Evolution of SN1987A
~From Progenitor Star to 30 Years after the Explosion~

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Astrophysical Big Bang Laboratory (ABBL)

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RIKEN (理化学研究所)
The largest comprehensive research institution in Japan

Main Campus of RIKEN

Main Research Build. in Main Campus

From Google Map

My Office in the Main Research Build.
One of Our Offices for PDs & Students.
Astrophysical Big Bang Lab. (ABBL)

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- Research Staff: Akira Mizuta
- Current PDs: H.Ito, G. Ferrand, H. He, M. Ono, O.Just, +3 Postdocs
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From 01.Apr.2013. 7th Year!
Interdisciplinary Theoretical & Mathematical Sciences Program (iTHEMS)
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From 01.Apr.2013. 7th Year!
§ Observations of SN1987A
SN 1987A & its Ring.

When: 23 February 1987
Where: Large Magellanic Cloud

Stellar progenitor: Sk -69°202

Nearest supernova explosion observed by human eyes in hundreds of years

Unique opportunity to watch a SN change into a SNR

(Smith+ 2013)
Detection of Neutrinos from SN1987A

Prof. Koshiba

Super-Kamiokande
BTW, Why Massive Stars Explode?

After: SN1987A

Before: Sanduleak -69° 202
Where is the Neutron Star in SN1987A?
Asymmetric Velocity Profile of Iron

Haas et al. 1990

Fe II lines

Blue Shift Side: Toward Us

Red Shift Side: Away from Us

Flux Density (normalized)

1.26 µm
18 µm

Velocity (km/s)
Asymmetric $^{44}$Ti Profile: Redshift Component is More.

Observations of $^{44}$Ti lines by NuSTAR
- Lines are redshifted with a Doppler velocity of about 700 km/s

59-80 keV NuSTAR spectrum of SN1987A with detected $^{44}$Ti emission lines.
[Credit: NASA/JPL-Caltech/UC Berkeley]
Figure from https://nustar.ssdc.asi.it/news.php

$^{44}$Ti $\sim 10^{-4} \, M_{\text{Solar}}$

c.f. Theories: $\sim 10^{-5} \, M_{\text{Solar}}$
(Hashimoto 95, Thielemann+96, Nagataki 97, Rausher+02, Fujimoto+11,...)
Bipolar Explosion is Seen in SN1987A

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
3D distribution of inner ejecta of SN 1987A

Observation from HST/STIS and VLT/SINFONI at 10,000 days after the explosion

Equatorial ring (ER)


Top: [Si I] + [Fe II] 1.644 μm

Bottom: Hα
Molecule distribution in 3D


ALMA observations of CO $J = 2 - 1$, SiO $J = 5 - 4, 6 - 5$ rotational transitions

![Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2–1 (red) and SiO 5–4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with HST shows the location of the circumstellar equatorial ring (Larsson et al. 2016).](image)

(An animation of this figure is available.)
§ Our Theories for SN1987A
Outline of Explosion Mechanism

From S. Yamada

-core collapse

$M \geq 8 M_\odot$

$e^- + p \rightarrow \nu_e + n$

$Fe + \gamma \rightarrow p + n$

- v trapping

$\rho_c \sim 10^{12} g/cm^3$

- core bounce

$\rho_c \sim 3 \times 10^{14} g/cm^3$

SN explosion

$E_{exp} \sim 10^{51} \text{erg}$

shock in envelope

shock propagation in core
Simulations of CC-SNe Using K-Computer of RIKEN

Takiwaki et al. 2012

Simulation by T. Takiwaki (A-ABBL)

京(KEI) = 10 Peta=10^{16}.
Rotation Can Change the Dynamics

Spiral Waves Convey Rotation Energy Outside.
The mass of the progenitor and rotation make various type of Explosion (or Non Explosion).
Neutrino/GW Signals from a Supernova

Time Evolution of Neutrino Luminosity

Signal of Gravitational Wave in Freq. Space

T. Takiwaki (A-ABBL).

H. Sotani (NAOJ → ABBL)
Lots of $^{44}$Ti Produced in Bipolar Explosions

Nagataki et al. 97, Nagataki 00

Produced amount of $^{44}$Ti:

$$(1-5) \times 10^{-4} \, M_\odot$$

Consistent with Obs. of $^{44}$Ti by NuStar

In Jet (bipolar) region, entropy per baryon becomes high!
For α-rich, High Entropy per Baryon.

- $S \sim T^3/\rho$.
- For High Entropy per baryon ($S$), high temperature & (relatively) low density are preferred.
- The balance between Fe $\Leftrightarrow$ He, p, n depends on entropy.
- $T$ is related with photo-dissociations, while $\rho$ is related with nuclear reactions.
Asymmetric Explosion & Neutron Star Kick

Model W15-6
Time: 15.10 ms
NS displacement: 0.00 km

A. Wongwathanarat
(A-ABBL)
Asymmetric Ejection of 56Ni & Neutron Star Kick

A. Wongwathanarat (A-ABBL)
Asymmetry with Respect of Equatorial Plane Is Suggested for SN1987A.

The Missing Neutron Star should be Moving toward Us (Blue-Shifted Side)!

Calculation:
Iron Velocity Distribution

Blue shifted (NS Side)
Red shifted

Fe, Ti (Red-shifted)

Wongwathanarat+ 2013
§ Advanced Studies for SN1987A: From Progenitor Star to 30 Years after the Explosion


Masaomi Ono (ABBL)
Supernova explosions to their supernova remnants (SNRs)

Supernova explosion  
$t < 1 \text{ sec}$

Shock breakout  
$t < 1000 \text{ sec}$

t < 1 yr

Supernova remnant  
$t \sim 500 \text{ yr}$

Radius of the progenitor star  
$10^{12} - 10^{14} \text{ cm}$

Mixing?

Electromagnetic signals

$\sim 10^{18} \text{ cm (1 pc)}$

Stellar evolution of the progenitor star

Asymmetric explosion

Explosive nucleosynthesis

Matter mixing

Formation of molecules and dust?

Asymmetric distribution of elements

Takiwaki (A-ABBL)

Chemical evolution (Nucleosynthesis/Molecule formation/dust formation) during the progenitor–SNe–SNRs sequence
Linking SNR 1987A to the SN and progenitor star

1D stellar progenitor model

3D cc SN model

3D SNR model

M. Ono (ABBL)

(Orlando+2019 submitted to Science Advances)

Progenitor star
- 16.3M⊙ BSG (Nomoto & Hashimoto 1988)
- 19.8M⊙ RSG (Woosley+2002)
- 18.29 M⊙ BSG resulting from the merging of 14 and 9 M⊙ stars (Urushibata+2018)

The 18.29 M⊙ BSG model reproduces the main observables of Sk −69° 202
- red-to-blue evolution
- total mass and position in the HR diagram at collapse (Blue Super Giant)

Bottom Line: Event Rate of Supernovae is Rare.
Can we find Imprints of Explosion Scenario in Young Supernova Remnants in Milky Way and/or nearby galaxies?
The progenitor of SN1987A was the outcome of a binary merger?

- 3D smoothed particle hydrodynamic (SPH) simulation

$$\sim 15 \, M_\odot$$ RSG  \quad \sim 5 \, M_\odot$$ MS star

Rapid Rotation is Introduced by the merger?

Morris & Podsiadlowsky 2007, Science, 315, 1103
The SN explosion

Simulations start:
- soon after the core-collapse
- SN explosion initiated by injecting kinetic and thermal energies artificially around the central compact object

Explored range of injected energy
(1.8 – 3.0) FOE, 1 FOE = 10^51 erg

Explored range of initial anisotropy:
\( v_{pol}/v_{eq} = \beta = [2.0 – 16] \)
\( v_{up}/v_{dw} = \alpha = [1.1 – 1.5] \)

Adapted from the model of Ono+ (2013) to 3D
- explosive nucleosynthesis through a nuclear reaction network (19 isotopes);

Numerical code: 
FLASH 
(Fryxell+ 2000)

Masaomi Ono
(ABBL) (Ono+2019, in prep.)
Post-explosion anisotropies: [Fe II] line profiles

(Orlando+ 2019, in prep.)

NS kick
~ 300 km/s
toward us to the north
(Nagataki 2000; Wongwathanarat 2013; Janka 2017)

Best-fit parameters
\( E_{\text{exp}} \sim 2 \times 10^{51} \) erg
\( \alpha = 1.5 \)
\( \beta = 16 \)
progenitor model = B18.3
Distribution of $^{44}$Ti in the evolved SNR

- **NuSTAR**: $^{44}$Ti lines redshifted with Doppler velocity $\sim 700 \pm 400$ km/s (Boggs+ 2015)

- **Model**: Velocity along the LoS of $^{44}$Ti $\sim 400$ km/s away from the observer
Molecular structure in the evolved SNR

- ALMA: torus-like structure evident in CO. SiO is inside of CO. (Abellan+ 2017)
- Model: modeled torus-like feature with similar orientation and size (Orlando+ 2019, Science Advances, Submitted)
X-ray Lightcurves

Abundances from Zhekov+ (2009)
ISM Absorption: 2.35e21 cm$^{-2}$ (Park+ 2006)
Distance: 51.4 kpc (Panagia 1999)
Date: 1993

Effects of B-Fields on X-ray Light Images


Athena (ESA, early in 2030)

\[ \sim 3\text{kG at Surface of Progenitor Star} \]
\[ \sim \mu\text{G at the Ring.} \]
Future Directions

- Molecule Formation with a Chemical Reaction Network.

Masaomi Ono (ABBL)

- Applying Our Method to Cas A.

A. Wongwathanarat (A-ABBL)  S. Orlando (Palermo Obs.)
Thank You Very Much!

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