

Core-collapse simulation of SN 1987A binary progenitor and its multimessenger signals

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Abstract. We perform a three-dimensional self-consistent core-collapse supernova simulation using a binary evolution progenitor model of SN 1987A. This progenitor model is based on a slow-merger of $14 M_{\odot}$ and $9 M_{\odot}$ stars and it satisfies most of the observational constraints such as red-to-blue evolution, lifetime, total mass and position in the Hertzsprung-Russell diagram at collapse, and chemical anomalies. We find that this progenitor model successfully present explosion and leave a $1.53 M_{\odot}$ neutron star with a kick velocity of 70 km s^{-1} and a spin period of 0.1 s. Assuming a detector sensitivity of Kamiokande-II and the distance to the supernova of 51 kpc, we obtain 16 neutrino detection events in one second. Some characteristic modes in its gravitational wave signal are also discussed in this article.

1. Introduction

SN 1987A, which emerged in the Large Magellanic Cloud located at a distance of 51.4 ± 1.2 kpc, is a landmark event in astrophysics. Multiwavelength studies of SN 1987A have provided unprecedented details of supernova features such as the time evolution of the bolometric luminosity and energy spectrum at all wave bands from infrared to γ -ray. Moreover, a supernova neutrino burst was detected by several neutrino detectors such as Kamiokande-II, IMB, and Baksan. Although only about two dozen of the $\sim 10^{28}$ supernova neutrinos that passed through the Earth were detected, they provide us with the first (and ever only one) direct evidence of the supernova driven by the collapsing core of a dying star. This detection implies that there had been a proto-neutron star at least for 10 seconds and it declares the dawn of the neutrino astrophysics.

The light curve and spectra indicate that SN 1987A has roughly typical explosion energy ($\sim 1.2 \times 10^{51}$ erg) and ^{56}Ni mass ($0.07 M_{\odot}$). On the other hand, SN 1987A is a unique supernova in many sense. First, a blue hot surface of the progenitor star Sk-69°202 found in the pre-explosion images, as well as the light curve without the typical plateau phase of type II-P SNe and the relatively short period of time delay (three hours) between the neutrino burst detection and the shock breakout emission, suggest that the progenitor was a blue-supergiant (BSG). Second, this BSG star is considered that it used to be a RSG at $\sim 2 \times 10^4$ yr since there are three ring-like nebulae surrounding the supernova remnant with the high He the CNO abundance rations and the expansion velocity comparable to the RSG wind velocity.

To explain these anomalous features, many pre-explosion evolution scenarios of the progenitor star have been proposed soon after the emergence of SN 1987A: extreme-mass-loss models,



helium-enrichment models, low-metallicity models, rapid-rotation models, and restricted-convection models. Also, binary interaction has been considered from early on: accretion models, companion models, and merger models. See [1] for a review of these classical progenitor models.

One of the possible scenarios to explain these features is a slow merger of binary stars where the stars in a close binary evolve into a common envelope phase then the secondary star is gradually being dissolved inside the common envelope in a much longer time-scale than the dynamical time-scale of the secondary. Recently a new progenitor model based on the slow merger scenario has been constructed [2]. In particular, the progenitor model successfully reproduces the most of the anomalous SN 1987A features such as red-to-blue evolution, lifetime, total mass and position in the Hertzsprung-Russell diagram at collapse, and the chemical anomalies.

In this article we report the results of our self-consistent 3D simulations for core-collapse SN employing this new progenitor model. We solve hydrodynamic evolution and energy-dependent neutrino transport from the center to the outer boundary at 10,000 km. The hydrodynamics code that we employ in this work is essentially the same as in our previous studies [3, 4]. For neutrino transfer calculation we use the state-of-the-art neutrino opacity [5] and solve the neutrino transport taking 20 energy bins with an upper bound of 300 MeV for electron, anti-electron, and heavy-lepton neutrinos.

2. Results

We perform a 3D self-consistent core-collapse supernova simulation using the latest binary progenitor model of SN 1987A. In this section we briefly describe time evolution of a shock wave and multi-messenger signals such as neutrino and gravitational wave.

2.1. Shock evolution

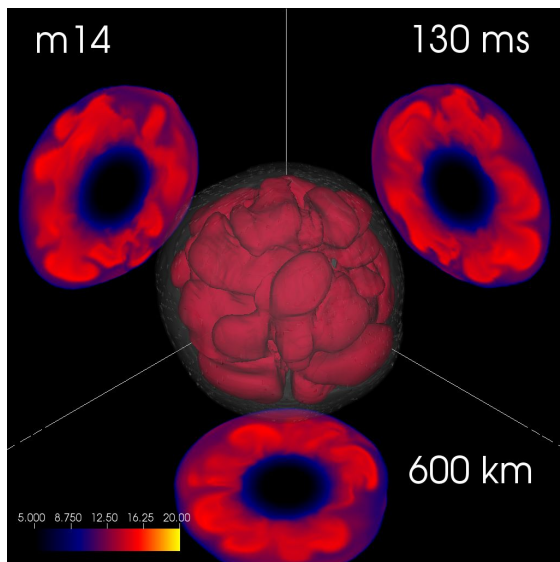


Figure 1. Entropy isosurface within the inner region of the exploding SN 1987A progenitor at 130 ms after bounce.

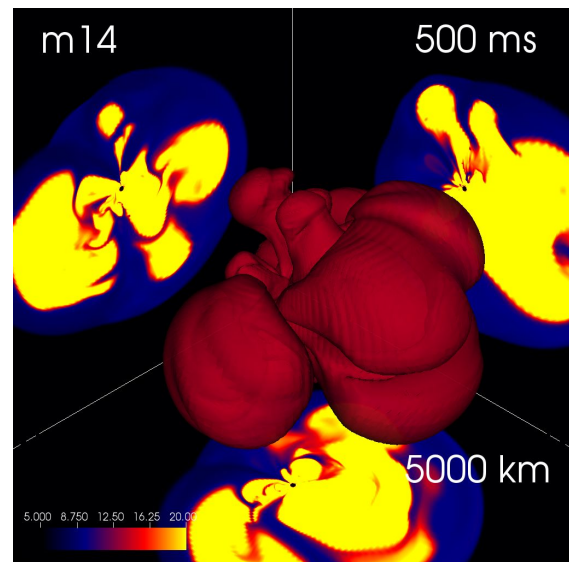


Figure 2. Same as Figure 1 but at 500 ms after bounce within a different box size (5000 km).

The shock of our 3D model once stalls at $r \sim 150$ km and turns to expand at ~ 220 ms after bounce. Figure 1 shows entropy isosurface of the inner region of our 3D model within a 600 km^3

box at 130 ms after bounce. The matter behind the shock is heated by neutrino and small-scale convective motions are developed. The shock is finally pushed outward via the neutrino heating and at 500 ms after bounce it reaches at ~ 2000 km from the center (Figure 2). At this later phase the morphology of the expanding matter is dominated by a few large-scale plumes and low-entropy downflows between them. Although our simulation is limited by the outer boundary at 10,000 km, the shock never recedes after the shock revival and it would successfully make supernova explosion when it reaches at a stellar surface.

2.2. Neutrino signal

Core-collapse SN emits a huge number of neutrinos from the core. Water Cherenkov detectors have a particular sensitivity to anti-electron neutrino via the inverse beta decay (IBD) process. In Figure 3 we estimate a cumulative neutrino detection event number assuming that a CCSN located at LMC emits neutrinos like our 3D CCSN model and we detect them by Kamiokande-II (K-II). We observe 14 neutrinos for 0.7 s and an appropriate extrapolation gives 16 events in 1 s. These numbers are larger than, but not so far from, the detection events in the case of SN 1987A (from this historical SN, K-II observed 11 neutrinos in ~ 10 s).

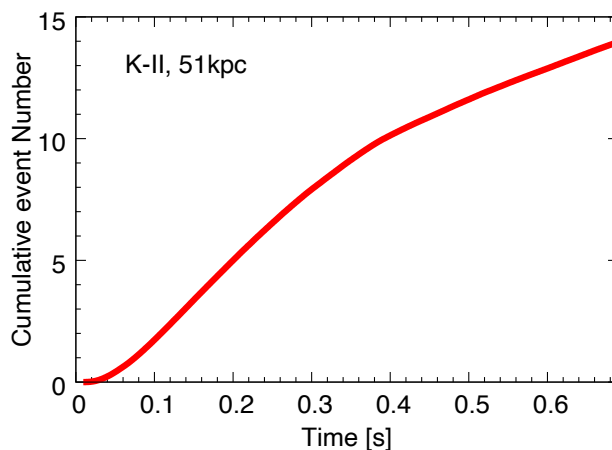


Figure 3. Expected neutrino events at Kamiokande-II (K-II) via IBD process. Here we assume the distance to the CCSN event of 51 kpc.

2.3. Gravitational wave signal

Gravitational wave from coalescence of compact objects such as black holes and neutron stars has been detected by laser interferometers. Non-spherical motions of dense matter in the SN core also produce the gravitational wave and we expect its detection in the future. Figure 4 shows gravitational waveform and spectrogram of our 3D CCSN model. The gravitational waveform CCSN is characterized by three phases: a prompt signal soon after the core bounce (< 50 ms) followed by a silent phase, a strong signals stimulated by hydrodynamic instabilities such as convection and Standing Accretion Shock Instability (so-called SASI) lasting for a few hundred ms, and explosion phase. The spectrogram presents that peak frequency of the strong signal shifts from ~ 500 Hz at 150 ms to > 1000 Hz at 500 ms after bounce. This feature is fitted by a turn-over frequency of downflows hitting the central proto-neutron star surface and reflected at a stable region against convection (white line in the bottom panel of Figure 4).

2.4. Central remnant

The neutrino detection from SN 1987A suggests that it leaves a neutron star for at least 10 s. Although the neutron star has not been discovered in the remnant of SN 1987A covered with dense dusts, our simulation leaves $1.53M_{\odot}$ neutron star with small kick velocity.

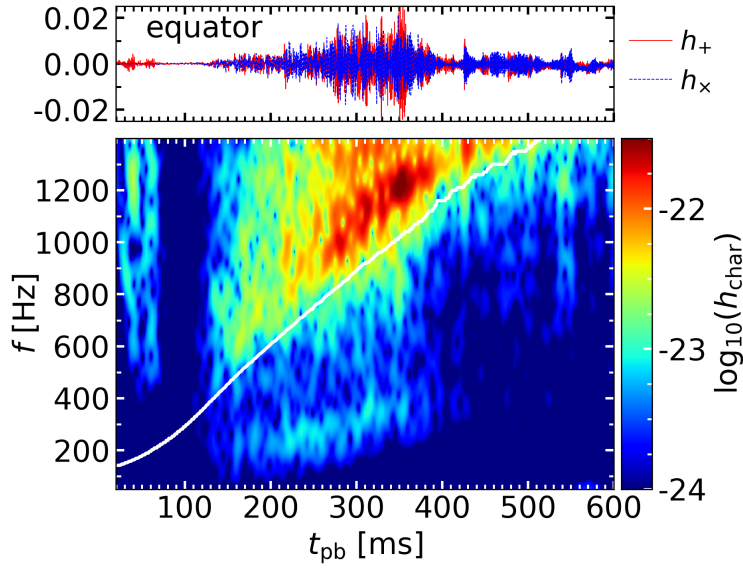


Figure 4. Gravitational wave features of our 3D model. Shown are the input waveform in the top panel and the Fourier-transformed spectrogram in the bottom panel.

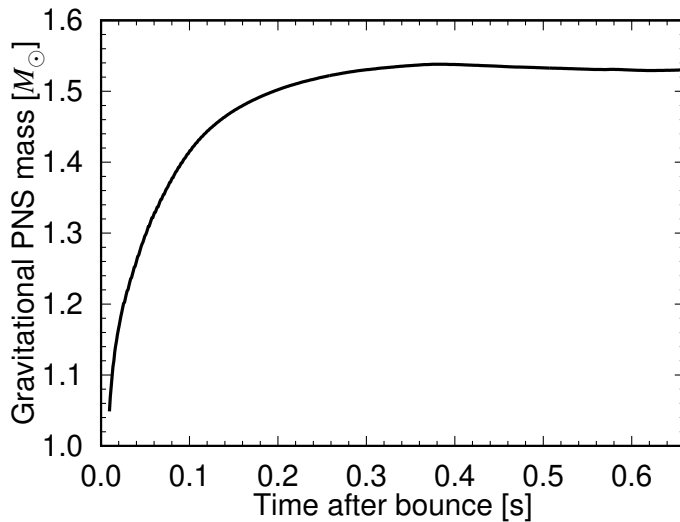


Figure 5. Time evolution of gravitational mass of the central proto-neutron star.

3. Acknowledgments

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