MHD-driven Core-Collapse Supernovae in Three Dimensions

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Core-Collapse Supernovae:
Explosions of Massive Stars

\[ 8M_\odot \leq M \leq 130M_\odot \]

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Core-Collapse Supernovae: Explosions of Massive Stars

8M☉ ≤ M ≤ 130M☉

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69 220a, 18 M☉
Core Collapse Basics

Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (\(\sim 0.5 \, M_{\odot}\))
- \(\rightarrow\) protoneutron star core.
  Shock wave formed.

Outer core accretes onto shock & protoneutron star
with \(O(1) \, M_{\odot}/s\).
- \(\rightarrow\) Shock stalls at \(\sim 100\) km, must be “revived”
to drive explosion

Reviews:
Bethe’90
Janka+‘12
Hyperenergetic Supernovae

Small fraction (0.1-1%) of CCSN:

- Hyperenergetic (10 - 100 B)
- doppler-broadened lines (Type Ic-bl)
- Relativistic outflows
- Some connected to long gamma-ray bursts

Supernova 1998bw
Image Credit: ESO
Hypernovae & GRBs

http://apod.nasa.gov/apod/ap000628.html
• 11 long GRB - core-collapse supernova associations.

• All GRB-SNe are of type “Ic-bl”: no H, He in spectra, relativistic velocities (bl: “broad lines”), hypernova energies ($\sim 10^{52}$ erg).

• But not all type Ic-bl supernovae come with GRBs

• Trace low metalliclicity and low redshift

• Neutrino mechanism is inefficient ($\eta \sim 10\%$); can’t deliver a hypernova.
• What mechanism/engine drives these extreme explosions?

• What determines additional XRF/GRB launch?
Magnetorotational Mechanism

[LeBlanc & Wilson ‘70, Bisnovatyi-Kogan ’70, Obergaulinger+’06, Burrows+ ‘07, Takiwaki & Kotake ‘11, Winteler+ 12]

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI]; difficult to resolve, but see, e.g, Obergaulinger+’09)

2D: Energetic bipolar explosions.
Energy in rotation up to 10B.

Results in ms-period proto-magnetar.
GRB connection?

Caveats: Need high core spin; only in very few progenitor stars? Magnetic field amplification?
Detailed Models: Ingredients

- Magneto-Hydrodynamics → Dynamics of the stellar fluid.
- General Relativity → Gravity
- Nuclear and Neutrino Physics → Nuclear EOS, nuclear reactions & ν interactions.
- Boltzmann Transport Theory → Neutrino transport.

• Additional Complication: Core-Collapse Supernovae are 3D
  • Rotation, fluid instabilities (convection, turbulence, advective-acoustic, rotational), MHD, multi-D structure from convective burning → Need 3D treatment.

• Route of Attack: Computational Modeling
  • Turbulence on scales 10 m but relevant radius of star is at least 10⁷ m; simulation timestep is 10⁻⁶ s but cooling time of protoneutron star is 10 s
3D Dynamics of Magnetorotational Explosions

Initial configuration as in Takiwaki+11, $10^{12}$ G seed field.

Octant Symmetry (no odd modes)  Full 3D
What’s going on here?

- m=1 spiral instability
- Growth rate, wavelength and helicity of fastest growing mode consistent with MHD kink instability; should hold independent of initial B-field strength

\[ \tau_{fgm} \approx \frac{4 a \sqrt{\pi \rho}}{B_{\text{tor}}} \approx 1 \text{ ms} \]

\[ \lambda_{fgm} \approx \frac{4 \pi a B_z}{B_{\text{tor}}} \approx 5 \text{ km} \]
MHD Kink Instability

- B-field near proto-NS: $B_{\text{tor}} \gg B_z$
- Unstable to MHD screw-pinched kink instability.
- Similar to situation in Tokamak fusion reactors!

Credit: Moser & Bellan, Caltech

Sarff+13

Braithwaite+ ’06
MHD Kink Instability

3D: Plasma flow unstable to MHD “kink” instability

Key for instability: $B_{\text{tor}}/B_z > 2\pi a/L$

[Shafranov+’56, Kruskal+’58]

$$\nabla (\rho + \frac{B^2}{8\pi}) = \frac{1}{4\pi} (B \cdot \nabla) B$$

- Magnetic pressure driven
- cannot be countered by magnetic tension
Entropy

Mösta et al. 2014
3D Volume Visualization of

\[ \beta = \frac{P_{\text{gas}}}{P_{\text{mag}}} \]

Mösta et al. 2014

\[ t = -4.95 \text{ ms} \]
Ongoing Simulation

- Tracking shock with lower resolution as scales become larger and larger
- Follow evolution with tracer particles to extract nucleosynthetic yields

Explosion?
Ongoing Simulation

- Geometry becomes even more tilted, but general wide-lobed trend continues.
- Expansion speed few percent of the speed of light; very different from 2D jet explosion.
Implications for Gamma-Ray Bursts

• Long gamma-ray bursts come with extreme supernovae.

• Central engine of GRB: black hole or neutron star?

• Simulations show: continued accretion on the equator in supernova phase.

• Favors formation of black-hole engine (collapsar).

Supernova remnant W49B; harboring a black hole? (Lopez+2013)
Summary

• MHD supernovae (and other high-energy astro systems) need to be modeled in 3D

• Developing jets become ‘kink’-unstable, but highly magnetized outflows drive shock into dual-lobe structure that transitions into explosion

• Accretion continues and mass of the proto-NS increases -> Allows for magnetar and collapsar LGRB models

• Implications for r-process in jet-driven outflows
Thank you!