Dynamical bar instability in relativistic rotational core collapse

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We investigate the rotational core collapse of a rapidly rotating relativistic star by means of a 3+1 hydrodynamical simulations in conformally flat spacetime of general relativity. We concentrate our investigation to the bounce of the rotational core collapse, since potentially most of the gravitational waves from it is radiated around the core bounce. The dynamics of the star is started from a differentially rotating equilibrium star of $T/W \sim 0.16$ (T is the rotational kinetic energy and W is the gravitational binding energy of the equilibrium star), depleting the pressure to initiate the collapse and to exceed the threshold of dynamical bar instability. Our finding is that the collapsing star potentially forms a bar when the star has a toroidal structure due to the redistribution of the angular momentum at the core bounce. On the other hand, the collapsing star weakly forms a bar when the star has a spheroidal structure. We also find that the bar structure of the star is destroyed when the torus is destroyed in the rotational core collapse. Since the collapse of a toroidal star potentially forms a bar, it can be a promising source of gravitational waves which will be detected in advanced LIGO.

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We investigate the role of dynamical bar instability in rotational core collapse by means of hydrodynamic simulations in conformally flat approximation in general relativity. We specifically focus on the structure of the star to see whether it takes a significant role in enhancing dynamical bar instability.

We find that the structure of the star takes a significant role in enhancing the dynamical bar instability at core bounce. Since the angular velocity of the collapsing star has already reached the maximum inside a certain cyrindrical radius to produce a toroidal structure, the angular momentum can only shift outward at the bounce. For a spheroidal star, the angular momentum can shift both inward and outward at bounce since it does not reach the "Keplarian". This means that rotational core collapse for the spheroidal case cannot significantly break the central core of the star. Consequently, in case of a toroidal star a bar structure can be easily constructed during the evolution. Note that for a soft equation of state ($n = 2.0$, 2.5) the amplitude of gravitational waves is also decreased, as the torus is destroyed in the rotational core collapse (see Fig. 1). Therefore the torus is the key issue to trigger the bar formation.

Once a bar has formed, the amplitude of gravitational waves has significantly increased due to the nonaxisymmetric deformation of the star. The previous 2D calculation shows that a peak amplitude of gravitational waves comes from the core bounce of the star, and its behavior also coincides with that of 3D calculation. In our result, gravitational radiation is dominantly generated in the bar formation process. The characteristic amplitude and frequency of gravitational waves in the collapsing star can be written as

$$f_{\rm gw} \approx \frac{1}{2\pi t_{\rm dyn}} = 100 \ [{\rm Hz}] \left(\frac{M_\odot}{M}\right) \left(\frac{40M}{R}\right)^{3/2},$$

$$h_{\rm gw} \approx 4.8 \times 10^{-23} \left(\frac{M}{M_\odot}\right) \left(\frac{10{\rm Mpc}}{d}\right) \left(\frac{rh/M}{0.01}\right).$$

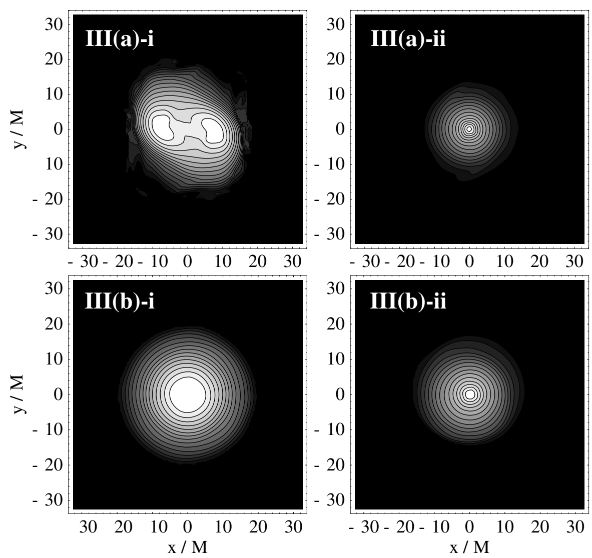

FIG. 1: Density contour in the equatorial plane of 2 collapsing stars (Model III[a] and [b] of Table I in Ref. [1]). Snapshots are plotted at the parameter $(t/t_{\rm dyn}, \rho^*_{\rm max})$ = III(a)-i $(3.19, 2.70 \times 10^{-4})$, III(a)-ii $(7.77, 4.02 \times 10^{-3})$, III(b)-i $(3.20, 3.28 \times 10^{-4})$, III(b)-ii $(7.77, 1.92 \times 10^{-3})$, respectively. The contour lines denote coordinate densities $\rho^* = \rho^*_{\rm max} \times 10^{-0.220(16-i)} (i = 1, \cdots, 15)$.

Therefore, gravitational waves from a dynamical bar in a collapsing neutron star can be detected in advanced LIGO.

A more detailed discussion is presented in Saijo (2005) [1].

[1] M. Saijo, submitted to Phys. Rev. D (2005).