What the Emerging Theory of Core-Collapse Supernova Explosions May Say About the Morphology of Their Remnants

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Important Questions in Supernova Theory

- Mechanism of explosion?
- Pulsar Kicks (proper motions)?
- Nucleosynthesis: Nickel, etc. Yields?
- R-process site?
- Blast Morphology (and polarization)?
- Pulsar Spins?
- Pulsar/AXP/Magnetar B-fields?
- Black Hole formation?
- Systematics with progenitor (and role of rotation/magnetic fields)?
- Connection with GRBs and Hypernovae?
Progenitor Star

Iron Core

Collapsing Core (~1.3 M)

Early Supernova

Hot Supernova Remark

Early Protonucleus Star

Core Protonucleus Star
Density Profiles of Supernova Progenitor Cores

Neutrino-driven Wind Explosions?

Mechanism? 3D Neutrino; Acoustic? MHD Jet?

2D SASI-aided, Neutrino-Driven Explosion?
Observed Asymmetry

Cas A SN Remnant: Chandra
Element Asymmetries in Cas A Remnant

DeLaney et al. 2009
Asymmetries in Supernovae and Remnants (cont.)

- **G11.2-0.3** remnant: Dense Fe Ejecta in Near IR - Asymmetrical line profiles (Moon et al. 2008)
- OI Doublet line shapes for many CCSN (e.g., SN 2007gr, SN 2007rz, SN 2007uy, SN 2008ax, SN 2008bo) evidence for asphericities (Milisavljevic et al. 2009)
- Ejecta Asphericity in Type Ib/c (39 SNe): Overall asymmetries in OI in ~39%: Evidence of no “jet” in most (Taubenberger et al. 2008)
- **SN 2005bf**: Spectropolarimetry = Large Top-bottom Asymmetry in Fe distribution and non-Coplanarity - larger, later (M. Tanaka et al. 2009)
Leonard et al. 2006

**POLARIZATION!**
Mechanisms of Explosion

- Direct Hydrodynamic Mechanism: always fails?
- Neutrino-Driven Wind Mechanism, ~1D (Burrows 1987) Lowest-mass massive stars, ~spherical (e.g., 8.8 solar masses, Kitaura et al. 2006, Burrows, Dessart, & Livne 2007)
- Convection/SASI-aided (Burrows et al. 1995; Blondin et al. 2003) Neutrino-Driven Wind Mechanism, 2D (e.g., 11.2 solar masses, Buras et al. 2006)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf (Dessart et al. 2006)
- Acoustic Power Mechanism (after delay), all progenitors explode (Burrows et al. 2006, 2007a)
Mechanisms of Explosion (cont.)


- MHD Jet Explosions - requires rapid rotation (e.g., Burrows et al. 2007b)

- The Key feature of almost all mechanisms is the Breaking of Spherical Symmetry
Neutrino-Driven Wind Explosions: Low Mass Progenitors
8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion

First shown by Kitaura et al. 2006

Burrows, Dessart, & Livne 2007;

Burrows 1987

NOTE

WIND

THAT

FOLLOWS

ONeMg: 8.8 Msun

Time = -500 ms

Radius = 300.00 km
Gain (Heating) Region
Cooling Region
Convective/SASI

\[ M \]
\[ L \]
\[ \nu \]

Shock
Shock
Shock

\[ \tau_{\text{adv}} \]
\[ \tau_{\text{H}} \]

2D/3D > 1D

(TQB 2005)

\[ \tau_{\text{adv}} : \]

What happens in 3D?
Marek & Janka 2009: 15 solar-mass model with soft (180 MeV) EOS, 1D “ray-by-ray” transport, 2D hydro:

- Higher-resolution, stiffer EOS - don’t explode??
- Long delay, weak explosion (?)
- $R_{\text{shock}}$ to $\sim 600$ km
- Higher-resolution. Smaller radius

GR?
Bruenn, Mezzacappa et al. 2009 with soft EOS, 1D “ray-by-ray” transport, 2D Hydro:

What is the difference?, What’s new? Inelastic scattering??, nuclear burning? …

**FIGURE 3.** Explosion energies as a function of post-bounce time.
VULCAN/2D Multi-Group, Multi-Angle, Time-dependent Boltzmann/Hydro (6D)

- Only code with multi-D transport used in supernova theory
- Arbitrary Lagrangian-Eulerian (ALE); remapping
- 6-dimensional (1(time) + 2(space) + 2(angles) + 1(energy-group))
- Moving Mesh, Arbitrary Grid; Core motion (kicks?)
- 2D multi-group, multi-angle, \( S_n \) (~150 angles), time-dependent, implicit transport (still slow)
- 2D MGFLD, rotating version (quite fast)
- Poisson gravity solver
- Axially-symmetric; Rotation
- MHD version (“2.5D”) - div \( B = 0 \) to machine accuracy; torques
- Flux-conservative; smooth matching to diffusion limit
- Parallelized in energy groups; almost perfect parallelism
- Livne, Burrows et al. (2004, 2007a)
Limitations of the VULCAN/2D Simulations

- Doppler shift terms not included in transport
- Inelastic redistribution not included (though subdominant), though could be
- No good (but ...) development path to 3D
Limitations of the ORNL Simulations

- Transport in 1D ("ray-by-ray"): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Energy conservation to only ~0.5 Bethes
- Core must stay at grid center (kicks?, acoustic mechanism?)
- Role of Nuclear Burning at Shock?
- Large Stalled Shock Radius?
Limitations of the MPIA Simulations

- Transport in 1D (“ray-by-ray”): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Core must stay at grid center (kicks?, acoustic mechanism?)
- (ORNL and MPIA 15-solar-mass explosion simulations very discrepant)
But, in 3D?
Critical Curve

Explosions!
(No Solution)

Steady-state accretion
(Solution)

$L_{ve}$

$\dot{M}$

Burrows & Goshy ‘93; Murphy & Burrows 2008
Steady-state solution (ODE) and Hydrodynamic Parameter Study
How do the critical luminosities differ between 1D and 2D?
Shift due to different mass cores

Murphy & Burrows 2008
3D and the Neutrino Mechanism?

Still Open Question
Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

Rapid Rotation!
AIC: 1.92 solar masses:
Core Oscillation/Acoustic Power Mechanism
Inner 600-km Look at the Advective-Acoustic Instability
Entropy

Density Isosurfaces

t = -199.98 ms
MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation

Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

Rotation Winding, the MRI and B-field Stress effects
MHD Jet Powers for Rapidly-Rotating Cores

HYPERNOVAE?
Pulsar Kicks: Pulsar B2224+65 and Bow Shock
V ≥ 1000 km s\(^{-1}\)

Cordes, Romani, Lundgren ‘93

Guitar Nebula
Pulsar Kicks

- Puppis A (RX J0822-4300) - 112 ms pulsar, weak field (Pdot) at birth (Gotthelf and Halperin 2008) - evidence against electromagnetic kick
- Puppis A (RX J0822-4300): kick of ~1500 km s\(^{-1}\) (transverse) (Winkler and Petre 2007) - asymmetric explosion, imparting ~3 \(\times\) 10\(^{49}\) ergs in kick K.E. - Oxygen knot recoil?
- Supernova kicks and misaligned Be Star Binaries (Martin, Tout, and Pringle 2007)
- Spin-Kick Correlation of Young Pulsars (Ng and Romani 2007)
Top-Bottom Asymmetry in Neutrino Luminosity after Explosion: Kicks!

![Graph showing Top-Bottom Asymmetry in Neutrino Luminosity after Explosion](image)

Solid line: $-z$
Dashed line: $+z$

$13M_\odot$ WHW02

$\nu_e$, $\bar{\nu}_e$
Multi-D: Simultaneous Explosion and Accretion is the Key?

- **Neutrino Mechanism**: Anisotropic $l=1$ explosion --> lower ram pressure at head, larger neutrino heating region, while accretion elsewhere maintains neutrino luminosity to drive the explosion.

- **MHD-Rapid rotation**: Explosion along poles, accretion of free rotational energy at equator (engine).

- **Acoustic Mechanism**: Explosion in one direction, accretion funnels from another, powering oscillation to maintain acoustic power.
Extra Slides
Multi-Dimensional Core-Collapse Simulations: Explosion Mechanisms

(A. Burrows, J. Dessart, E. Livne, C. Ott, J. H. Haney, & J. Murphy)

CAC
Computational Astrophysics Consortium

Core Oscillation: Acoustic Mechanism

2-D Multi-Group Radiation Magnetohydrodynamic Capability: VULCAN

Many New Simulation Results

New BETHE Code Development: Multi-D Neutrino Mechanism

BETHE: Hydro
- Compatible Arbitrary Lagrangian-Eulerian (A.L.E.) approach
- Multidimensional timeshifted shock tubes
- Non-linear compressible advection
- Implicit Eulerian advection
- Inviscid/heat flow
- Shock and core oscillation to late explosion

BETHE: Transport
- Radiation transport
- Shock-heated fluid models
- Power-law opacity
- Blackbody emission
- Multi-group, multi-angle
- Multi-composition, multi-angle
- Absolute transfer
- Multi-composition, multi-angle

3D General Relativistic Rotational Collapse
- Gravitational Radiation

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