Multidimensional modeling of core-collapse supernovae: New challenges and perspectives

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Outline

- Introduction
  - Current status/importance of multi-dimensional SN models
- 3D Supernova Explosion Models and Signatures of Gravitational Waves
- MHD collapse and explosions of massive stars
- Summary (with perspectives)
Core-collapse Supernovae
marking catastrophic ends of massive stars (> ~10 M$_{\text{sol}}$)

Not yet!
A kind of Rosetta stone

GW astronomy
Up to now only SN1987A

Relevance to
Neutino Astronomy

Neutron stars/Black holes
Magnetars
Nucleosynthesis, etc..

The explosion mechanism is still a topic of debate over 40+ years.
Neutrino heating mechanism

- Best-studied and most promising way to explode massive stars.

(Wilson ’82, Bethe & Wilson ’85)

**neutrinos diffuse** out of opaque proto-neutron star \( (\tau_\nu \sim 1) \)

**neutrinos heat matter** in semi-transparent \( (\tau_\nu \sim 1) \) post-shock region ---* convection with coexisting downflows and rising hot bubbles *sets in*

**neutrinos stream freely** through stellar envelope \( (\tau_\nu << 1) \)

Illustration adapted from Mezzacappa (2003)
Energy budget problem

Typical observed explosion energy:

\[ E_K \sim 1 - 2 \times 10^{51} \text{erg} \]

Releasable energy = binding energy of neutron star,

\[ \approx 3 \times 10^{53} \text{erg} \left( \frac{M}{1.4 M_{\odot}} \right)^2 \frac{10 \text{km}}{R} \]

essentially carried away by neutrinos.

For the neutrino heating mechanism working,

• ~1% energy transfer via neutrinos to matter.
• Energy conservations should be kept < 1%, over the entire simulations (for 2D, \sim 10^{20} operations, 1 CPU year/ one simulation @ 10Tflops supercomputer.)
• Supernova simulations (6D radiation-hydro problem):
  Grand challenge in computational astrophysics.
Looking back 40+ Years of Modeling & Theory

- Bounce shock always stall. Direct "prompt" hydrodynamic explosion fails.

- **Neutrino-heating mechanism** (Wilson '82, Bethe'85) in spherical symmetry (may work for lower mass progenitors with O-Ne-Mg cores) (Kitaura et al. 2006) fails to explode massive stars with iron cores.
  
  (Rampp&Janka 02, Liebendoerfer+.02, Sumiyoshi+04)

- CC SNe are generally aspherical.
  
  (Wang+.01,02)

- Multidimensional explosions are favorable for reproducing the synthesized elements.
  
  (Nagataki+.97, Maeda+.03, Kifonidius+.07, Maeda+08…)

Multidimensional modeling is crucial!
A garden variety of candidate mechanisms

○ Neutrino-heating mechanism + convection/SASI:
  SASI: Low modes oscillatory instability of standing accretion shock
  : Explosion of 2D, low-stars (11.2 Ms), (Buras+ 2006)
  : Onset of SASI-aided neutrino driven explosion of 15 Ms star
    (Marek & Janka 07)

○ Acoustic mechanism: (Burrows+ 2005,6, Ott+07)

○ Rapid Rotation & Anisotropic neutrino radiation:
  (Shimizu,Sato+94, KK+ 03, Walder+05,Ott+08)

☆ Which one is the final answer?
☆ Some 2D models show (weak) explosions, however,
  (Marek, Janka 07, Burrows+06).

do they explode in 3D?
☆ To look into the heart of the engines: gravitational waves (GWs)
  (plus neutrinos) should be helpful (albeit for a galactic source).
• SASI/Convection-aided neutrino-driven explosion in 3D and the gravitational-wave signatures

Even for 2D, it takes more than 1 CPU year for 1 run. Setting 100 angular grids for $\phi$ direction (360 degree), it may take more than 100 years (!) for 1 run in 3D.
Standing shock

$\nu_5$ km

Contracting neutron star interior is replaced by the fixed boundary.

Changing the neutrino luminosity, we hope to study qualitatively how the GW waveforms change with the explosion dynamics. (This simplification may be the unique way to study GWs from 3D exploding SN.)

Numerical computations:
Hydro: ZEUS-MP (Hayes et al. 06)
Neutrino transport: Light-bulb approach.
Mesh #: 300(r)*120(\theta)*120(\phi), 3 weeks for 1 run (512 CPUs), using XT4 @ NAOJ (Scheck+04, 06, Ohnishi, KK, Yamada,06,07, KK+07, Blondin+07, Iwakami+08)

Entropy distribution at the shock-stall, using current SN progenitor model by Heger et al. 05. (KK et al. 07)

Concept of the SASI simulations

Animation for SASI in 2D.
Features of neutrino-originated GWs in 2D

waveform

KK et al. (2007)

GWs from anisotropic neutrino radiation in 2D,

(Epstein78, Mueller & Janka97)

\[
h_{TT}^\nu = \frac{8G}{c^4R} \int_{-\infty}^{t-R/c} dt' \int_0^{\pi/2} d\theta' \int_0^{\pi/2} d\phi' \Phi(\theta') \frac{dL_\nu(\theta', t')}{d\Omega'},
\]

- angle dependent factor * neutrino luminosity per solid angle
- angle dependent factor is a function of the angle from the symmetry axis.
3D detailed simulations of SASI

Exploding model


Animation!
Details in the Waveforms among 3D models

The neutrino luminosity differs only 0.5%.

\[ L_\nu = 6.8 \times 10^{52} \text{ ergs s}^{-1} \text{ (model A)} \]

\[ L_\nu = 6.676 \times 10^{52} \text{ ergs s}^{-1} \text{ (model B)} \]

- GW signals,
- SASI-neutrino heating vs acoustic mechanisms, a clue to the explosion mechanism.

GW from acoustic mechanism (Ott + 07)
Estimation of Neutrino Anisotropy using Ray Tracing Methods

- Degree of the anisotropic neutrino radiation is essential to determine the GW amplitudes (and dynamics).
- So far, we have assumed the ray-by-ray treatments for simplicity. (Burrows & Hayes 96, Mueller & Janka '97, Fryer+04, KK+07)

GWs from neutrinos

SASI explosion
3000 rays densely near the PNS, sparsely far outside.

Boltzmann equation

\[ \frac{df}{d\Sigma} = \frac{f(E_\nu)}{h(E_\nu)} \left( 1 - f(E_\nu) \right) - \frac{f(E_\nu)}{\Lambda(E_\nu)} \]
Boltzmann equation

\[ \frac{df}{d\tau} = \mathcal{J}(E_u)(1 - f(E_u)) - \frac{f(E_u)}{\lambda(E_u)} \]
Neutrino anisotropy becomes one-order-of magnitude smaller, thus the GW amplitudes are also...

Unfortunately… 3rd generation GW detectors are needed to tell the difference between two mechanisms.
Switching Gears:
MHD explosion of core-collapse supernovae
Since “Magnetars” are minor…

Zhang et al. 00

Surface B fields

Log(periods)

Zhang et al. 00

Log(B_p)

Log(P) (s)

10^{16} G

10^{14} G

10^{12} G

Log(periods)
MHD supernovae: Renaissance!

Relevant to magnetars and GRBs.

Combination of rapid rotation & strong B fields, often called as unrealistic, are considered to be possible for the rapidly rotating metal poor stars. (Yoon & Langer 06, Woosley & Heger 06)
Special Relativistic MHD computations of core-collapse supernovae

The first MHD simulation from onset of collapse to jet propagation.

Prompt MHD explosions (strong $B \sim 10^{12}$ G, rapid rotation $T/|W| \sim 2\%$

in the context of collapsar progenitor)
Delayed MHD Explosions (recent collapsar progenitor model; weak B, slow \( \Omega \))
• Magnetic shock revival occurs when the magnetic pressure becomes strong, due to the field wrapping, enough to overwhelm the ram pressure of the accreting matter. The epoch is delayed here for the slow rotation.
• It’s found that the magnetic shock revival can blow up the canonical collapsar progenitors.
Magnetic contributions to GWs!

- An indicator of the B fields deep inside the cores.
- In the MHD exploding models, **Type IV** waveforms will be emitted (see also Obergaulinger et al. 06).
Neutrino oscillation in stellar core-collapse

- Important probe into neutrino oscillation parameters.
  (mixing angles, mass squared differences and mass hierarchy).
  S. Ando & K. Sato (2004)....
Signature in SK events, especially from the L resonance, could be a characteristic feature for the MHD explosions. (∵ shock reaches much earlier than the usual $\nu$-heated models)

For details, see poster (A27) by Shiou Kawagoe.
After the MHD explosions: the route to magnetar or GRBs

collapse  bounce  first jet  funnel

Magnetar?  Disk, BH?  second jet – GRBs?
Equilibrium configurations of Magnetars

  Mixed poloidal and toroidal fields : Pseudo GR gravity with realistic EOSs

  full GR + Purely toroidal magnetic fields with realistic EOSs
  (From core-collapse sim, toroidal fields are up-to 2 orders of mag. > the poloidal ones.)

- Strong toroidal B fields ($10^{18}$ G), like a rubber belt, can distort magnetars prolately.
  (Given the same mass and the same magnetic flux, the deformation becomes higher for the softer EOS.)
Fixing baryon mass,

At the phase transition, the vast energy release of $10^{52} \text{ ergs}$ accompanied by the burst-like emissions of gravitational waves and neutrinos.

☆ a clue to the phase transition physics (albeit very speculative).
After MHD explosions: the route to magnetar or GRBs

collapse

bounce

first jet

funnel

Magnetar?

Disk, BH?

Collapsar – GRBs?
Collapsar simulation in SRMHD

Harikae, Takiwaki, KK in prep.

- Based on a recent collapsar progenitor (Woosley & Heger 06), much slower rotation with weaker B fields of $10^{11}$ G than previously assumed (Proga+03, MacFadyen & Woosley 1993).

Moderate

Neutrino pair annihilation using ray methods

~5.6 sec

☆ We do observe the launch of MHD jets in much later phase than previous study (~ 2 sec).
(note that for the stable simulations, SR is important ! )
Origin of large magnetic fields

Two candidate scenarios:

- **Fossil hypothesis** by Ferrario et al. (2004)
- **Dynamo** processes in rapidly rotating proto-neutron stars. (Thompson & Duncan 1993)
- **Generation of large magnetic fields by SASI.** (Endeve, Cardall, Mezzacappa, astro-ph 2008)

Saturation level is insensitive to the initial field strength.

\[ 10^{15} \text{G} \]
SASI in MHD

Magnetic field generation by the stationary accretion shock instability

E. Endeve$^{1,2,3}$, C. Y. Cardall$^{1,2}$, R. D. Budiardja$^2$ and A. Mezzacappa$^1$

Saturation level is insensitive to the initial field strength.

Saturation level is just due to the difference in the initial field strength.
Magnetic effects are not only through...

\[
\rho \frac{dv}{dt} = -\nabla p - \rho \nabla \Phi + \frac{1}{4\pi} (\nabla \times B) \times B - \nabla \cdot \left[ \sum_f \int d\omega (P(\omega) + \tilde{P}(\omega)) \right]
\]

☆Lorentz force  
☆Equation of state

The onset of Landau quantization of electrons occurs for the field strength larger than \( B_{\text{QED}} \), (e.g., Lattmier & Prakash 07)

\[
B_c = \frac{m_e^2 c^3}{e\hbar} = 4.414 \times 10^{13} \text{ G}
\]

Such circumstances can be satisfied for (any!) MHD explosion models.
Construction of EOS tables including magnetic effects

KK, Ichikawa, Sumiyoshi in prep

- We derived analytic formulae for the expressions of pressure, number density, etc., which helps a lot to reduce the computational time for constructing a EOS table with wide density, Ye, temperature range.

\[
\frac{\rho Y_e}{m_N} = n_e^-(B) - n_e^+(B) = \frac{eB}{2}\sum_{n=0}^{\infty} g_n m_s(n) \sum_{k=1}^{\infty} 2 \cosh k\phi_e (K_0)
\]

\[
\epsilon_{\text{tot}}(B) = \epsilon_e^+(B) + \epsilon_e^-(B) = \frac{eB}{2\pi^2} \sum_{n=0}^{\infty} g_n m_s^2(n) \sum_{k=1}^{\infty} 2 \cosh k\phi_e (K_0)
\]

\[
P_{\text{tot}}(B) = P_e^-(B) + P_e^+(B) = \frac{eB}{2\pi^2} \sum_{n=0}^{\infty} g_n m_s^2(n) \sum_{k=1}^{\infty} (2 \cosh k\zeta) \frac{1}{k\zeta} K_1(k\zeta)
\]

- Difference of pressure with B from without.

- Phase diagram of \(\frac{(P_{B\neq 0} - P_{B=0})}{P_{B=0}}\)

The pressure including the B-fields contributions can be ~2 times larger behind the shock.

☆ This might affect the MHD explosions.
Putting things together......
Summary,
new challenges and perspectives
Summary

☆ 3D SASI-aided neutrino-driven core-collapse supernovae: with idealized situations (e.g., excision of the PNS and approximate neutrino transport), to study the explosion dynamics and gravitational waves.

☆ MHD mechanism of core-collapse supernovae: characteristic signatures in gravitational-waves and neutrinos.

☆ As a remnant of the MHD explosions, evolution of magnetars/neutron stars (with some exotic flavors).

☆ Applications of MHD simulations: collapsar simulations (: collapse of Pop III stars) Suwa+07,08

Relevance with each study? Where is our study towards? Do we choose the research themes, out of whim?

**NO!!**
To understand their formation mechanisms in a unified way!
To put the cards on the table...

The policy of division of SN research of K. Sato’s group,

☆ Clarifying the roles of rotation and magnetic fields, is a (kind of) tradition.

Yamada & Sato
ApJ, 1994,

Nagataki et al.

☆ Studying the neutrino and GW signals is also a best subject.

Sato & Suzuki,
PRL 1987

Totani & Sato

Yamada & Sato

<table>
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<th>Time (sec)</th>
<th>Event number</th>
<th>$\bar{E}$ (MeV)</th>
<th>$T$ (MeV)</th>
<th>$\langle E \rangle$ (MeV)</th>
<th>Integrated luminosity (ergs)</th>
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<td>0.000~0.107</td>
<td>2</td>
<td>18.1</td>
<td>3.2</td>
<td>10.0</td>
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<tr>
<td>0.000~1.915</td>
<td>8</td>
<td>18.7</td>
<td>3.3</td>
<td>10.4</td>
<td>$2.7 \times 10^{32}$</td>
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<tr>
<td>0.000~12.439</td>
<td>11</td>
<td>16.7</td>
<td>2.8</td>
<td>8.9</td>
<td>$4.8 \times 10^{32}$</td>
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<tr>
<td>1.541~12.439</td>
<td>6</td>
<td>19.1</td>
<td>3.4</td>
<td>10.7</td>
<td>$1.9 \times 10^{32}$</td>
</tr>
</tbody>
</table>
Stellar evolutions and their fate:

(1) Importance of rotation & magnetic fields

(2) Necessity of coincident analysis between GWs and neutrino detections

Time changes, the policy kept unchanged!
On-Going Numerical Challenges:

The ultimate tool needed,

**3D full GRMHD with spectral neutrino transport simulations**

: Hydro
1D Lagrangian: Sato & Takahara (1984~)
2D SRMHD: Takiwaki (2007~)
3D full GR hydro codes: Kiuchi, KK, Yamada in prep

: Neutrino transport
2D: MGFLD: KK & Ohnishi(2006~)
3D: IDS (Suwa, KK with Basel group), Sn methods: Sumiyoshi, KK, Ohnishi
Yamada et al. in prep

Q: How long will it take for the mariage ?
A: Within this 5 years (of course, with a few approximations in the transport)
Q: Are you serious ??
A: Yes, we can !

Thank you very much !