+ transition)
Double-bubble DFD

20051012 – 8 km [y+100, y-25]

Log J density [g cm⁻²]

Z [cm]

R [cm]

Time = 0.000 ps
Number of blocks = 1378
AMR levels = 14
Some DFD-related Work

- Gamezo et al. (2004, 2005)
  - 3D DDT models, but deep ignition

- Röpke, Woosley, & Hillebrandt (2007)
  - Parameter study in both 2D and 3D
  - Found important correlations
  - Partial confirmation of this work

- Fesen et al. (2007) SNR 1885
  - 2D off-center DD by-hand model
  - Used by Gerardy et al. (2003hv, 2005df)

- Röpke & Niemeyer (2007)
  - 3D off-center DD by-hand models
Comments on Röpke et al.

- Collision process modeling
  - Substandard resolution
    order of magnitude lower in 2D, even more in 3D

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta x_{\text{coll}}$ [10$^6$ cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B50d200a</td>
<td>7.87</td>
</tr>
<tr>
<td>2B50d200b</td>
<td>5.02</td>
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<tr>
<td>2B50d200c</td>
<td>5.09</td>
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<tr>
<td>2B50d200d</td>
<td>5.02</td>
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<tr>
<td>2B50d200e</td>
<td>3.82</td>
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<td>9.03</td>
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<td>2B25d200b</td>
<td>6.25</td>
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<td>4.89</td>
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<td>2B25d200e</td>
<td>2.44</td>
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<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta x_{\text{coll}}$ [10$^7$ cm]</th>
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<tbody>
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<td>3B25d100</td>
<td>1.26</td>
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<td>3P25d100</td>
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</tr>
<tr>
<td>3P50d100</td>
<td>2.48</td>
</tr>
<tr>
<td>3B25d200</td>
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</tr>
<tr>
<td>3T1d200</td>
<td>3.29</td>
</tr>
<tr>
<td>3T2d200</td>
<td></td>
</tr>
</tbody>
</table>

- Simplified approach to detonation
  no feedback from nuclear burning
  necessary but not sufficient detonation criterion
  same is true for some preignition models (Kuhlen, Woosley, & Glatzmaier, Zingale & Dursi);
  Höflich & Stein are exceptions but have other problems; Townsley et al. model as well?
Comments on Röpke et al.

- System on the loose?
  - Important correlation $T_{\text{col}}(Z_{\text{bub}})$

- But 3D 100/200 RWH results inconsistent (and counterintuitive)

<table>
<thead>
<tr>
<th>Model</th>
<th>$T_{\text{max}}$ at coll. [10^9 K]</th>
<th>$E_{\text{max}}$ at coll. [10^{50} \text{ erg}]</th>
<th>$\rho$ at coll. [g cm^{-3}]</th>
<th>$\Delta x_{\text{coll}}$ [10^7 cm]</th>
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</thead>
<tbody>
<tr>
<td>3B25d100</td>
<td>1.035</td>
<td>2.79</td>
<td>$&lt; 2 \times 10^5$</td>
<td>1.26</td>
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<tr>
<td>3P25d100</td>
<td>1.412</td>
<td>1.01</td>
<td>$&lt; 5 \times 10^5$</td>
<td>0.949</td>
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<tr>
<td>3P50d100</td>
<td>0.828</td>
<td>1.78</td>
<td>$&lt; 5 \times 10^5$</td>
<td>2.48</td>
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<tr>
<td>3B25d200</td>
<td>no collision: WD unbound</td>
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<tr>
<td>3T1d200</td>
<td>0.308</td>
<td>3.30</td>
<td>$&lt; 3.2 \times 10^3$</td>
<td>3.29</td>
</tr>
<tr>
<td>3T2d200</td>
<td>no collision: WD unbound</td>
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</tbody>
</table>
Comments on Röpke et al.

- **Numerical convergence**
  - At higher resolution deflagration is less energetic (+results in higher-res)

<table>
<thead>
<tr>
<th>Model</th>
<th>Bubble radius [km]</th>
<th>Resolution</th>
<th>( T_{\text{max}} ) at coll. ([10^6 \text{ K}])</th>
<th>( E_{\text{int}} ) at coll. ([10^{50} \text{ erg}])</th>
<th>( T_{\text{max}}(\rho &gt; 3 \times 10^6 \text{ g cm}^{-3}) ) at coll. ([10^9 \text{ K}])</th>
<th>( T_{\text{max}}(\rho &gt; 1 \times 10^7 \text{ g cm}^{-3}) ) at coll. ([10^9 \text{ K}])</th>
<th>Delta ( x_{\text{int}} ) [10^5 cm]</th>
<th>Delta ( x_{\text{coll}} ) [10^6 cm]</th>
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<tr>
<td>2B50d200a</td>
<td>50</td>
<td>128 × 256</td>
<td>2.61</td>
<td>1.14</td>
<td>1.54</td>
<td>—</td>
<td>no</td>
<td>4.50</td>
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<td>2.92</td>
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<td>2.60</td>
<td>—</td>
<td>yes</td>
<td>2.97</td>
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<td>256 × 512</td>
<td>2.22</td>
<td>1.46</td>
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<td>no</td>
<td>2.21</td>
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<td>50</td>
<td>384 × 768</td>
<td>2.53</td>
<td>1.44</td>
<td>0.959</td>
<td>—</td>
<td>no</td>
<td>1.47</td>
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<tr>
<td>2B50d200e</td>
<td>50</td>
<td>512 × 1024</td>
<td>2.29</td>
<td>1.39</td>
<td>0.954</td>
<td>—</td>
<td>no</td>
<td>1.10</td>
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<td>2.40</td>
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<td>2.08</td>
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<td>1.50</td>
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<td>192 × 384</td>
<td>1.97</td>
<td>1.47</td>
<td>0.224</td>
<td>—</td>
<td>no</td>
<td>2.97</td>
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<tr>
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<td>25</td>
<td>256 × 512</td>
<td>2.60</td>
<td>1.09</td>
<td>2.32</td>
<td>—</td>
<td>yes</td>
<td>2.21</td>
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<tr>
<td>2B25d200d</td>
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<td>384 × 768</td>
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<td>1.47</td>
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<tr>
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<td>512 × 1024</td>
<td>3.83</td>
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<td>3.83</td>
<td>3.80</td>
<td>yes</td>
<td>1.05</td>
</tr>
</tbody>
</table>

- But this works in favor of hot spot formation!!
Comments on Röpke et al.

Realistic, better resolved models needed.
Realistic, better resolved models needed!
DFD Phases

- Deflagration
- Transition to detonation (takes finite amount of time)
- Detonation
Deflagration Modeling: A “Side” Comment

Cabot & Cook (2006): Re number effects on RTI
BG/L model on 3072^3 grid (Re~10^4)

The starting length-scale problem
Our results suggest that proper representation of fine-scale initial perturbations is essential for obtaining the correct growth history.

Basic physics problem
[...] it seems prudent to ensure that the model for turbulent flame speed faithfully reproduces RTI physics before invoking other schemes to increase the burning rate, such as multi-point ignition, background turbulence from thermal convection and/or deflagration-to-detonation transition.
DFD Phases: Deflagration

- Weaker compared to Gamezo-like models
- Takes place at large radii rather than close to the core
- **Amount of energy released controls expansion**
- **Expansion sets the ICs for a detonation**
- Controls the mass and composition of the expelled material
- Controls surface flow energetics (kinematics and orbital motion)
Transition To Detonation

SDT: shock-to-detonation transition
observed in DFD but uncertain, other possibilities available

Zel'dovich's gradient mechanism
self-ignition wave transforms into a detonation when the speed of ignition train approaches sound speed

Oppenheim's detonation bubbles
shock-compressed gas explodes in neighboring exothermic centers producing spherical blast waves – these collide resulting in the onset of detonation kernels that lead to detonation

SWACER: shock wave amplification through coherent energy release
(Lee et al. 1978, Khokhlov, Oran, & Wheeler 1997)
Oppenheim's amplified by the Zel’dovich gradient mechanism
Most are through some form of "microexplosions" - strong vs. mild ignition modes. Presence of induction time gradients associated with temperature and composition gradients seems common.

**SDT is a strong, volumetric violent process** rather than from exothermic centers (hot spots) in compressed region. As in strong detonation, weak waves are present.

**Necessary conditions**
- presence of a shock wave
- gas energy sufficient to sustain reignition in expanding gas

**Aspects**
- compression
- induction time
- auto-ignition (energy transfer to support constant shock propagation)
- fuel composition
Transition To Detonation Examples

expanding nozzle

diverging-contracting tube

Yu (2001)

resonator PDE

<table>
<thead>
<tr>
<th>Suction</th>
<th>Compression</th>
<th>Ignition and operating</th>
<th>Compression outflow and suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supersonic jet</td>
<td>Shock wave</td>
<td>Focus</td>
<td>Detonation wave</td>
</tr>
</tbody>
</table>

Levin et al. (2001)

Gelfand et al. (1991)
DFD/Inertial Confinement Fusion

Omega/Rochester

Z-machine/SNL

NIF/LLNL

Peak compression

Smalyuk et al. (2007)
### DFD/Perturbations

<table>
<thead>
<tr>
<th>ICF experiment – different ICs</th>
<th>ICF simulation – single ICs</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="ICF experiment" /></td>
<td><img src="image2" alt="ICF simulation" /></td>
</tr>
</tbody>
</table>

- **Smalyuk et al. (2007)**
- **Atzeni et al. (2005)**

### Classic Deflagration + Small Perturbations

![Diagram](image3)

> > 0.07 foe
**DFD Detonation Phase**

- **Ejecta mildly aspherical**
  - progenitor perturbed
  - finite shock-crossing time on non-static background
  - crossing-time short, < 0.5 second

- **Bulk of nucleosynthesis (alpha network)**
  - burns at local densities + compression factor
  - penetrates both unburned and burned material

- **Leaves very little unburned material (< 0.1 M\(_{\odot}\)) behind**
  - may leave pockets in outer layers
  - the core region fully burnt

- **Current model energy/nickel mass estimates are upper limits**
  - realistic WD is not pure C/O
  - nuclear network is only approximate
Ejecta mildly aspherical

Clumpy outside, smooth inner part

Very little unburned material and only at high velocities

Current yields approximate, > 0.1-0.3 \( M_\odot \) IME, \( \sim 1 \) \( M_\odot \) IGE

\( E_{\text{exp}} = 1.2 - 1.3 \times 10^{51} \) ergs

### Final Model Properties

<table>
<thead>
<tr>
<th>Model</th>
<th>Y12</th>
<th>Y125</th>
<th>Y125</th>
<th>Y1200</th>
<th>Y75YM25</th>
<th>Y100YM25</th>
<th>Y75YM50</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{t} )</td>
<td>1.357</td>
<td>1.496</td>
<td>1.515</td>
<td>1.516</td>
<td>1.464</td>
<td>1.384</td>
<td>1.075</td>
</tr>
<tr>
<td>( E_{t} )</td>
<td>( 1.59 \times 10^{-4} )</td>
<td>( 8.38 \times 10^{-5} )</td>
<td>( 7.15 \times 10^{-5} )</td>
<td>( 7.09 \times 10^{-5} )</td>
<td>( 5.34 \times 10^{-4} )</td>
<td>( 2.87 \times 10^{-5} )</td>
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<td>0.895</td>
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</table>
Kasen, Thomas, & Nugent (2006): Multi-dimensional time-dependent Monte Carlo radiative transfer
Y12 DFD Model Validation: Polarization

Polarization: ejecta morphology

- **Outermost ejecta**
  - smooth layer
  - unburned material (oxygen/carbon)

- **Outer IME shell**
  - strongly perturbed, clumpy layer
  - IME elements

- **Inner IME shell + IGE core**
  - smooth region, stratified
  - IME/IGE elements (silicon shell over nickel core)
  - can possibly be probed with xray/SNRs

Wang, Baade, & Patat (2007)
Y12 DFD Model Validation: Polarization

Polarization: ejecta morphology

- Outer IME shell
  - strongly perturbed, clumpy layer
  - IME elements

IME asphericity
controlled by the deflagration phase in the DFD model

Kasen & Plewa (2007)
Equatorial view
Reasonable quality, comparable or better than W7

Orientation effects controlled by the deflagration phase in the DFD model

Kasen & Plewa (2007)
Aspherical IGE core controlled by the deflagration phase in the DFD model

Kasen & Plewa (2007)

DFD Model Validation: Spectroscopy

DFD (+ 90°)

WT

Y12 @ B_max

Y12 @ B_{max} + 14
DFD Model Validation: Velocity Evolution

Orientation effects controlled by the deflagration phase in the DFD model

Benetti et al. (2005)

Kasen & Plewa (2007)
Spectroscopy: high-velocity features

- **Growing body of evidence**
  - (Mazzali et al. 2005, Garavini et al. 2007)

- **Theory**
  - impossible to obtain in detonations
  - highly unlikely in pure deflagrations
  - equally hard in DD (Yamaoka et al. 1992)
  - CSM interaction (Gerardy et al. 2004, Quimby et al. 2006)
  - combination of factors (Tanaka et al. 2006)
  - DFD feature (Kasen & Plewa 2005)
DFD Model Validation: IME

Surface pollution controlled by the deflagration phase in the DFD model

Kasen & Plewa (2005)
Some Intriguing Observations

- HVF require IME-enhanced material detached from bulk ejecta
  Hard to imagine in deflagrations
  Perhaps possible in DD given transition below $10^7 \text{ g cm}^{-3}$ (wavy IME production)

- Polarimetry indicates the outer layers are clumpy but the IGE core is smooth
  Pure deflagrations are likely to produce turbulent cores
  DD as well if detonation cannot penetrate through ashes
  And even if it can, how to retain clumpy structure at high velocities?

- MIR observations are indicative of high-density burning products in the central region of ejecta
  How pure is it?
  Do we model deflagration correctly?
  Is it another indication of off-center late detonation?
  Or perhaps progenitors we use are not realistic?
Progressive Core Growth Ignition

- Consider a C/O Chandrasekhar mass WD
- Convective rotating core $\Rightarrow$ temperature fluctuations $\Rightarrow$ sparks
- Bubbles are known to be unstable, gravity is low, buoyancy inefficient, but turbulence strong $\Rightarrow$ breakup, quenching
- Core heating $\Rightarrow$ progenitor (pre)expansion $\Rightarrow$ lower central density moderates burning
- Convective core consumes fuel $\Rightarrow$ becomes rich in stable IGEs, grows in size $\Rightarrow$ spark production moves to larger radii
- Greater buoyancy, role of turbulence decreases $\Rightarrow$ sparks more stable
- Once stable enough $\Rightarrow$ successful *overshoot* $\Rightarrow$ *ignition*
What Does It Give Us?

- Partially pre-expanded progenitor
- Stable IGE in the core
- IGE composition possibly from variable density/slow expansion
- Global asymmetry due to rotation

Need a low-Mach flow solver: poster by Ju Zhang
Y12 Detonating Failed Deflagration Model

- subject to detailed validation process
- matches key characteristics of observed objects
- room for improvement identified:
  - too luminous, crude nucleosynthesis,
  - polarized low velocity lines, inadequate RT
- emphasized importance of the initial conditions
- detonation in inertially confined flow
- natural chain of events – no user intervention
- for now the only not “by hand” DD model

**CP1: The initial conditions**
**CP2: The detonation fuse**

*To be continued!*