Probes of the Supernova Engine

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- Direct Probes of the SN Engine
  - Neutrinos
  - Gravitational Waves
- Indirect Probes
  - Progenitors
  - Light Curves
  - Ejecta Remnants
  - Compact Remnants
  - Nucleosynthetic Yields
Supernova 1987A

After – SN 1987A
Before – Sanduleak -69 202
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:
  - Iron dissociates into alpha particles
  - Electrons capture onto protons
  - Core collapses nearly at freefall!

Core reaches nuclear densities
  - Nuclear forces and neutron degeneracy increase pressure

Bounce!
Neutrino-Driven Supernova Mechanism: Convection

Infalling Material Produces Accretion Shock

\[ P_{\text{shock}} = \frac{1}{2} \rho_s v_{\text{ff}}^2 \]

The Convective Region Must Overcome this Pressure to Launch an Explosion

Fryer 1999
Proto-Neutron Star
Accretion Shock
Anatomy Of the Convection Region
Upflow
Downflow
Fryer & Warren 2002
Neutrinos probe the structure of the core and the behavior of matter at nuclear densities (e.g. Roberts et al. 2012, Reddy et al. 2012).

With modern detectors, a Galactic supernova could be used to probe neutrino physics such as neutrino oscillations.
Gravitational Waves

- One of the uncertainties limiting what we can learn from neutrinos is the core rotation.

- Gravitational Waves are direct probes of this rotation.
Gravitational Waves

• For a sufficiently strong signal, we could even probe the nature of the convection.

• Unfortunately, even with the next generation of detectors, such detailed neutrino and gravitational wave signals are limited to Galactic (or local group) supernovae.

Murphy et al. 2009
Indirect Probes

• With indirect probes, we will have to use theory to connect the observations to the physics we want to study.

• With these tests, errors can multiply. Need to constrain the initial conditions and include multiple diagnostics to minimize the errors.
Observing the Progenitor

• Thanks primarily to the HST archive, we now have a growing list of supernovae whose pre-explosion progenitor has been observed.
• However, even with observations, the errors can still be large.
• Better theory is needed to take advantage of this data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass</th>
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<tr>
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<td>SN1993J</td>
<td>~ 15M(_\odot)</td>
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<td>6-12M(_\odot)</td>
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<td>SN2005cs</td>
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<td>~31-35M(_\odot) [62, 63]</td>
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Smartt 2009 + Fryer et al. 2014
Shell Burning

- Shell burning can be explosive (Smith & Arnett 2013, Arnett et al. 2014, Herwig et al. 2014). This will alter the core masses as well as the circumstellar medium.
Stellar Models

Key

• New mixing algorithms may burn helium (through more dynamic shell burning), increasing the $\text{Ic}/\text{Ib}$ ratio (Frey et al. 2013)
Binaries and mass loss

• Binary searches in clusters suggest that >50% of massive stars are in close binaries (Kobulnicky et al. 2012, Sana et al. 2012).

• Mass transfer, Common envelope will affect circumstellar media and, in some cases, stellar structure.

• The strength and asymmetries in wind mass loss has also changed over the last decade.

• All these, mixing, winds, binary effects, can dramatically alter the light curves and we have a lot of work to understand these effects.
• First Pass, an expanding sphere:

\[ L = 4\pi r^2 \sigma T^4 \]

• If we assume adiabatic expansion:

\[ S \propto a T^3 / \rho \rightarrow T \propto S^{1/3} M^{1/3} r^{-1} \]

\[ \rightarrow L \propto r^{-2} M^{4/3} S^{1/3} \]

• What is missing?

- Entropy at photosphere is not constant: Transport, $^{56}{\text{Ni}}$ decay, shock heating.
- Photosphere doesn’t expand with ejecta. Is a photosphere even well-defined?
Applying Early Light-Curve Models

Litvinova and Nadezhin (1985) derived relations for ejecta mass \((m)\), radius \((r)\) and explosion energy \((E)\) as a function of \(V\) magnitude, time since explosion \((t)\) and photospheric velocity \((v)\) based on their simulations:

- \(\log(E_{\text{foe}}) = 0.135 \times V + 2.34 \log(t) + 3.13 \log(v) - 4.205\)
- \(\log(M_{\text{solar}}) = 0.234 \times V + 2.91 \log(t) + 1.96 \log(v) - 1.829\)
- \(\log(R_{\text{solar}}) = -0.572 \times V - 1.07 \log(t) - 2.74 \log(v) - 3.350\)

Hamuy (2003) fits with this formulae predict extremely high masses (too high to be believed).
Difficulties in Modeling Supernovae

• Initial Conditions
  - Progenitor structure, circumstellar medium (progenitor mass ejections), explosion energy, explosion asymmetry

• Radiation Transport
  - Simplifications in solving the Boltzmann Equation
  - Opacities: number of levels, LTE vs. NLTE, steady state approximations
  - Ion/electron coupling

• Radiation Hydrodynamics
  - 1T, 2T, 3T (radiation/matter decoupling)
  - Hydrodynamic shocks and radiation
  - Radiation effects on hydrodynamics
Radiation Transport

\[
\frac{1}{c} \frac{\partial I}{\partial t} + \Omega \cdot \nabla I + (\sigma_a + \sigma_s)I = \int \int I(r,t,\Omega',E')\sigma(E' \rightarrow E,\Omega' \rightarrow \Omega)d\Omega'dE' + S(r,t,\Omega,E)
\]

- Average over angle:
  - First moment: diffusion
  - Second moment: Variable Eddington Factor
- Average over Energy Group: Gray (Rosseland, Planck)
- Remove time dependent term
- Ignore Spatial Terms
Accurate Opacities critical: the kilanova example

- The presence of heavy elements at such cold temperatures requires the calculation of near-neutral ions with many (> 50) bound electrons.
- Furthermore, the presence of the $4f^4$ subshell (lanthanides) requires the seniority quantum number to properly account for the angular momentum coupling when calculating the fine-structure levels (extra code development was required to obtain atomic structure).
- Just 25 configurations leads to 27,000 levels and 300,000,000 lines.
Sm (Z=62) Opacity

\[ \rho = 10^{-13} \text{ g/cm}^3 \]
Radiation Hydrodynamics in Shock Breakout

- Even when the radiation is trapped, it can lead the shock – the shock position moves faster than Sedov solution would predict.
- After breakout, the radiation begins to decouple from the material.
In most core-collapse supernovae, shocks are more important than $^{56}\text{Ni}$ in powering the light curve.
Testing our codes: Physics experiments of Shock Breakout

• The Univ. of Michigan CRASH center developed an experiment to test shock breakout.
• This experiment demonstrated many of the difficulties with modeling shock breakout: radiation pre-heat, turbulence, ….
Opacity Experiments

- Early results showed good agreement with iron measurements, but the most recent iron experiments do not agree with state-of-the-art atomic physics.
- Kurucz results have trouble getting agreement with the atomic physics community.

**FIG. 1.** The sample composition for (a) an Fe+Mg sample and (b) an Al+Fe+Mg sample and their synthetic transmission spectra under 10% gradient with the average $T_e$ and $n_e$ of 195 eV and $8 \times 10^{22}$ cm$^{-3}$. Layer numbers correspond to the subscript $i$ in Eqs. (1) and (2).

Nagayama et al. 2012
Ejecta Remnants – Probing Low Mode Convection

- In most simulations, low mode convection driven by Rayleigh-Taylor or advective-acoustic instabilities seem to dominate the flows.
- Although this has dominated the focus of theorists for nearly 20 years, until recently, we had no evidence of such flows.
NuSTAR has provided a new window in the supernova mechanism
Greffenstein et al. 2014
• The mass distribution of compact remnants (black holes, neutron stars) depends on the nature of the explosion engine. For example, the delay in the engine: 100ms vs. 1s can have a big effect on the long-term masses.
Remnant Masses and the Explosion

Note that, even at low metallicity, variability in stellar mixing can cause the remnant mass to decrease with increasing mass.
Compact Remnants

- The masses of compact remnants can be measured in binary systems (e.g. binary pulsar systems and X-ray binaries) and these observations are producing a growing list of masses.
- Advanced LIGO could dramatically increase these mass estimates.
Distribution of BNS Masses

STD Model: $Z=0.02$ and NS mass $+0.1M_\odot$

- **pulsar (first born)**
- **companion (second born)**

Number of events on the y-axis.

NS mass [$M_\odot$] on the x-axis.
Remnant Masses

By combining

• population synthesis
• merger models
• EOS understanding

we can predict fractions of HMNS, direct BHs, and systems which collapse to a BH after a given time.

If we can distinguish between these events, we ultimately will have a nice probe of the maximum NS mass. Preliminary results argue that we are quite sensitive (but stay tuned).
Probing the Supernova Engine

• Direct probes (neutrinos, gravitational waves) can both probe the supernova engine and nuclear physics. Their drawback is that we need a local group SN for these probes to be effective.

• Indirect probes must be coupled to theory and theoretical uncertainties must be considered in interpreting results.

• BNS mergers are probes of both the lower (determined by progenitor/core-collapse calculations) and maximum (EOS) neutron star masses.