Core Collapse Supernovae

Perspectives on the Core Collapse Supernova Mechanism

Explosion Mechanism

Pre-Explosion Post-Explosion
Progenitors
Fe Core Masses

Rauscher et al. 2002
Limingi & Chieffi 2003
Thielemann et al 1996
Progenitors

• Uncertainties
  A. Certain reaction rates, particularly $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
  B. Weak Interactions
  C. Mass loss
  D. Convection
  E. Rotation & Magnetic Fields
\( ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \) rate

I. Rate still uncertain by a factor \( \sim 2 \) after 30 yrs

II. Determines, along with convection, \( X(^{12}\text{C}) \) and \( X(^{16}\text{O}) \)

A. \( 2\alpha(\alpha,\gamma)^{12}\text{C} \)

B. \( ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \) rate

III. Effects are convolved with convection

A. Low-mass stars - semiconvection
   (Castellani et al. 1985. Imbriani et al. 2001)

B. Massive stars - overshooting

IV. \( X(^{12}\text{C}) \) affects mass-radius relation of star, and therefore,

A. mass of the remnant

B. nucleosynthetic yields
Effect of $X^{(12C)}$ on the Size of the Remnant

$M(R)$

$R(E_{expl})$

$X_1^{(12C)}$

$X_2^{(12C)}$

$X_1^{(12C)} < X_2^{(12C)}$
\[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \text{ rate} \]

V. Rate can be inferred modulo convection, by

A. Yields (some elements scale directly with \(X(^{12}\text{C})\), some inversely) (Weaver & Woosley 1993, Imbriani et al. 2001)

\[
\begin{align*}
X(^{12}\text{C}_1) & > X(^{12}\text{C}_2) \\
\end{align*}
\]


$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ rate

B. Surface appearance during central He burning


V. Observations suggest $X(^{12}\text{C}) \sim 0.2$ after He burning
Weak Interactions

I. Effects:
   A. Sensitively affects nucleosynthesis of nuclei with $N = Z$
   B. Determines progenitor structure, in particular, the size of the Fe core, since pressure is mainly due to degenerate electrons.

II. Uncertainties
   A. Many excited states of nuclei with uncertain properties are involved
   B. However, kinetic equilibrium sets in after Si exhaustion, and $Y_e$ converges to $\sim 0.43$ (Heger et al 2001a,b)
Mass Loss

I. Mass loss rates
   A. Rates are highly uncertain except for wind-driven mass loss from hot stars
   B. MLR increases with metallicity
   C. MLR increases with mass
   D. MLR increase with rotation (Vardya 1985, Nieuwehuijzen & de Jager 1988), but rate of increase controversial

II. Effects of mass loss
   A. Significant loss of angular momentum (Langer & Heger 1998)
   B. Outer layers of stars undergo more differential rotation with increase in mass because of increased mass loss (Maeder & Maynet 2000)
   C. Composition structures can be different for the same final mass if the initial masses are different
Convection

I. Overshoot
   A. Possible occurrence
      1. Borders of formally convective regions
   B. Possible effects
      1. Convective overshoot determines lower mass limit of SN progenitor
      2. Possible merging of multiple burning shells of heavy elements

II. Semiconvection
   A. Possible occurrence
      1. Regions that are Ledoux stable but Schwarzschild unstable
      2. Opacity increase beyond a convective border (e.g., He-H interface in massive stars (Schwarzschild & Härm 58))
      3. Opacity decrease beyond a convective border (e.g., CO-He interface in a low mass star (Castellani et al 1995))

III. Convective and nuclear time scales become comparable during the latest evolutionary stages
Semiconvection

Colder, low-μ material

Hotter, high-μ material

Heat

μ
Rotation & Magnetic Fields

I. Observations

A. Upper MS stars typically rotate with 
\[ v_{\text{equator}} \sim 200 \text{ km s}^{-1} \] (Fukuda 1982)

B. Effects attributed to rotation

1. He-enrichments in fast O rotators (Herrero et al. 1992, Maeder & Maynet 2000)
2. Rise in He/H ratios with \( t/t_{\text{ms}} \) for O and B stars (Lyubimkov 1996)
3. N/H enhancements in O and B supergiants (Herrero et al 1999, McEarlean et al 1999, Venn 1995a,b))
4. The ratio of the number of blue to red supergiants in galaxies (ratio increases rapidly with Z) (Langer & Maeder 1995)
5. SN 1987A?, e.g., blue supergiant progenitor, N enhancements in circumstellar material
6. Others…
Rotation & Magnetic Fields

II. Models

A. Equations can be made 1-dimensional
   1. Case that effective gravity is conservative (e.g., $\Omega$ constant on cylinders) (Kippenhahn & Thomas 1970)
   2. Shellular rotation (e.g., $\Omega$ constant on isobars) (Zahn 1992, Meynet & Maeder 1999, 2000)

B. Transport of Composition and angular momentum must be incorporated “by hand”
   1. Transport of $x$ different than that of $J$
      a) $X$: diffusion and advection operate on $\Omega$
      b) $J$: diffusion and advection operate on $(\text{rsin}\theta)^2\Omega$
      c) Result is that vertical transport of composition is much smaller than angular momentum
2. Mixing mechanisms

a) Eddington-Sweet circulation (Eddington 1925, Vogt 1925, Sweet 1950, Mestel 1953)

b) Shear Instabilities (Zahn, 1992, 1994)
   - Dynamical (adiabatic)
   - Secular (induced by thermal conduction)
Rotation & Magnetic Fields

c) Solberg-Høiland instability
( semiconvection?)

d) Goldreich-Schubert-Fricke (Goldreich & Schubert 1967, Fricke 1968)
• Solberg-Høiland with heat conduction
• flows driven if the rotational profile is not conservative
C. Effects of Rotation, Rotational Mixing and Redistribution of Angular Momentum

1. Sun
   a) Solid-body rotation of core
   b) Solid, longitudinal velocity preserving rotation of envelope

2. Composition mixing processes more efficient in more massive stars, but inefficient after MS phase

3. Leads to larger He and C-O cores (sensitive to treatments of $\mu$-gradients) (Heger & Langer 2000, Maeder and Maynet 2000) -- Star behaves like a larger MS star

4. Mass loss rates are increased (Langer, 1998)
5. Favors production He and other alpha-rich nuclei

6. He and C ejection by winds

7. Does the core collapse rotating rapidly or slowly?
   a. Breakup rotation at C-burning (Endal & Sofia 1978)
   b. 10 rad s\(^{-1}\) at core collapse, \(f_\mu = 0.05\) (Heger et al 2000)
   c. 100 rad s\(^{-1}\) at core collapse, \(f_\mu = 0\) (Heger et al 2000)

8. What about magnetic fields?
   a. Magnetic coupling will lead to very slow rotation (Spruit 1998, Spruit & Phinney 1998)
   b. Magnetic coupling is not so strong (Livio & Pringle 1998)
Pulsar Kicks

I. Observations

A. Distribution wrt galactic plane
B. Pulsar-supernova remnant associations
C. Measured proper motions
D. Scintillation speed measurements

A, B, C, D ⇒

\[ P(v_1; \sigma_1, \sigma_2, w) = \frac{w}{\sqrt{2\pi\sigma_1}} e^{-v_1^2/2\sigma_1^2} + \frac{1 - w}{\sqrt{2\pi\sigma_2}} e^{-v_1^2/2\sigma_2^2} \]

\( \sigma_1 = 99 \text{ km s}^{-1} \) 1-D (170 km s\(^{-1}\) 3-D)
\( \sigma_2 = 294 \text{ km s}^{-1} \) 1-D (507 km s\(^{-1}\) 3-D)
\( w = 0.2 \)

Pulsar Kicks

II. Models

A. Prenatal --- binary disruption
   1. Leads to ~ 150 km s\(^{-1}\) rms velocities << observed velocities
   2. Cannot explain the alignment between the projected spin axis and proper motion (for Vela and Crab)
   3. Cannot explain the spin-orbit misalignment in the binary pulsar systems

B. Natal --- momentum impulse imparted through asymmetry of explosion
   1. Prompt Convection: \(v_{\text{kick}} < 220\) km s\(^{-1}\), typically, \(v_{\text{kick}} \sim 50 - 100\) km s\(^{-1}\) (Janka & Müller 1994)
   2. Convection above v-sphere: \(v_{\text{kick}} < 500\) km s\(^{-1}\), typically, \(v_{\text{kick}} \sim 50 - 120\) km s\(^{-1}\) (Janka & Müller 1994)
   3. Aspherical accretion: \(v_{\text{kick}} < 220\) km s\(^{-1}\) (Janka & Müller 1994)
Pulsar Kicks

4. Global Asymmetries:
   a. g-modes in the supernova progenitors (Lai & Goldreich, 2000)
Pulsar Kicks

i. $v_{\text{kick}} \sim 530 \text{ km s}^{-1}$ (Burrows & Hayes 1996)

ii. $v_{\text{kick}} < 200 \text{ km s}^{-1}$ (Fryer 2004)

b. vortical-acoustic instability in standing accretion shocks (Blondin, et al. 2003)

i. $v_{\text{kick}} \leq \sim 500 \text{ km s}^{-1}$ (Scheck 2004)
Pulsar Kicks

C. Postnatal

1. E&M rocket due to off-center, misaligned M-dipole (Harrison & Tademaru 1975, Lai et al. 2001)

\[ \nu_{\text{kick}}^{\text{max}} \approx 1400 \left( \frac{1 \text{ ms}}{P_{\text{ms}}} \right)^2 \text{ km s}^{-1} \]

   a. Requires \( P_{\text{ms}} \approx 1 \text{ ms} \) to generate large velocities
   b. Fails if gravitational radiation carries away most of the energy
   c. Spin-orbit misalignments in binary pulsars may be a problem
   d. May be inconsistent with neutron star binary populations

2. Asymmetric neutrino radiation

\[ \varepsilon = c \left( \frac{M}{1.4M_\odot} \right) \left( \frac{v_{\text{kick}}}{1000 \text{ km s}^{-1}} \right) \left( \frac{3 \times 10^{53} \text{ ergs}}{E_{\text{expl}}} \right) \]
Pulsar Kicks

a. Weak interaction parity violation in the presence of strong magnetic fields (Vilenkin 1995, Arras & Lai 1999a, 1999b)

\[ v_{\text{kick}} \sim 50 B_{15} \text{ km s}^{-1} \]

b. Difference in field strengths at the two opposite stellar poles (Lai & Qian 1998)

\[ \Delta B \sim 10^{16} \text{ G} \]

c. Neutrinosphere “spots” (Thompson & Duncan 1993)

\[ B \geq 10^{15} \text{ G} \]
Bipolar Explosions

I. Evidence for bipolar explosions

A. Polarization (Shapiro & Sutherland 1982)

  (Wang et al. 2001); SN 1998S (Leonard et al. 2000); SN 1999em Leonard et
  al. 2001); SN 1997ds, SN 1998A, SN 1999gi (Leonard & Filippenko 2001); SN
  2002ap (Wang et al. 2003)

1. Core collapse SN are polarized at ~1% level
2. Degree of polarization increases with decreasing envelope mass
3. Degree of polarization generally increases after optical maximum


C. SN - γ-ray burst connection extrapolated to lower energies?

D. Axisymmetric ejecta of SN1987A (Wang et al. 2002)

1. Bipolar structure of ejecta
2. Ejection of $^{56}$Ni at velocities $\geq 5000$ km s$^{-1}$
Bipolar Explosions

E. Light curve modeling of SNe 1998bw, 1997ef, & 2002ap (hypernovae) are better fit with bipolar explosions (Maeda et al. 2003, Maeda & Nomoto 2003)


G. Distribution of matter densities exposed to high temperatures (Maeda & Nomoto 2003)
Bipolar Explosions

1. Enhanced production of α-rich freezeout material (e.g., $^{44}$Ti)
2. Inversion of the velocities among the various isotopes (cf., Ni bullets in Cas A)
3. Extremely metal poor stars
   a. $(\text{Sc,Ti})/\text{Fe} > \text{solar}$: (α-rich freezeout)
   b. $(\text{Si,S})/\text{Fe} < \text{solar}$ (accretion of incomplete Si burning products)
Explosion Mechanisms

I. Neutrino Transport


C. Rotational with polar jets arising from the rotational suppression of equatorial convection (Fryer & Warren 2002, 2004)

D. Rotational with polar neutrino beaming arising from a highly oblate neutrinosphere (Yamada & Sato 1994)

II. Magnetohydrodynamical
