Collapse of differentially rotating supermassive stars: Post black hole formation

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We investigate the collapse of differentially rotating supermassive stars (SMSs) by means of 3+1 hydrodynamic simulations in general relativity. We particularly focus on the onset of collapse to understand the final outcome of collapsing SMSs. We find that the estimated ratio of the mass between the black hole (BH) and the surrounding disk from the equilibrium star is roughly the same as the results from numerical simulation. This suggests that the picture of axisymmetric collapse is adequate, in the absence of nonaxisymmetric instabilities, to illustrate the final state of the collapse. We also find that quasi-periodic gravitational waves continue to be emitted after the quasinormal mode frequency has decayed. We furthermore have found that when the newly formed BH is almost extreme Kerr, the amplitude of the quasi-periodic oscillation is enhanced during the late stages of the evolution. Geometrical features, shock waves, and instabilities of the fluid are suggested as a cause of this amplification behaviour. This alternative scenario for the collapse of differentially rotating SMSs might be observable by LISA.

We have investigated the collapse of differentially rotating supermassive stars, especially focusing on the post black hole (BH) formation stage, by means of three dimensional hydrodynamic simulations in general relativity. We particularly focus on the onset of collapse to form a rapidly rotating BH as a final outcome.

We have found that the qualitative results of the evolution for the mass and spin of the final BH and disk are quite similar to the estimates that can be computed from the equilibrium configuration when the estimated, final BH has $J_{(\mathrm{BH})}/M^2_{(\mathrm{BH})} < 1$. This result suggests that in the absence of a nonaxisymmetric instability, the estimate of the BH mass and the disk mass agree with a simple axisymmetric picture that the specific angular momentum is conserved throughout the evolution, and the newly formed BH swallows the matter up to the radius of the innermost stable circular orbit.

We have also found that a quasi-periodic wave occurs after the ringdown of a newly formed BH. As we would normally expect the ringdown waveform to damp, it seems likely that the cause of this waveform is due to the presence of the disk in some form. Furthermore, when the newly formed BH is sufficiently close to extreme Kerr with sufficient surrounding matter we have found that the wavesignal may be significantly amplified.

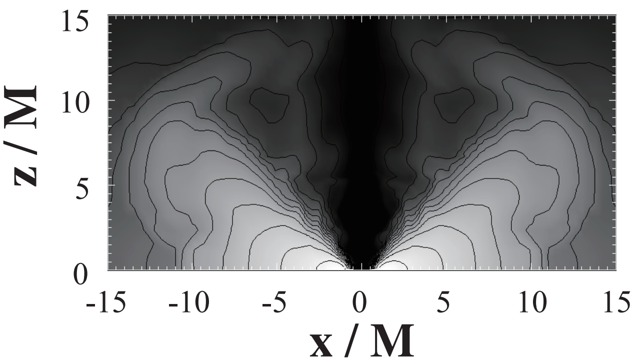

FIG. 1: Contours of the rest mass density in the meridional plane for rapidly rotating black hole formation. Snapshots are plotted at values of $(t, \rho_{\mathrm{max}}) = (869M, 4.85 \times 10^{-5})$ (M: gravitational mass of the equilibrium star), with a cutoff density of $\rho_{\mathrm{cut}} = 1.56 \times 10^{-13}$. The contour lines denote rest mass densities $\rho/\rho_{\mathrm{max}} = 10^{-(15-i)d}$ $(i = 1, \cdots, 14)$, where $d = (\log \rho_{\mathrm{max}} - \log \rho_{\mathrm{cut}})/15$. Note that the apparent horizon exists after $t = 770M$, and the coordinate radius of the apparent horizon in the equatorial plane are $r_{\mathrm{hrz}} = 0.180M$.

We have discussed several possibilities for the origin of these amplified waves. The most likely possibilities seem to be (a) corotation resonance between the disk and the BH, (b) long-lived gravitational waves from the near-extreme BH amplified by perturbations in the disk, or (c) shocks from the infalling, accreting matter.

Finally we discuss the detectability of gravitational waves from this system. Since the main targets of LISA are gravitational radiation sources between 10^{-4} and 10^{-1} Hz, it is possible that LISA can search for the burst and quasi-normal ringing waves accompanying rotating supermasive star collapse and formation of a supermassive BH. Moreover, the frequency of the quasi-periodic waves after the quasinormal ringing is quite similar to that of quasinormal ringing, so is in the detectable regime. Also the amplitude of the quasi-periodic wave is roughly 10% of the burst at the horizon, and hence this feature can also be seen in LISA.

Although we focus on the case of the collapse of differentially rotating supermassive star to a supermassive BH in this paper, our model is also applicable to the collapse of population III stars which are also radiation pressure dominated. In this case, the mass range of the collapsing object becomes of the order of a few hundred solar masses. Therefore the most sensitive region for the detection of burst waves and quasinormal ringing waves becomes the order of hertz. Such gravitational waves might be seen in Deci-hertz interferometer gravitational wave observatory (DECIGO).

A more detailed discussion is presented in Saijo and Hawke (2009) [1].

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[1] M. Saijo and I. Hawke, Phys. Rev. D **80**, 064001 (2009).