論文の内容の要旨

論文題目
Formation and growth of massive black holes in the early universe
(宇宙初期での大質量ブラックホールの形成と成長)

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Observations of high-redshift quasars have revealed the existence of supermassive black holes (SMBHs) in the early universe. Importantly, the SMBHs are believed to have grown within 1 Gyr to as massive as $\gtrsim 10^9$ solar masses ($\mathrm{M}_\odot$), suggesting a big problem in the context of structure formation in the early universe that "how does a SMBH grow so fast?".

As origins of the high-redshift SMBHs, theoretical astrophysicists often consider that a small 'seed' BH, left as a remnant of a massive star, grows via gas accretion and mergers to become a SMBH. As a comparative model for formation of such a seed, a BH of mass $\sim 100\,\mathrm{M}_\odot$, which is left after death of a first star or a Population III (Pop III) star, is thought to grow via a nearly Eddington accretion rate. This means that a SMBH of mass $\sim 10^9\,\mathrm{M}_\odot$ is marginally formed within the age of the universe at $z \sim 6$. Unfortunately, this model has a problem that the BH growth is delayed due to effects of radiation, which is emitted when gravitational energy is released from accreting gas and is converted to radiation energy. This radiation feedback significantly suppresses the accretion rate well below the Eddington accretion rate and makes the SMBH formation impossible by the Pop III BH model.

As alternative models to facilitate the formation of the high-redshift SMBHs, there are three models: the direct collapse model, the super-Eddington accretion model and the runaway stellar collision model. These models have been intensively studied by many authors, but there still remain many things to be examined. Specifically, previous works often consider idealized situations, whereby the validity of the models cannot be correctly discussed.

In this thesis, we study the BH formation models by considering more realistic situations in order to examine the validity of the models.

First, we work on the direct collapse model, where a supermassive star (SMS) of mass $\sim 10^5\,\mathrm{M}_\odot$ almost entirely collapses at the end of stellar lifetime, directly leaving a $\sim 10^5\,\mathrm{M}_\odot$ BH. A SMS can form under peculiar conditions, e.g., inside an atomic-cooling halo strongly irradiated by Lyman-Werner radiation emitted from external sources, whereby a rapid gas accretion of $\sim 0.1 - 1\,M_\odot\,\mathrm{yr}^{-1}$ on to a growing protostar is realized. However, there is a problem that, during the formation of a SMS via rapid gas accretion, strong stellar radiation is expected to stop the accretion by UV radiation feedback. To clarify if the expectation is true or not, Hosokawa et al. (2013) compute stellar evolution of the accreting SMS, by assuming a constant accretion rate. They find that a growing SMS is actually largely inflated with a low surface temperature of $\sim 5000\,\mathrm{K}$ and emit a small amount of UV photons to cause the UV feedback. The SMS evolution is contrasted to a relatively slowly accreting Pop III star which contracts and emit a significant amount of UV radiation. In a more realistic case, the accretion history will be highly variable with time, since the accretion occurs through a gravitationally unstable disk where fragments form and migrate to fall on to the central protostar, causing accretion bursts. In this case, the evolution of the growing SMS can be affected if there are long, quiescent accretion phases during which the star can contract.

We examine stellar evolution of an accreting SMS with a highly variable, episodic accretion history, where burst accretion followed by quiescent accretion is repeated. We construct an analytic model of episodic accretion histories with parameters characterizing the burst and quiescent phases, and then calculate the evolution. It is found that the SMS significantly contracts during the quiescent phases and emits a copious amount of UV photons, likely resulting in the efficient radiation feedback, if the length of the quiescent phases is longer than a thousand years. We also investigate the effect of a more realistic episodic accretion history, which is obtained from 2D hydrodynamics simulations of a gravitationally unstable disk, on the SMS evolution. In this case, the duration of the quiescent phases is typically shorter than 10^3 yr and the accreting protostar does not contract. Then, the protostar is able to grow to become as massive as $\sim 10^5\,\mathrm{M}_\odot$ without UV feedback and the direct collapse BH formation is viable.

Next, we study the super-Eddington model, in which a BH grows with very rapid super-Eddington gas accretion and becomes a SMBH in a short time. How can such super-Eddington accretion be realized? It is naively expected that such a rapid gas accretion flow near the BH causes strong radiation force with emitting nearly Eddington luminosity, which halts the accretion and stops the BH growth. Photon trapping, however, is thought to reduce the emerging luminosity. In fact, several studies including numerical simulations and (semi-)analytical studies show that the super-Eddington accretion is not prevented by the radiation force within the BH accretion flow near the BH. On the other hand, radiation heating can suppress gas accretion at larger scales where gas pressure and BH gravity is comparable. Thus, the small and large scale regions need to be self-consistently investigated. To this end, Inayoshi, Haiman & Ostriker (2016) perform a 1D radiation hydrodynamical simulation of a spherical accretion flow at the large scales, assuming a functional form of luminosity emerging from the central region, which is at most the Eddington luminosity for this spherical case. They find that transition occurs from the usual Eddington accretion to a 'hyper-Eddington' accretion, which is essentially a Bondi accretion. The transition occurs because an ionized region is initially smaller than the Bondi radius at which BH gravity balances gas pressure. More realistically, however, the emerging luminosity can exceed the Eddington luminosity due to the deviation from the spherical morphology, i.e., due to formation of an accretion disk where emitting radiation can preferentially escape through polar directions.

We examine the large-scale BH accretion flow with a super-Eddington luminosity source by performing 1D radiation hydrodynamics simulations, in order to see whether the transition to the steady hyper-Eddington accretion occurs in this high-luminosity case. We construct an analytical model of the central source which exceeds the Eddington luminosity. It is shown that the transition occurs even when the luminosity reaches at most 100 times the Eddington luminosity. We argue, using analytic models and numerical results, that the transition is realized because ram pressure of accreting gas in addition to gas gravity overcomes the radiation force from the super-Eddington luminosity source. Thus, the BH growth would continue not to be halted by the strong radiation.

Finally, we study the runaway stellar collision model, in which stars in a dense star cluster successively collide and merge with a specific star residing near the center. The star eventually becomes as massive as $\sim 1000\,\mathrm{M}_\odot$ and collapses to leave an intermediate-mass BH (IMBH), possibly serving as a seed for forming a SMBH at high redshift. Although several studies have shown that star cluster formation is likely to occur within metal-enriched atomic-cooling halos in the early universe, it is still uncertain whether such a runaway collision process is prevalent. Katz et al. (2015) perform direct N-body simulations of star clusters formed in a mini-halo system, which is identified in cosmological simulations. They show that the runaway collision and IMBH formation are very likely outcomes in mini-halos.

This work encourages us to statistically examine the star cluster dynamics and evolution for clusters forming in atomic-cooling halos. We first perform cosmological simulations to find star cluster forming sites. We then generate star cluster initial conditions for direct N-body simulations assuming star formation efficiency and an initial mass function. For the star clusters, direct N-body simulations are conducted, to follow stellar collisions and mergers. It is found that in all the clusters except one the runaway stellar collisions occur and massive stars of mass $400 - 1900\,\mathrm{M_{\odot}}$ form, which would leave IMBHs at the end of their lives. The diversity of the final stellar masses is attributed to the diversity of the parent atomic-cooling halo properties as virial mass, central gas density and central gas velocity dispersion. We also derive an IMBH mass-cluster mass relation for our simulated clusters and compare it with a SMBH mass-bulge mass relation in the local universe.

We conclude that the three models are viable until the seed BH formation. However, it is still unclear whether the seed BHs grow to the SMBHs. In future works, we will study the subsequent evolution in the context of the three models considered in this thesis. Specifically, we will follow the evolution and growth of the IMBHs left inside the star clusters. We will focus on tidal disruption of stars and BH merger which would occur during the IMBH growth and estimate the event rates to compare to the future X-ray/gravitational-wave observations. The comparison would greatly help us to further understand the origin of the SMBHs in the early universe.