Models of Core-Collapse Supernovae

Outline:
• Core-Collapse Basics
• Status of the Field
• Neutrino Production
  (a selection)

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Core Collapse Supernovae

- CCSNe are some of the brightest astrophysical phenomena in the modern universe.

- Astrophysical importance:
  - nucleosynthesis
  - trigger and regulate star formation
  - source of neutron stars and black holes.

- Unique and fantastic laboratory for studying high density/temperature and neutron rich conditions.
  - Need to observe central engine
    - Neutrinos!
    - Gravitational Waves!

Centaurus A

Damian Peach
SN2016adj
4Mpc!
Collapse Phase

- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000 km, or 1/10^6 of the star’s radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

\[- \frac{3}{5} \left( \frac{GM^2}{1000 \text{ km}} - \frac{GM^2}{12 \text{ km}} \right) \sim 300 \times 10^{51} \text{ ergs} \]

Iron Core
1000 km
M \sim 1.4M_{\text{sun}}

Protoneutron Star
\sim 30 \text{ km}
CCSNe: The Stages

- **Iron core collapse** ($t = -5\text{ms}$)
  - Sonic point
  - $\rho \approx 10^{12} \text{ g cm}^{-3}$

- **Bounce** ($t = 0\text{ms}$)
  - Shock

- **Shock stagnation** ($t = \sim 100\text{ms}$)
  - Stalled shock

- **Explosion** ($t > \sim 200\text{ms}$)
  - Expanded envelope
  - $l \sim 150\text{ km}$
**CCSNe: The Stages**

- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
  - Neutrinos from core heat outer layers
  - Drives convection
  - Turbulence pressure support aids heating and drive explosion
- Very successful in 2D*, many successful explosions
- Success in 3D too: fewer simulations

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*The explosion requires some mechanism to drive explosion.*

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The Core-Collapse Supernova Problem

Understanding the transition from an imploding iron core to an exploding star has been a persistent and difficult problem in astrophysics.

Requires:
- 3D - (Magneto)hydrodynamics
- General Relativity
- Nuclear Reactions
- Progenitors
- Nuclear Equation of State
- Neutrino Transport & Interactions
- Computational Physics

EO & Couch (2018b)
Explosion Successes in multiD – 2D

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Explosion Successes in multiD – 2D

Woosley & Heger (2007) progenitors

Bruenn et al. (2013)

Vartanyan et al. (2018)
Explosion Successes in multiD – 3D

Burrows et al. (2019)

Lentz et al. (2015)

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Explosion Successes in multiD – 3D

Melson et al. (2015b)

\[
\begin{align*}
R_{\text{shock}} & \quad \langle R_{\text{shock}} \rangle \\
R_{\text{gain}} & \quad \langle R_{\text{gain}} \rangle \\
R_{\text{NS}} & \quad \langle R_{\text{NS}} \rangle
\end{align*}
\]

Ott et al. (2018)

Woosley & Heger (2007) progenitors
Global effort towards agreement

- Want to demonstrate the community’s ability to simulate SN
- Comparison of 6 core-collapse supernova codes
- *Very carefully* control input physics and initial conditions to ensure fair comparison

Global Comparison of Core-Collapse Supernova Simulations in Spherical Symmetry

Evan O’Connor¹, Robert Bollig²,³, Adam Burrows⁴, Sean Couch⁵,⁶,⁷,⁸, Tobias Fischer⁹, Hans-Thomas Janka², Kei Kotake¹⁰, Eric Lentz¹¹, Matthias Liebendörfer¹², O. E. Bronson Messer¹³,¹¹, Anthony Mezzacappa¹¹, Tomoya Takiwaki¹⁴, David Vartanyan¹

Journal of Physics: G 45 10 2018
Excellent Agreement in 1D

EO+ 2018

Si/O interface

Radius [km]

Shock Radius
PNS Radius

3DnSNe-1DSA
Agile-Boltztran
FLASH
Fornax
GR1D
Vertex

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Excellent Agreement in 1D

[Graph showing luminosity vs. time for different models, with labels for each curve and a zoomed-in inset highlighting the Si/O interface.]
• When the matter reaches nuclear density and the supernova shock forms, it liberates the nucleons from the nuclei
• Recently freed and no longer suppressed, protons now rapidly capture electrons, producing a burst of $\nu_e$

$$\frac{1}{2} \frac{M_\odot}{m_N} \times 0.2 \times \frac{10 \text{ MeV}}{5 \text{ ms}} \sim 4 \times 10^{53} \text{ erg s}^{-1}$$
Neutronization Burst

- $\nu_e$'s take a bit of time (few ms) before the density at the shock is low enough for the $\nu$'s to escape

- anti-$\nu_e$ and $\nu_x$ neutrinos luminosity is low. anti-$\nu_e$ are suppressed because high electron degeneracy, $\nu_x$ because $T$ is low

- Little progenitor dependence, universal* nature of collapse

Iron core mass increasing ->

Matter temperature increasing ->

Luminosity [10$^{53}$ erg/s]

$\nu_e$

$\nu_x$

$\nu_e$

$\bar{\nu}_e$

$t - t_{bounce}$ [ms]
Accretion Phase: Role of Neutrinos

- After the burst, $\nu_e$ and anti-$\nu_e$ emission is powered by accretion
- Infalling matter is shock heated and then is cooled via neutrino emission
- Charged current processes
- Thermal production processes
- After ~10-20ms, positron production no longer inhibited
- Thermal emission is dominant production process for heavy lepton neutrinos as $T$ is too low for charged-current processes with $\mu$’s and $\tau$’s
Accretion Phase

- The accretion phase introduces first progenitor dependence of luminosities
  - High ‘compactness’: higher mass accretion -> more binding energy released -> higher luminosities

- Detection will reveal progenitor properties and constrain stellar evolution
Standing Accretion Shock Instability (SASI) can impact signal, periodic variations.

Observable in HyperK and IceCube, perhaps not Dune. Timescales too short: \(~10\text{ms}\)
Rotation in Core-Collapse Supernovae

- Rotation impacts neutrinos
  - Less energy released, lower luminosities initially

- Rotating collapse excites the newly formed protoneutron star
  - Correlated signal in GWs and neutrinos
Rotation-induced Oscillations in neutrinos

• Must be close to see such small signal. In IceCube: \( \sim 1 \) kpc

*Realizations take into account statistical noise and detector background noise
Cooling Phase

- How the protoneutron star cools relays info about the EOS -> traced by neutrino emission
- Variations in neutrino luminosities and energies can be detectable and help constrain the nuclear EOS
- Particularly, differences in the $<E>$ between $\bar{\nu}_e$ and $\nu_e$ is important and can impact nucleosynthesis

Horowitz et al. (2016)
Not all core collapses will succeed

- Progenitors of Type II-P CCSNe suggest a maximum mass of \( \sim 16.5 \pm 1.5 \, M_{\odot} \) – but RSG extend to \( 25 \, M_{\odot} \)

- Stellar mass black holes exist!

- We have seen preliminary evidence that massive stars disappear, perhaps following a failed supernovae
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Black Hole Formation

- Failure rate could be ~15%
- Smoking gun signature is prompt shutoff of neutrinos
- Would give detailed information regarding progenitor and nuclear EOS

\[ L_\nu \sim 400 \text{ B/s!} \]
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Summary

• Core Collapse models in multiD explode via the turbulence-aided neutrino mechanism, *across codes and progenitors*

• Models predict several interesting neutrino-signal-related phenomena
  
  • Neutronization Burst (Universal)
  • Neutrino mass ordering likely discernible from signal
  • Accretion Luminosity (probes progenitor)
  • SASI predicts large time variations in signal
  • Rotation predicts correlated neutrino and GW signals
  • Equation of State sets cooling curve over ~5-100s
  • Failed supernovae predict sharp cutoff on neutrinos