Multi-messengers from Core-Collapse Supernovae

“Multi-Dimensionality as a key to bridge theory and observation”

Kei Kotake
(National Astronomical Observatory of Japan)

with Tomoya Takiwaki(NAOJ), Yudai Suwa(Kyoto)
Matthias Liebendoerfer(Basel Univ.), Katsuhiko Sato(IPMU)

Astrophysical transients: Multi-messenger-probes of Nuclear Physics @ INT July, 2011
ADS survey on “Multi-messenger” as of yesterday


✓ Please keep in mind what I’m going to talk today may contain a number of premature (speculative) proposals!
✓ In my talk, I put together our best knowledge of current theoretical predictions of SN multi-messengers.
✓ Comments are welcome, and let’s discuss future directions!

Outline

✓ General introduction
  - what is the “headache” to SN modelers over 40 years?

✓ Current Supernova Paradigm
  - based on multi-D supernova simulations

✓ Multi-messengers from Supernova Explosions
  - Gravitational Waves, Neutrino Signals, and photons

✓ Summary and Perspectives
  - how we can learn the mechanism of the engine from multi-messenger observations?
The supernova shock reaches to the stellar surface somehow... with its kin. E of $10^{51}$ erg!

SN 1987A  
Progenitor: $\sim 20M_{\text{sun}}$

Before  
After

But... we don’t understand the mechanism of explosion over these 40 years! (the supernova problem)
Neutrino heating mechanism

- Best-studied and most promising way to explode stars (> 10M$_{\text{sun}}$).

(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 ($\tau_\nu \ll 1$)

Illustration adapted from Mezzacappa (2003)
Looking back 20+ Years of Modeling & Theory

• **Neutrino-heating mechanism** (Wilson ’82, Bethe’85) in spherical symmetry fails to explode massive stars with iron cores.

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

• Multidimensional explosions are favorable for reproducing the synthesized elements. (Kifonidis+03, Hungerford+05, Maeda-Mazzali+08…)

Multidimensional modeling is crucial!
Requirement of core-collapse supernova simulations?

Neutrino Distribution Function

\[ f(t, x, y, z, p_x, p_y, p_z) \]

Spacial Dimensions

1D, 2D, 3D

Gray, Multi-

Energy

Adiabatic

Transport Dimensions

TYPE II: Full simulations

Ott+08

Marek & Janka 09

Iwakami+08,09

Ohnishi+07

Suwa+09

Burrows+07

Bruenn+09

Marek & Janka 09

Ott+08

Fryer et al. 02

Blondin + 03

Blondin + 07

Kotake+9,11

Neutrino Distribution Function

1D

2D

3D

TYPE I:

Experimental simulation,

✓ excision inside PNS

✓ νluminosity is changed by hand.

Spacial Dimensions (hopefully with GR)
A la carte of recent 2D exploding models

From Garching simulations (MPA),

✓ non-rotating 11.2 Msun star (Buras et al. (2006))
✓ mildly-rotating 15 Msun star (Marek & Janka 2009)
✓ Rapidly-rotating 13 M\(_{\odot}\) star (Tokyo)


From Oak Ridge simulations

☆ Fundamental problems remained!
✓ The obtained explosion energies are typically underpowered by 1 or 2-orders-magnitudes compared to observation (SN kinetic energy of 10\(^{51}\) erg).
✓ All of the exploding models assume a very soft nuclear EOS (K=180 MeV).
Two representative EOSs in conventional SN simulations \((Lattimer & Swesty'91)\) incompressibility \(K = 180, 220, 315 \text{ MeV}\) \((Shen et al. '98)\).

Demorest et al. Nature; Volume: 467, Pages: 1081–1083

\(M_{\text{ns}} \sim (1.97 \pm 0.04)M_{\odot}\)

“Message to nuclear theorists” Send email when you ....!
2D model with $K=220\text{MeV LS EOS}$

✓ 15$M_{\odot}$ progenitor by Woosley et al. (2002)

(the IDSA for the spectral neutrino transport: a la Liebendoerfer + 09)

✓ After bounce, the bounce shock stalls.

✓ “Standing Accretion Shock Instability (SASI)” is observed:
  “low-modes” oscillations of the stalled shock

✓ The traveling timescales of matter in the neutrino-heated regions become longer due to non-radial oscillations.

✓ At around 300 ms after bounce, the neutrino-driven explosion sets in.

Suwa, Kotake, Takiwaki, Liebendoerfer, Sato in preparation

Right panel is zoom up in the central region

Entropy per baryon (color)
2D model with H.SHEN EOS

✓ The SASI continues. but we have not observed the shock-revival yet.

✓ This model seems not to be exploding …

☆ In 2D, it’s more easier to obtain explosions than 1D. (because the non-radial motions can elongate the neutrino-heating timescales)

☆ In 3D, one might expect a more favorable situation! (because matter can travel freely in the azimuthal(φ) direction!)

Suwa, Kotake, Takiwaki, Liebendoefer, Sato in preparation
3D Results with Spectral $\nu$ transport

✓ 13 Ms progenitor
✓ Numerical Resolution
  • Grid: 300(r) x 32($\Theta$) x 32($\phi$) x 20(energy)
  • Processors: 512 (~ 3 months)
  • Non-rotating case
Easy to obtain explosions in 3D? (Yes or No!)

For working the neutrino-heating mechanism, the residency timescales become longer in 3D than in 2D.

From the hydrodynamic point of view, it may be more easier for 2D. (because matter motions can be concentrated along the special direction.)
For working the neutrino-heating mechanism, the advection timescales become longer in 3D than in 2D. From the hydrodynamic point of view, it may be easier for 2D (because matter motions can be concentrated along the special direction). Suwa+ (2010)

Please stay tuned for our high resolution 3D simulations.
### Energy-drivers for explosions:

<table>
<thead>
<tr>
<th>Type</th>
<th>Mechanism</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino heating</td>
<td>Neutrino heating mechanism aided by convection/SASI</td>
<td>Marek &amp; Janka 09, Suwa et al. 10</td>
</tr>
<tr>
<td></td>
<td>also aided by rotation</td>
<td>KK+03,06, Walder+05, Ott+08, Suwa et al. 10</td>
</tr>
</tbody>
</table>

### Explosion

- Likely! (but the explosion energy is still less than $10^{51}$ erg.)

### Which one is the final answer?

To pin down the proposed explosion scenarios, \( \Rightarrow \) important to discuss a connection to observables!

- Primary observables: “direct” information of engine
- Supernova nucleosynthesis
- Gravitational-wave and neutrino astronomy
Gravitational Wave (GW) is "a ripple" of space-time, predicted Einstein’s theory of GR (1916).

Emitted when matter moves with acceleration.
- stellar collapse or neutron star mergers

Nobody ever detected the strain.

GW amplitude
First LIGO (America)
(see recent reviews in Kotake et al. (2006), Ott (2009), Fryer & New (2011))

Multidimensionality (origin of anisotropy)
Exp. Mechanism
GW emission

Gravitational Wave (GW) is "a ripple" of space-time, predicted Einstein’s theory of GR (1916).

Emitted when matter moves with acceleration.
- stellar collapse or neutron star mergers

Nobody ever detected the strain.

GW amplitude
First LIGO (America)
(see recent reviews in Kotake et al. (2006), Ott (2009), Fryer & New (2011))
Gravitational-wave features in MHD explosions
(e.g., Kotake et al. 2004, Obergaulinger et al. 2006, Shibata et al. 2006, Takiwaki & Kotake 2010)

✓ The MHD mechanism works only when pre-collapse core has rapid rotation ($P_0 < 4$ s) and strong magnetic fields ($B_0 > 10^{11}$ G).

✓ GW amplitudes from prolately expanding material positively increase

Gravitational waveform from MHD explosion

✓ In the MHD exploding models, the gravitational waveforms show an increasing trend after bounce.
Gravitational Waves from Neutrino-driven Explosions

(KK et al. 09, KK et al. 11, see also Fryer et al. (02), Murphy et al. (09), Mueller et al. (11), Mueller & Janka (97))

✓ In absence of rapid rotation, 3D explosions: axis-free
✓ GWs from convection/SASI change stochastically with time (governed by turbulent and chaotic fluid motion in non-linear hydrodynamics)
Comparison of Waveforms between candidate mechanisms

- Acoustic-wave mechanism

Burrows +06

- MHD mechanisms

(Takiwaki and KK 10)

A clear correlation: between the explosion mechanism and the GW signals!
Detectability of GW signals

To detect the GW signals, the next generation detectors are needed.

By only by GWs, it is difficult to tell the difference between them.
Could have a great impact on the elementary physics

Useful as a tomography, i.e., the time evolution of the SN dynamics!
Neutrino signatures in MHD explosion of supernovae

Kawagoe, Takiwaki, Kotake, JCAP(2009)

These features are inherent to MHD explosions.
✓ Good measure to tell the difference from other scenarios.

For a more in-depth review, see Cecilia Lunardini’s talk!
Electromagnetic messengers from CC supernovae

(Kifonidis et al. (2003,2006), Hungerford et al. (05), Young et al. (2006), Maeda et al. (2008))

✓ Explosive nucleosynthesis in SASI-aided 2D explosions

(Fujimoto, Kotake + 2011)

Si-rich jets, as in Cas A?

Spherical model

Ni\textsuperscript{56}-rich

O\textsubscript{16}-rich

1.5 s

Matter Mixing

✓ Explosive nucleosynthesis occurs more drastically along the direction of explosion

✓ This may account for some observational features such as in Cas A and SNR in the Cygnus loop.
“Three eyes” to decipher the SN mechanism!

Time 0 milliseconds, seconds (?), > hours

Bounce

Expected event number

Shock-revivals (?)

Neutrinos

Electromag. rad.

Nucleosynthesis

X-ray, optical, radio..

GWs

MHD bounce

@10kpc

Neutrino-heating

Total
First LIGO
Advanced LIGO
LCGT

@10kpc

Convection
SASI
G-mode?

Convection
SASI
G-mode?

GWs

Neutrinos

Shock-revivals (?)

Electromag. rad.

Nucleosynthesis

X-ray, optical, radio..
### Summary of “SN Multi-messengers”

<table>
<thead>
<tr>
<th>Messenger Mechanism</th>
<th>Gravitational Waves</th>
<th>Neutrinos</th>
<th>Photons (nucleosynthesis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino-heating mechanism</td>
<td><strong>Stochastic</strong> (Convection &amp; SASI)</td>
<td><strong>Stochastic</strong> (Convection &amp; SASI)</td>
<td>$\nu p$ process</td>
</tr>
<tr>
<td>Neutrino heating mechanism</td>
<td>Excess for equator (Spiral SASI modes)</td>
<td>Polar excess</td>
<td>Anisotropic explosive nucleosynthesis</td>
</tr>
<tr>
<td>MHD mechanism</td>
<td>Burst &amp; tail (rapid rotation + magnetic fields)</td>
<td>Disappearing signals</td>
<td>No photon (?)</td>
</tr>
<tr>
<td></td>
<td>Anisotropy in SK events (MSW effect)</td>
<td>$\bar{\nu}_e$ bursts (RSF)</td>
<td>$r$-process cites (?) Path to hypernovae (?)</td>
</tr>
</tbody>
</table>
Summary of “SN Multi-messengers” (Kotake +11)

<table>
<thead>
<tr>
<th>Messenger</th>
<th>Gravitational Waves</th>
<th>Neutrinos</th>
<th>Photons (nucleosynthesis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism</td>
<td>Stochastic (Convection &amp; SASI)</td>
<td>Stochastic (Convection &amp; SASI)</td>
<td>$\nu p$ process</td>
</tr>
<tr>
<td></td>
<td>Canonical rotation</td>
<td>Anisotropic explosive nucleosynthesis</td>
<td></td>
</tr>
</tbody>
</table>

**Brandt et al. (2010) PRD**

- **Model s20.nr**
  - $\bar{\nu}_e$
  - $\frac{\bar{\nu}_e + 2\nu_\mu}{3}$
  - $\bar{\nu}_e$, Equator
  - $\bar{\nu}_e$, Pole

<table>
<thead>
<tr>
<th>Time Post-Bounce [ms]</th>
<th>IceCube Count Rate at 10 kpc [cpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model s20.nr</td>
</tr>
<tr>
<td></td>
<td>Model s20.π</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Post-Bounce [ms]</th>
<th>Super-K Count Rate at 10 kpc [cpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brandt et al. (2010) PRD</td>
</tr>
</tbody>
</table>

- **Disappearing signals**
  - No photon (?)

- **Anisotropy in SK events** (MSW effect)
  - $\nu_e$ bursts (RSF)

- **r-process cites**
  - Path to hypernovae?
Summary of "SN Multi-messengers" (Kotake +11)

Brandt et al. 2010 PRD

South pole
North pole
Equator

Stochastic
(Convection & SASI)

Anisotropic explosive nucleosynthesis

Excess for equator
(Spiral SASI modes)

Polar excess

Burst signals
(bounce & BH formation)

Disappearing signal

MHD mechanism

Burst & tail
(rapid rotation + magnetic fields)

Anisotropy in events (MSW)

$\nu_e$ bursts (RS)

Model A2 ($L_\nu=6.0\times10^{52}$ erg/s, rapid rotation)

$H^T_{\text{total}} [10^{-22}]$

Time [ms]

Rapidly Rotation

Brandt et al 2010 PRD

$\nu p$ process

Photons
(nucleosynthesis)

South pole
Equator
North pole

$\nu_e = \int_{\Omega} P_\nu d\Omega$

$\nu^T = 4\pi P_\nu(\mu) \times [10^{51} \text{ erg s}^{-1}]$

$\mu = \cos(\theta)$

South pole
Equator
North pole
A correlation analysis of these messengers should be very important to get a unified picture of stellar collapse that bifurcates between NS or BH forming SNe!

Multi-dimensionalities (convection, SASI, rotation, B-fields) hold a key to bridge the SN theory (incl. nuclear theory) and these multi-messenger observation.
Multimessengers from core-collapse supernovae: multidimensionality as a key to bridge theory and observation

Kei Kotake¹,², Tomoya Takiwaki², Yudai Suwa³, Wakana Iwakami Nakano⁴, Shio Kawagoe⁵, Youhei Masada⁶, and Shin ichiro Fujimoto⁷

¹Division of Theoretical Astronomy, National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo, 181-8588, Japan
kkotake@th.nao.ac.jp

²Center for Computational Astrophysics, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

³Yukawa Institute for Theoretical Physics, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto, 606-8502, Japan

⁴Department of Aerospace Engineering, Aoba, Tohoku University, Sendai, 980-8579, Japan

⁵Knowledge Dissemination Unit, Oshima Lab, Institute of Industrial Science. The University of Tokyo, Bunkyo-ku, Tokyo, 113-8657, Japan

Thank you very much!