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Towards gravitational-wave astronomy of core-collapse supernova explosion

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Abstract. We study properties of gravitational waves based on the three-dimensional (3D) simulations, which demonstrate the neutrino-driven explosions aided by the standing accretion shock instability (SASI). Pushed by evidence supporting slow rotation prior to core-collapse, we focus on the asphericities in neutrino emissions and matter motions outside the protoneutron star. By performing a ray-tracing calculation in 3D, we estimate accurately the gravitational waveforms from anisotropic neutrino emissions. In contrast to the previous work assuming axisymmetry, we find that the gravitational waveforms vary much more stochastically because the explosion anisotropies depend sensitively on the growth of the SASI which develops chaotically in all directions. Our results show that the gravitational-wave spectrum has its peak near $\sim 100$ Hz, reflecting the SASI-induced matter overturns of $\sim O(10)$ ms. We point out that the detection of such signals, possibly visible to the LIGO-class detectors for a Galactic supernova, could be an important probe into the long-veiled explosion mechanism.

1. Introduction

The gravitational-wave astronomy is now becoming reality. In fact, significant progress has been made on the gravitational wave detectors, such as LIGO,VIGRO,GEO600,TAMA300, and AIGO with their international network of the observatories (e.g., [1] for a review). For the detectors, core-collapse supernovae especially in our Galaxy, have been supposed as one of the most plausible sources of gravitational waves (see, for example, [2, 3] for recent reviews).

Traditionally, most of the model calculations of gravitational waves (GWs) have focused on the bounce signals in the context of rotational and magnetorotational core-collapse (e.g., see [4, 5, 2, 3] and references therein). However recent stellar evolution calculations suggest that such rapid rotation assumed in most of the previous studies, albeit attracting much attention currently as a relevance to collapsar [6], is not canonical for progenitors of core-collapse supernovae with neutron star formations [7, 8].

In the case of the slowly rotating supernova cores, two other ingredients are expected to be important in the much later phases after core bounce, namely convective motions and anisotropic neutrino emissions. Thus far, various physical ingredients for producing asphericities and the resulting GWs in the post-bounce phase, have been studied such as the roles of precollapse density inhomogeneities [9, 10], moderate rotation of the iron core [11], g-mode oscillations of protoneutron stars (PNSs) [12], and the standing-accretion-shock-instability (SASI) [13, 14].

However, most of them have been based on two-dimensional (2D) simulations that assume axisymmetry. Then, the growth of SASI (e.g., [15, 16, 17, 18]) and the large-scale convection,
both of which are now considered to generically develop in the post-bounce phase and to help the neutrino-driven explosions [20, 21], develop along the symmetry axis preferentially, thus suppressing the anisotropies in explosions. So far very few three-dimensional (3D) studies have been conducted [10, 19]. Moreover, neither the growth of the SASI nor its effects on the GWs have been studied yet because SASI is suppressed artificially owing to the limited computational domain [10] or to the early shock-revival [19], which has not been discovered by other supernova simulations.

In this contribution, we report the properties of the gravitational radiation based on the 3D simulations, which demonstrate the neutrino-driven explosions aided by SASI [22]. Supported by the evidence of the slow rotation prior to core-collapse [7, 8], we focus on the asphericities outside the protoneutron stars, which are produced by the growth of SASI. By performing a ray-tracing calculation in 3D [23], we estimate accurately the gravitational waveforms from anisotropic neutrino emissions. We show that the features of the gravitational waveforms are significantly different than the ones in the axisymmetric cases, which should tell us the necessity of the 3D supernova modelling.

**Figure 1.** An example of ray-tracing of neutrinos for estimating $dl_{\nu}(\Omega)/d\Omega$ towards a given direction of $\Omega$. The central region colored by red represents the surface of the protoneutron star (PNS) (located at 50 km in radius), which is the inner boundary of our computation. The color-scale on the rays indicates the values of $f_{\nu}$, the neutrino occupation probability, which is calculated by the line integral of the neutrino transport equations. For this snapshot taken from our simulations, the higher values of $f_{\nu}$ are seen to come just in front of the PNS (yellow on the rays), while $f_{\nu}$ becomes smaller in the distant regions from the PNS.
2. Computation of Gravitational Waves from Anisotropic Neutrino Emission

Following the method in [24, 10], we derived the two modes of the GWs from anisotropic neutrino emissions as follows,

\[ h_+ = C \int_0^t \int_{\Omega} d\Omega' (1 + s(\theta') c(\phi') s(\xi) + c(\theta') c(\xi)) \times \]
\[ \frac{(s(\theta') c(\phi') c(\xi) - c(\theta') s(\xi))^2 - s^2(\theta') s^2(\phi') dl_\nu(\Omega', t')}{[s(\theta') c(\phi') c(\xi) - c(\theta') s(\xi)]^2 + s^2(\theta') s^2(\phi') d\Omega',} \]

and

\[ h_\times = 2C \int_0^t \int_{\Omega} d\Omega' (1 + s(\theta') c(\phi') s(\xi) + c(\theta') c(\xi)) \times \]
\[ \frac{s(\theta') s(\phi') (s(\theta') c(\phi') c(\xi) - c(\theta') s(\xi)) dl_\nu(\Omega', t')}{[s(\theta') c(\phi') c(\xi) - c(\theta') s(\xi)]^2 + s^2(\theta') s^2(\phi') d\Omega'}, \]

where \( s(A) \equiv \sin(A), c(B) \equiv \cos B, C \equiv 2G/(c^3 R) \) with \( G, c \) and \( R \), being the gravitational constant, the speed of light, the distance of the source to the observer respectively, \( dl_\nu/d\Omega \) represents the direction-dependent neutrino luminosity emitted per unit of solid angle into direction of \( \Omega \), and \( \xi \) is the viewing angle (e.g., [23]). For simplicity, we consider here two cases, in which the observer is assumed to be situated along ‘polar’ (\( \xi = 0 \)) or ‘equatorial’(\( \xi = \pi/2 \)) direction. To determine \( dl_\nu/d\Omega \), we perform a ray-tracing calculation (see Figure 1). Since the regions outside the PNSs are basically thin to neutrinos, we solve the neutrino transport equations in a post-processing manner to estimate the neutrino anisotropy, in which neutrino absorptions and emissions by free nucleons, dominant outside the PNSs, are taken into account (see [23] for more details). To get the numerical convergence, we need to set 45000 rays to determine the luminosity for each given direction of \( \Omega \). The GW amplitudes from mass motions are extracted by using the standard quadrupole formula (e.g., [10]), and their spectra with the FFT techniques.

3. Results

Figure 2 depicts the 3D hydrodynamics features of SASI from the early phase of the non-linear regime of SASI (top left) until the shock break-out (bottom right) with the gravitational waveform from neutrinos inserted in each panel.

After about 100 ms, the deformation of the standing shock becomes remarkable marking the epoch when the SASI enters the non-linear regime (top left of Figure 2). At the same time, the gravitational amplitudes begin to deviate from zero. Comparing the top two panels in Figure 3, which shows the total amplitudes (top) and the neutrino contribution only (bottom), it can be seen that the gross structures of the waveforms are predominantly determined by the neutrino-originated GWs with the slower temporal variations (\( \geq \sim 30 - 50 \) ms), to which the GWs from matter motions with rapid temporal variations (\( \leq \sim 10 \) ms) are superimposed. So, we first pay attention to the neutrino GWs in the following and discuss the importance of the matter GWs later in the spectrum analysis.

As seen from the top right through bottom left to right panels of Figure 2, the major axis of the growth of SASI is shown to be not aligned with the symmetric axis (\( Z \) axis in the figure) and the flow inside the standing shock wave is not symmetric with respect to this major axis (see the first and third quadrant in Figure 2). This is a generic feature in the computed 3D models, which is in contrast to the axisymmetric case. The GW amplitudes from SASI in 2D showed an increasing trend with time due to the symmetry axis, along which SASI can develop preferentially [13, 23]. Free from such a restriction, a variety of the waveforms is shown to appear (see waveforms inserted in Figure 2). Furthermore, the 3D standing shock can also oscillate in...
Figure 2. Four snapshots of the entropy distributions of a representative 3D supernova explosion model. The second and fourth quadrant of each panel shows the surface of the standing shock wave. In the first and third quadrant, the profiles of the high entropy bubbles (colored by red) inside the section cut by the ZX plane are shown. The side length of each plot is 1000km. The insets show the gravitational waveforms from anisotropic neutrino emissions, with ‘+’ on each curves representing the time of the snapshot. Note that the colors of the curves are taken to be the same as the top panel of Figure 3.

all directions, which leads to the smaller explosion anisotropy than 2D. With these two factors, the maximum amplitudes seen either from the equator or the pole becomes smaller than 2D. On the other hand, their sum in terms of the total radiated energy are found to be almost comparable between 2D and 3D models, which is likely to imply the energy equipartition with respect to the spatial dimensions.

Figure 3 shows the gravitational waveforms for different luminosity models. To trigger explosions, we employed the so-called light-bulb approximation (see, e.g., [17]) and adjust the neutrino luminosities from the PNSs. The input luminosity for the two pair panels differs only 0.5%. Despite the slight difference in the luminosities, the waveforms of each polarization are shown to exhibit no systematic similarity when seen from the pole or equator. This is found to be due to the chaotic nature of SASI influenced by small differences.

The GW spectrum of model A, being a representative 3D explosion model, is presented in Figure 4. It can be seen that the neutrino GWs, albeit dominant over the matter GWs in the lower frequencies below \( \sim 10 \) Hz, become very difficult to detect for ground-based detectors whose sensitivity is limited mainly by the seismic noises at such lower frequencies (e.g., [1] for a review about detectors). On the other hand, the gravitational-wave spectra from matter motions peak near \( \sim 100 \) Hz, reflecting the growth of the \( \ell = 2 \) mode of SASI with timescales of \( O(10) \) ms. Such signals from a Galactic supernova are probably within the detection limits of the LIGO-class detectors, and seem surely visible to the next-generation detectors such as
Figure 3. Gravitational waveforms from neutrinos (bottom) and from the sum of neutrinos and matter motions (top), seen from the polar axis and along the equator (indicated by ‘Pole’ and ‘Equator’) with polarization (+ or × modes) for models A and B. The distance to the SN is assumed to be 10 kpc.

Figure 4. Characteristic gravitational-wave spectra from anisotropic neutrino emissions (‘Neutrino’) and matter motions (‘Matter’) with optimal detection limits of TAMA, the first LIGO, advanced LIGO, and LCGT for a supernova at a distance of 10 kpc.

the advanced LIGO and LCGT. It is noted that another peak in the GW spectra near ∼ 1kHz is from the rapidly varying matter motions of $O(\text{ms})$, induced by the local hydrodynamical instabilities. These gross properties in the GW spectra are found to be common to the other luminosity models. Thus the peak in the spectra near ∼ 100Hz is a characteristic feature for the 3D models studied in this paper.
4. Discussion

Here it should be noted that the simulations highlighted in this paper are only a very first step towards realistic 3D modelling of the supernova explosions. The approximations adopted in this paper, such as the replacement of the PNS by the fixed inner boundary and the light-bulb approach with the constant neutrino luminosity, should be improved. The exploration of these phenomena will require consistent simulations covering the entire stellar core and starting from gravitational collapse with neutrino transfer coupled to the 3D magnetohydrodynamics. Besides, the effects of rotation on the SASI are yet to be investigated [26], although the construction of the rotating steady accretion flows is still a major undertaking.

Bearing these caveats in mind, the stochastic nature of the GWs, which is illuminated here by the 3D models, is qualitatively new. It should be also mentioned that the GW spectra for the acoustic mechanism showed a very strong peak near ~ kHz, reflecting the g-modes oscillations of the PNS [12], and are significantly different from the waveforms discussed here for the SASI-aided neutrino-driven models. This means that the successful detection of the GW signals will supply us a powerful tool to probe the explosion mechanism. Recently the next-generation detectors, by which the GWs studied here could be surely visible for a Galactic source, are planned to be on line soon (2014!) [27]. Towards the gravitational-wave astronomy to unveil the supernova mechanism, it is an urgent task for theorists to make precise predictions of the GW signals based on more sophisticated 3D supernova modelling.

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