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COLLAPSE OF DIFFERENTIALLY ROTATING SUPERMASSIVE STARS

Motoyuki Saijo
Department of Physics, Kyoto University, Kyoto 606-8502, Japan
E-mail: saijo@tap.scphys.kyoto-u.ac.jp
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ABSTRACT

We investigate the gravitational collapse of rapidly rotating relativistic supermassive stars by means of a 3+1 hydrodynamical simulations in conformally flat spacetime of general relativity. We study the evolution of differentially rotating supermassive stars of $q \equiv J/M^2 \sim 1$ (J is the angular momentum and M is the gravitational mass of the star) from $R/M \sim 65$ (R is the circumferential radius of the star) to the point where the conformally flat approximation breaks down. We find that the collapse of the star of $q \gtrsim 1$, a radially unstable differentially rotating star form a black hole of $q \lesssim 1$. The main reason to prevent the formation of a black hole of $q \gtrsim 1$ is that quite a large amount of the angular momentum stays at the surface. We also find that the collapse is coherent and that it likely leads to the formation of a supermassive black hole with no appreciable disk nor bar. In the absence of nonaxisymmetric deformation, the collapse of differentially rotating supermassive stars are the promising sources of burst and quasinormal ringing waves in the Laser Interferometer Space Antenna.

Subject headings: Gravitation — hydrodynamics — instabilities — stars: neutron — stars: rotation

We investigate the collapse of a differentially rotating supermassive stars (SMSs) by means of hydrodynamic simulations in conformally flat approximation in general relativity. We start our collapse from $R/M \sim 65$, where R is the circumferential radius of the star, to the point where conformally flat approximation breaks down.

First we find that the cosmic censor conjecture even holds for gravitational collapse of radially unstable equilibrium star of $J/M^2 \gtrsim 1$. The main reason to prevent to form a black hole (BH) of $J/M^2 \gtrsim 1$ is that the angular velocity of each cylindrical radius approaches to the Keplarian one. Note that even a thin disk near the surface of the star can hold relatively a large amount of angular momentum if the radius is large.

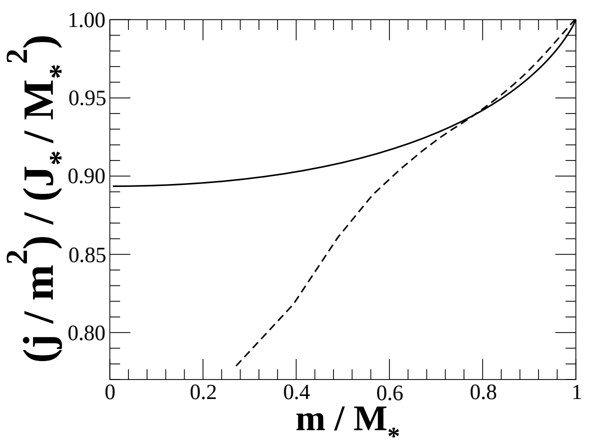

Fig. 1.— Profile of j/m^2 as a function of cylindrical mass m for Model II (Table 2 of Ref. [1]). Solid and dashed line denotes the profile at $t = 0$ and $t = 5.64\ t_{\rm dyn}$, respectively. Note that J_* is the cylindrical angular momentum, M_* is the rest mass, $t_{\rm dyn}$ is the dynamical time defined in Ref. [1].

Second, collapse of a differentially rotating, relativistically unstable SMS is coherent and likely leads to the formation of a supermassive black hole (SMBH). This situation is quite similar to the collapse of a uniformly rotating SMS. Combining these two results, we conclude that collapse of a SMS is coherent within the order of dynamical time.

Third, we cannot find any evidence of bar formation nor significant disk formation from rotating collapse prior to BH formation. The phenomena of no bar formation also comes from the fact that mass density collapses first to form a BH. In such case, T/W cannot scale in R^{-1} due to the growth of the degree of differential rotation, and as a fact the star of T/W cannot reach the dynamical instability criterion of ~ 0.27.

Finally, rotating SMS collapse is a promising source of burst gravitational waves and of quasi-normal mode ringing waves. We can estimate the strength and the frequency of the wave burst and the wave quasinormal ringing emitted from this rotating collapse as $f_{\rm burst} \sim 3 \times 10^{-2}(10^6 M_\odot/M)(M/R)^{3/2}$[Hz]. The wave amplitude can be estimated by employing the quadrupole formula according to $h_{\rm burst} \sim 1 \times 10^{-18}(M/(10^6 M_\odot))(1{\rm Gpc}/d)(M/R)$, where Q is the quadrupole moment of the star and d is the distance from the observer. We set $R/M = 1$, a characteristic mean radius during BH formation. The characteristic frequency $f_{\rm QNM}$ and strength $h_{\rm QNM}$ of this radiation in rotating star collapse are $f_{\rm QNM} \sim 2 \times 10^{-2}(10^6 M_\odot/M)$[Hz], $h_{\rm QNM} \sim 6 \times 10^{-19}((\Delta E_{\rm GW}/M)/10^{-4})^{1/2}(2 \times 10^{-2}[{\rm Hz}]/f_{\rm QNM})^{1/2}(M/(10^6 M_\odot))^{1/2}(1{\rm Gpc}/d)$, where $\Delta E_{\rm GW}$ is total radiated energy. 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 waves and the quasinormal ringing waves accompanying rotating SMS collapse and formation of a SMBH.

A more detail discussion is presented in Saijo (2003)[1].

[1] Saijo, M. 2003, ApJ, submitted