Supernovae, Neutrino-Driven Winds, and Nucleosynthesis

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Outline

• Introduction: The Supernova Problem
  – Scales, Important Processes, & Outstanding Questions
• Dynamical Models of Core-Collapse
  – Breakout, Spectra, & Detector Signatures
• Protoneutron Star Winds
  – Neutrino-Driven Outflows & Nucleosynthesis
  – Magnetic Fields
• Summary, Conclusions, & The Future
• What is a Core-Collapse Supernova?
  – An explosion initiated by a dynamical instability
  – The death of a massive star
  – The birth cry of a neutron star or black hole
  – An agent of chemical and dynamical galactic evolution

• Characteristics of Supernovae:
  – Total kinetic energy: \( \sim 10^{51} \) erg
  – Luminous energy radiated: \( \sim 10^{49} \) erg
  – Temperatures: 0.1 – 50 MeV (10 MeV \( \sim 10^{11} \) K)
  – Densities: \( 10^{9} – 6 \times 10^{14} \) g cm\(^{-3}\)

• Neutrino Production:
  – Neutrino energy radiated: \( \sim 2-3 \times 10^{53} \) erg
  – Core is opaque to neutrinos of all flavors! \( \tau_{\text{Diff}} \approx 1 \) s
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(Burrows, Hayes, & Fryxell 1995)

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Dynamical Models of Supernovae

- **Ingredients:**
  - Hydrodynamics: Newtonian, explicit, artificial viscosity
  - High-density EOS: Lattimer-Swesty, liquid drop model (Lattimer & Swesty 1991)
  - Neutrino Transport: Fautrier technique, tangent-ray, ALI (Eastman & Pinto 1993; Burrows et al. 2000)
  - Microphysics: Neutrino opacities, emission/absorption, new inelastic scattering algorithm, bremsstrahlung (Rampp & Janka ‘00, ‘02; Liebendorfer ‘00; et al. ‘01)

- **Tests & Verification**

  Thompson et al. ‘02
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Variations & Detection

- Progenitor Mass: 11, 15, 20, 30, 40, 75 $M_{\odot}$
- Microphysics:
  - Opacities: Neutral-current scattering/10  (Liebendorf ‘00)
  - Nucleon-Nucleon Bremsstrahlung  (Thompson et al. ‘00)
  - Inelastic Neutrino Scattering  (Bruenn 1985; Thompson et al. ‘02)
  - Weak Magnetism/Recoil Correction  (Horowitz ‘97, ‘02)
- Nuclear Compressibility: 180, 220, 375 MeV Modulus
- SK, SNO, ICARUS  
  Thompson et al. 2002
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\[ \langle E_{\nu_\mu} \rangle \]

\[ L_{\nu_\mu} \]

\[ 11 M_{\odot} \]

\[ \text{time (s)} \]

ICARUS, \( D = 10 \text{ kpc} \)

Total \( \nu_e \)

\( \nu_e + \text{Ar} \rightarrow \nu_e + e^- \)

\( \nu_e + e^- \rightarrow \nu_e + e^- \)

All Others

\[ \text{dN/dt} \]

\[ \text{dN/dt} (50 \text{ s}^{-1}) \]

\[ \text{N}(<t) \]

\[ \text{time (s)} \]
Supernova Model Summary

- Dynamical models constructed
- Precision neutrino spectra calculated for several progenitors  
  (AVAILABLE ONLINE! See me!)
- EOS & Opacity variations assessed
- Detector signals calculated

No Explosions in 1D!

(Burrows, Hayes, & Fryxell 1995)
What is the origin of the heavy nuclei we find in nature?

s-Process and r-Process

The Rapid Neutron Capture (r) Process

- Seed nuclei neutron-capture on timescales much shorter than those for beta decay.
- If neutron-to-seed ratio $\sim 100:1 \Rightarrow$ heaviest nuclei.
  - Ratio set by entropy, dynamical timescale, & electron fraction

- The r-process is responsible for roughly half of all nuclei above the iron group.

(Burbidge, Burbidge, Fowler, and Hoyle 1957; Cameron 1957)
The r-Process Path

(from S. Wanajo)

Remarkable Concordance

(Sneden et al. 2000)
Motivation:

Suggests a universal r-process site that acts early in the chemical enrichment history of the galaxy.

(Burris et al. 2000; Cayrel et al. 2001)

What is the astrophysical site?

Possible Sites:

- Protoneutron Star Winds
  - Rate ~ 1 every 50 yr
  - Required mass ejected ~ $10^{-5} - 10^{-6} M_{\text{sun}}$
- Neutron Star-Neutron Star Mergers
  - Rate ~ 1 every $10^5$ yr,
  - Required mass ejected ~ $10^{-1} M_{\text{sun}}$

  – Both are neutron rich
What are the physical characteristics of neutrino-driven winds?

Are these conditions suitable for a robust r-Process?

Entropy, dynamical timescale, and electron fraction

Neutrino-Driven Steady-State Winds

- Physics: eigenvalue problem \( \dot{M} = 4\pi r^2 \rho u \)
  - Three critical, coupled ODEs for \( \rho, T, \) and \( v \)
  - Neutrino heating and cooling
  - Electron fraction \( (Y_e) \) evolution
  - General Relativity, Schwarzschild metric
  - EOS: Arbitrary lepton degeneracy and relativity

Thompson, Burrows, & Meyer 2001

(Paczyński & Prószyński 1986; Duncan et al. 1986)
Wind Velocity Profiles

Radius (km)

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Transonic neutrino-driven winds from 1.4$M_{\odot}$ $R=10$km neutron stars fail to produce 3$^{rd}$-peak r-process nucleosynthesis

Qian & Woosley ‘94; Otsuki et al. ‘00; Thompson et al. ‘01; Wanajo et al. ‘01; Sumiyoshi et al. ‘00; but, see Terasawa et al. ‘02
What about magnetic fields and rotation?
Closed Loops, Trapping, and Entropy Amplification

- Closed loops trap matter, but not permanently

- Trapping Timescale:
  \[ \tau_{\text{Trap}} \approx \frac{B^2/8\pi - P}{q\rho} \]

- Entropy Enhancement:
  \[ \Delta s \approx \frac{\tau_{\text{Trap}}q}{T} \]

  Thompson 2003
Magnetic Protoneutron Star Winds

- Neutrino-driven winds from PNSs with magnetar-like field strengths are magnetically dominated.
- In regions where the field dominates P, closed loops will form.
- These loops may trap matter temporarily, leading to higher asymptotic entropy.
- This entropy enhancement may be sufficient for robust r-process nucleosynthesis.
Some Open Questions

- Complex field topologies
- MHD instabilities
- Convection & Rotation - footpoint motion
- Spindown

The Future

- Dynamical models of explosion, wind emergence, and evolution (reverse shocks, fallback, etc)

- 2D & 3D models of neutrino-driven magnetohydrodynamic protoneutron star winds.
The Fundamental Equations

\[ \frac{dv}{dr} = \frac{v}{2r} \left[ \frac{v^2}{y^2} \left( \frac{1-c_e^2/l_c^2}{c_v^2-v^2} \right) - 4c_e^2 \left( \frac{1-v^2/l_c^2}{c_v^2-v^2} \right) \right] + \frac{D}{c_v T} \dot{q} \left( \frac{1-v^2/l_c^2}{c_v^2-v^2} \right) \]

\[ \frac{dP}{dr} = \frac{2\rho}{r} \left( \frac{v^2-v_e^2/4y^2}{c_v^2-v^2} \right) + \frac{\rho}{v y C_v T} \frac{D}{c_v^2-v^2} \dot{q} \]

\[ \frac{dT}{dr} = \frac{2}{r \rho C_v} \left( \frac{D}{P} + \frac{e}{c^2} \right) \left( \frac{v^2-v_e^2/4y^2}{c_v^2-v^2} \right) + \frac{\dot{q}}{C_v (vy)} \left( \frac{(1-D/l_c^2) c_T^2-v^2}{c_v^2-v^2} \right) \]

where \( D = c^2 \left( \frac{T}{\epsilon + P} \right) \left. \frac{\partial P}{\partial T} \right|_\rho \) and \( y = \gamma \left( 1-2GM/rc^2 \right)^{1/2} \)
Example: Neutrino-Electron Scattering

\[ \dot{q}_{\nu,e} = c n_e n_{\nu_i} \langle \sigma_{\nu,e} \omega_{\nu,e} \rangle = \int \frac{dn_e}{d\epsilon_e} d\epsilon_e \frac{dn_{\nu_i}}{d\epsilon_{\nu_i}} d\epsilon_{\nu_i} \sigma_{\nu,e} \omega_{\nu,e} \]

\[ \omega_{\nu,e} = \frac{1}{2} (\epsilon_{\nu_i} - 4T) \]

\( (\text{Bahcall 1964}) \)

\[ \sigma_{\nu,e} \approx \kappa_i T \epsilon_{\nu_i} \]

\( (\text{Tubbs and Schramm 1975}) \)

\[ \dot{q}_{\nu,e} \approx \frac{c}{\rho} \left[ \frac{T^3}{(\hbar c)^3} \frac{F_2(\eta_r)}{\pi^2} \right] \frac{L_p}{4 \pi R^2 c(\epsilon_{\nu_i})} \Phi^4 \frac{2 \Xi(r)}{r} \text{erg g}^{-1} \text{s}^{-1} \]

\[ \times \left[ \frac{\kappa}{2} \frac{F_4(\eta_r)}{F_3(\eta_r)} \right] \left( \frac{\langle \epsilon_{\nu_i} \rangle}{\Phi} \frac{F_4(\eta_r)}{F_3(\eta_r)} - 4T \frac{F_3(\eta_r)}{F_3(\eta_r)} \right] \]

\( (\text{Also Tubbs 1975; Janka 1999; Salmonson and Wilson 1999}) \)

Neutrino Interactions: Heating and Cooling \( (\dot{q}) \)

- **Charged Current**: \( \nu_e n \leftrightarrow e^- p \) and \( \nu_e p \leftrightarrow e^+ n \)
  also affect \( Y_e \) evolution

- **Scattering**: \( \nu_i e^{-} \leftrightarrow \nu_i e^{-} \) and \( \nu_i n, p \leftrightarrow \nu_i n, p \)

- **Pair Processes**: \( e^- e^+ \leftrightarrow \nu_i \bar{\nu}_i \)
Tools:

- **Algorithm:**
  - 2-point boundary value problem
  - Relaxation on adaptive radial mesh
    (London and Flannery 1982)

- **Physical BCs:**
  - Optical depth
  - Triple Newton-Raphson
  - Sonic Point ($v = c_s$)

\[
\tau_v(R) = \frac{2}{3} = \int_R^{\infty} \kappa \rho \, dr
\]

\[
\dot{q}(R) = 0; \quad \left. \frac{dY_e}{dr} \right|_R = 0
\]

Mass Density Profiles

Density (g/cc) vs. Radius (km)

- $M_e = 1.4 M_\odot$
- $R_e = 10$ km
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**Matter Temperature**

- **Temperature (MeV)** vs **Radius (km)**
- Curves indicate different neutrino luminosities and matter temperatures.
- Critical point marked.

**The Neutrino Heating Rate**

- **Energy Deposition Rate** vs **Radius (km)**
- Various symbols and lines represent different heating rates.
- Observation of quick asymptotes and formation points.

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Composition

\[ Y_e^a \sim 0.48 \]

Dynamical Timescale

- Increased by including GR
  - Redshift
  - Bending of null geodesics
- Not constant, evolves in radius

\[ \tau_\rho \propto L_v^{-0.75} \langle \epsilon_v \rangle^{-2.6} \]

Thompson, Burrows, & Meyer 2001
Asymptotic $Y_e$

is set by ratio of luminosities and magnitude of energies.

$$Y_e^a \approx \frac{\Gamma_{e,n}}{\Gamma_{e,n} + \Gamma_{\nu,n}} \approx \left( \frac{L_{e\nu} \langle \epsilon_{\nu} \rangle - 2\Delta + 1.2\Delta^2 / \langle \epsilon_{\nu} \rangle}{L_{\nu} \langle \epsilon_{\nu} \rangle + 2\Delta + 1.2\Delta^2 / \langle \epsilon_{\nu} \rangle} \right)^{-1}$$

$Y_e^a > 0.45$  \hspace{1cm} (Qian et al. 1993)

Asymptotic Entropy

- Increased 20-30 units by GR: more compact
- Important Feedbacks
  - Cannot arbitrarily increase net heating
  - Broader deposition profile increases $s$

$$S_a \propto L_{\nu}^{-0.15} \langle \epsilon_{\nu} \rangle^{-0.4}$$
Modeling Evolution with Steady-State Winds

- Posit L_ν(t), R(t), and ε_ν(t)
- Calculate mass ejected
  \[ M_{\text{ejected}}(t) = \int_{0}^{t} \dot{M}(t') \, dt' \]
- Timescales:
  - Sound crossing time
  - Escape time
  - Luminosity decay time
  \[ \tau_{\text{sound}}, \tau_{\text{escape}} \ll \tau_{\text{decay}} \]

Assessing the Wind’s Potential for r-Process Nucleosynthesis

What is the neutron-to-seed ratio in the wind?

- Entropy
  - asymptotes in \sim 100 \, \text{km}
- Y_e
  - asymptotes in \sim 10 \, \text{km}
- Dynamical Timescale
  - sets slope of density profile
  \[ \tau_{\rho} = \frac{1}{(\nu_y)} \left[ \left. \frac{1}{\rho} \frac{\partial \rho}{\partial r} \right|_{T=0.5 \text{MeV}} \right]^{-1} \]