Black Hole Formation, Explosion and Gravitational Wave Emission from Rapidly Rotating Very Massive Stars

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Gravitational collapse induced by pair instability (PI) is one of the final fates of very massive stars (VMSs) with mass $\gtrsim 100M_{\odot}$. Several observations suggest the existence of VMSs in the universe, however, their formation and evolution process are still highly unknown. It is suggested that when a rotating VMS collapses to a BH, strong electromagnetic waves and gravitational waves would be emitted. If the signal from this event can be observed, we obtain the information about the internal structure of the VMS, which is considered to be of great use for understanding the nature of VMSs. Also, if the detected signal is from the Population III (PopIII) VMS, we also obtain the information about the nature of the PopIII stars, which are closely related to the evolution of the universe. To study the observability and properties of the signals from this event, we perform axisymmetric numerical relativity simulations of the gravitational collapse of rotating PopIII VMSs in this thesis.

First, we perform long-term simulations of the gravitational collapse of rotating VMS to explore the formation process of the BH torus system and to study the properties and time evolution of the BH, torus and outflow formed after the collapse. We select a progenitor star with the initial mass of $M_{\rm ZAMS} = 320M_{\odot}$ (ZAMS: zero-age main sequence) and rotating rigidly with the rotation velocity of 50% of the Kepler rotation at its surface. One-dimensional (1D) stellar evolution calculation is performed from the ZAMS stage until the central temperature reaches $10^{9.2}$ K including the effects of hydrodynamical instabilities on the transport of angular momentum. At this stage, we map the resulting 1D stellar evolution model onto two-dimensional (2D) grids for axisymmetric gravitational collapse simulations as an initial condition. To consider the cases where the angular velocity is decreased due to other additional angular momentum transport mechanisms, we simulate two additional models for which the angular velocity is decreased uniformly by a factor of 0.7 and 0.4 at the start of gravitational collapse. We find that for the fast rotating model, a fraction of the initial mass forms a torus surrounding the remnant black hole (BH) and a fraction of the torus material forms an outflow by a hydrodynamical effect. In several seconds after the BH formation, the torus eventually relaxes to a nearly stationary state with mass $10M_{\odot}$ composed mainly of light elements generated by photodissociation, while the outflow continues to expand forming shocks and sweeping the material in the core. On the other hand, for other more slowly rotating models, only a small or no torus is formed and outflow does not occur or falls immediately onto the BH even though it is driven at the formation of the torus. We discuss the possible evolution scenario of the torus by considering the viscous effect and estimate a bolometric luminosity of the explosion assuming that the energy injection from the torus to the envelope of the progenitor star occurs. We estimate that if the energy of the order of 10^{52} erg is injected to the envelope, the bolometric luminosity and timescale of the explosion could be of the order of 10^{43} erg/s and a year, respectively.

Second, we study the gravitational wave emission associated with the BH formation of rotating VMSs by performing high-resolution simulations. For the progenitor star, we use

the same star as we used in the first study. We find that gravitational waves are composed of a short precursor and ringdown oscillation associated with the formed BH for all the models. The peak strain amplitude and the corresponding frequency of the axisymmetric mode of gravitational waves are $\sim 10^{-22}$ and $f \approx 300$–$600\,\mathrm{Hz}$ for an event at the distance of $D = 50$ Mpc. Such gravitational waves will be detectable only for $D \lesssim 10$ Mpc by the second generation detectors, advanced LIGO, advanced VIRGO, and KAGRA, even if the designed sensitivities for these detectors are achieved. However, the third-generation detectors will be able to detect such gravitational waves for an event up to $D \sim 100$ Mpc.