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Quasi-Periodic Gravitational-Wave Emission due to The SASI Motion

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We present results from fully relativistic three-dimensional core-collapse supernova (CCSN) simulations of a non-rotating $15M_\odot$ star using three different nuclear equations of state (EoSs). From our simulations, we show that the development of the standing accretion shock instability (SASI) differs significantly depending on the stiffness of nuclear EoS. By evaluating the gravitational-wave (GW) emission, we find a new quasi-periodic GW signature on top of the previously identified high frequency ($\sim 500 - 1000$ Hz) one, which is originated from the g-mode oscillation of the photo-neutron star (PNS) surface. The newly found signal appears in relatively low frequency range from $\sim$ 100 to 200 Hz. By analyzing the cycle frequency of the SASI sloshing and spiral modes as well as the mass accretion rate to the emission region, we show that the SASI frequency is correlated with the newly found GW emission frequency. This is because the SASI-induced temporary perturbed mass accretion strikes the PNS surface leading to the quasi-periodic GW emission.

KEYWORDS: supernovae, gravitational waves, nuclear equation of state

1. Introduction

Clarifying a correspondence between CCSN dynamics and the GW signals is a next major challenge after the first detection coined by LIGO for the black hole merger event [1]. Traditionally most of the theoretical predictions have focused on the GW signals from rotational core collapse and bounce (see, e.g., [2, 3]). While in the non-rotating core model, the evolution of convective activities in the PNS surface regions are considered to be the primal emission mechanism as a result of the g-mode oscillation, whose frequency appears at relatively high region ($\sim 500 - 1000$ Hz) depending on the PNS surface properties [4].

In this study, we report the GW emission from a non-rotating $15M_\odot$ star by performing 3D-GR hydrodynamic simulations with an approximate neutrino transport. Using three modern nuclear EoSs, we investigate its impacts on both the postbounce dynamics and the GW emission. Our results reveal a new GW signature where the SASI activity is imprinted.

2. Numerical Methods

In our full GR radiation-hydrodynamics simulations, we solve the evolution equations of metric, hydrodynamics, and neutrino radiation (see [5] for more details). Regarding the metric evolution, we evolve the standard BSSN variables $\tilde{\gamma}_{ij}$, ϕ, $\tilde{A}_{ij}$, K and $\tilde{\Gamma}^i$. The gauge is specified by the "1+log" lapse and by the Gamma-driver-shift condition. In the radiation-hydrodynamic part, the total stress-energy

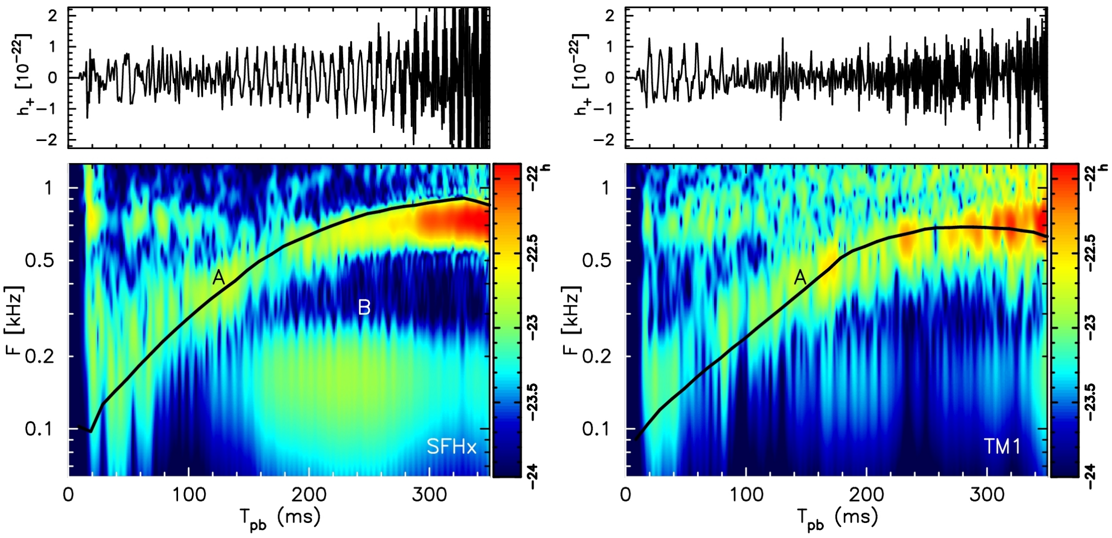

Fig. 1. In each set of panels, we plot, top; gravitational wave amplitude of plus mode h_+, bottom; the characteristic wave strain in frequency-time domain $\tilde{h}$ in a logarithmic scale which is over plotted by the expected peak frequency $F_{\rm peak}$ (black line denoted by "A"). "B" indicates the newly found low frequency component. Left and right panels are for TM1 and SFHx, respectively.

tensor $T^{\alpha\beta}_{\rm (total)}$ is expressed as $T^{\alpha\beta}_{\rm (total)} = T^{\alpha\beta}_{\rm (fluid)} + T^{\alpha\beta}_{(\nu)}$, where $T^{\alpha\beta}_{\rm (fluid)}$ and $T^{\alpha\beta}_{(\nu)}$ are the stress-energy tensor of fluid and neutrino radiation field, respectively, and are evolved numerically in a conservative way.

We use three EoSs based on the relativistic-mean-field theory with different nuclear interaction treatments, which are DD2 and TM1 of [6] and SFHx of [7]. By considering, such as, their symmetry energy at nuclear saturation density and the radius of cold NS, SFHx is the softest EOS followed in order by DD2, and TM1 [8]. Our 3D-GR models are named as DD2, TM1 and SFHx, which simply reflects the EoS used. We study a frequently used 15 $M_\odot$ star of [9]. Regarding the numerical resolution, the minimum grid size near the origin is $\Delta x = 458$m. Extraction of GWs from our simulations is done by the conventional quadrupole formula.

3. Results

In Fig. 1, we plot time evolution of the GW strain h (only plus mode h_+ extracted along the Z-axis with assuming the source distance of $D = 10$ kpc) in upper panel and its spectrogram $\tilde{h}(F)$ in lower one. Here F is the GW frequency. From spectrograms (lower panels), we see a narrow band spectrum (labeled as "A" in both models) which shows an increasing trend in its peak frequency. By following Eq.(17) in [4], we overplot $F_{\rm peak}$ in lower panels (black line). In both models $F_{\rm peak}$ indeed tracks spectral peak quite well which argues for that the component "A" is originated from the g-mode oscillation of the PNS surface [4]. The component "B" is the newly found signal and is found only in SFHx which uses the softest nuclear EoS.

Since the component "B" is found only in SFHx, here we touch the differences in the hydrodynamics evolution between SHFx and the other two models TM1/DD2. From time evolution of the spherical harmonics modes of the standing accretion shock front, SFHx experiences violent sloshing and spiral motions of the SASI when "B" appears, whereas the SASI activities are less developed in other models. We therefore investigate if these SASI activities are the origin of the GW emission "B". By spatially decomposing the quadrupole moment of matters into several spherical shells, we roughly localize this emission "B" at $10 < R < 20$ km. According to a back-of-the-envelope estimation of the

GW amplitude

$$D|h| \sim 2\epsilon MR^2/T_{\rm dyn}^2 \sim 2\epsilon R^2\dot{M}^2/M, \tag{1}$$

we expect that the significant time variation in the mass accumulation $\dot{M}$ onto the PNS can potentially lead to the GW emission. In the above equation, ϵ, M, R, and $T_{\rm dyn}$ represent the deformation parameter of the PNS surface from spherical symmetry, mass, size, and dynamical time scale of the system, respectively, in geometrized unit. In addition, we have used the following reasonable assumptions

$$T_{\rm dyn} \sim M/\dot{M}. \tag{2}$$

Coming back to the correlation between the SASI activities and the GW component "B", we plot spectrograms of normalized mode amplitude of the sloshing-SASI mode $|\tilde{A}_{10}|$, the mass accretion rate $|\tilde{\dot{M}}|$ measured at $R = 17$ km, normalised quadrupole deformation of the isodensity surface $\tilde{\epsilon}_l$ for $l = 2$ mode, and a rough measurement of the GW energy spectrum in Fig. 2. $\tilde{\epsilon}_l$ denotes a Fourier component of normalised mode amplitude ϵ_l defined by

$$\epsilon_l \equiv \sqrt{\sum_{m=-l,l} \left(R^{14}_{l,m}\right)^2} \Big/ R^{14}_{0,0} \ , \tag{3}$$

where $R^{14}_{l,m}$, with (l, m) being the spherical harmonics order, is evaluated by the spherical polar expansion of the isodensity surface R^{14} extracted at $\rho = 10^{14}$ g cm^{-1}. Although several other modes, i.e., $l \neq 2$, are excited at the surface, only the leading contribution ($l = 2$) to the GW emission is shown in the panel. As a reference, the isodensity surface R^{14} locates ~ 13.5 km during $150 < T_{\rm pb} < 300$ ms in SFHx. From the last relation in Eq.(1), we plot the expected GW strain $\log_{10}|h| \sim \log_{10}\epsilon\dot{M}^2 + $const. in panels (d) of Fig. 2 with assuming $M = 0.5M_\odot$, which is a mass contained in $10 < R < 20$ km, and $R^{14} = 13.5$ km stays nearly constant.

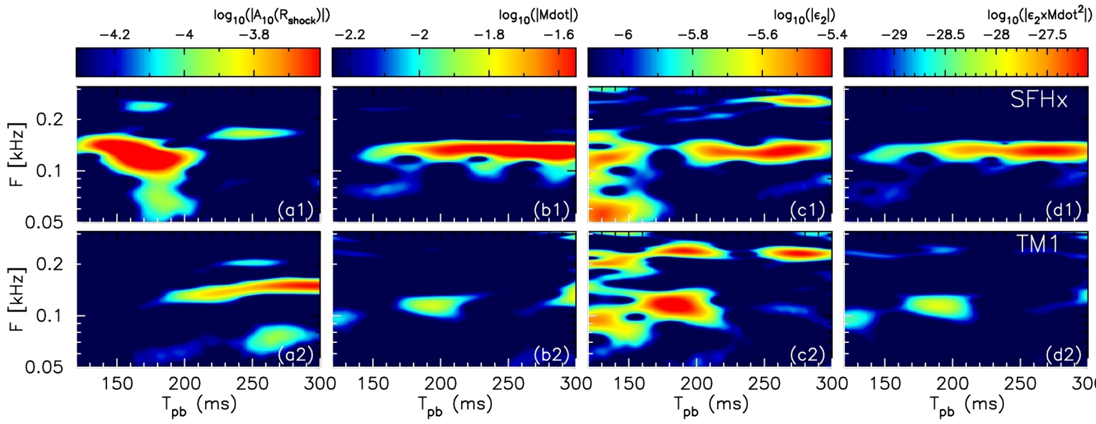

Fig. 2. Spectrograms of; (a) Fourier decomposed normalized mode amplitude $|\tilde{A}_{10}|$ of the shock surface for the sloshing-SASI mode, i.e., $(l, m) = (1, 0)$ mode, (b) the mass accretion rate $\tilde{\dot{M}}$ (with a dimension of $M_\odot$), through surface of a sphere with radius of $R = 20$ km, (c) deformation of the isodensity surface $\tilde{\epsilon}_l$ for $l = 2$ mode and (d) a rough measurement of the GW energy spectrum which is proportional to $\sim \epsilon R^2\dot{M}^2M^{-1}$ (see text). Top and bottom rows are for SFHx and TM1, respectively.

During $140 < T_{\rm pb} < 180$ ms in SFHx, we see a strong sloshing motion which has its peak frequency at $100 < F < 200$ Hz (a1). With some time delay (~ 50 ms) from the appearance of it, the mass accretion rate $\dot{M}$ starts showing a quasi-periodic oscillation at the same frequency range $100 < F < 200$ Hz (b1) and it excites oscillation on the isodensity surface (c1). The combination of large $\dot{M}$ and ϵ_2 expect GW emissions appearing in panel (d1) and it can well explain the emission "B" found in Fig. 1. We thus consider the emission mechanism of the component "B" is the temporary perturbed mass accumulation on to the PNS as a consequence of the violent SASI motion.

4. Summary and Discussion

We have presented relativistic 3D SN simulations with three different nuclear EoSs. The overall pictures of SN dynamics are qualitatively the same among all three models, although the development of the SASI differs quantitatively. The softer the EoS is, the more the SASI develops, since the prompt shock stalls at smaller radii. The evolution shows the first prompt convection phase, the sloshing-SASI phase which shifts to the spiral mode and finally to the neutrino-driven convection phase.

Regarding the GWs, we have also confirmed previously reported emissions originated from the PNS surface g-mode oscillation [4]. For this emission, we found a dependence on the nuclear EoS. The peak frequency appears at $F = 635$, 671, and 681 Hz in TM1, DD2, and SFHx, respectively, which is in order of the stiffness of nuclear EoS. Other than this GW emission, in the softest EoS model SFHx, in which the most vigorous SASI motion was observed, we have found another low frequency ($100 < F < 200$Hz) quasi-periodic emission. This emission was spatially localized at $10 < R < 20$ km. Through a spectrogram analysis of the SASI modes, of the mass accretion rate at $R = 20$ km and of the quadrupole mode of the central core deformation, we consider that the temporary perturbed mass accretion in association with the SASI downflows penetrate into the PNS surface and excite the oscillation at $10 < R < 20$ km, which then leads to the GW emission. Just recently, [10] has also reported a similar result that the low frequency GW emission occurs due to the SASI, which supports what we have found in this study.

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