Formation of supermassive black holes in the high-redshift universe

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In the Universe, there is an enormous number of structures and objects such as galaxies, stars, and planets. Remarkable progresses of observations grow our understanding about their origins and formation processes. Among them, recent observations of high-redshift quasars reveal that supermassive black holes (SMBHs) with mass of $\gtrsim 10^9\ M_\odot$ have already formed as early as the beginning of the universe. As the formation processes of such BHs, the gas accretion and mergers of the remnant BHs formed by the collapse of first generation stars ($\sim 100\ M_\odot$) have been considered. However, various radiative feedbacks prevent the efficient BH growth and thus the required time to form SMBHs becomes longer than the age of the high-redshift universe.

As a solution of this problem, formation of supermassive stars (SMSs; $M_* \gtrsim 10^5\ M_\odot$) and their subsequent collapse directly to the BHs in the first galaxies has been considered. Seed BHs formed by the direct collapse are expected to sufficiently shorten the formation time even with the radiative feedbacks. Formation of SMSs in first galaxies irradiated with strong far ultraviolet (FUV) radiation has often been studied. In such cases, the primordial gas clouds are supposed to collapse monolithically and form stars without strong fragmentation since H_2 molecules, which are the main coolants of primordial gas and promote gas fragmentation, are photo-dissociated.

In this thesis, we discuss the unified scenario of the seed BH formation through the direct collapse of SMSs. We have investigated the formation of SMSs in the following three parts; (i) formation of supermassive clouds in the first galaxies, (ii) collapse phase of the supermassive cloud, and (iii) evolution of the protostar up to a SMS.

We first reconsider conditions of the SMS formation requiring the H_2 photodissociation by the strong FUV radiations. Candidates of FUV sources, including star-forming galaxies, are probably sources of strong CRs and X-rays too. We find that external ionization promotes H_2 production and elevates the threshold FUV intensity needed for SMS formation as $J_{\rm crit} \propto U_{\rm CR}^{1/2}$ ($\propto J_X^{1/2}$) in the high CR (respectively X-ray) limit. Therefore, the SMS

formation under the strong FUV radiations is strongly suppressed by the ionizations due to the external high-energy radiations (CRs and X-rays).

Following the result, we propose the new pathway to form SMSs without assuming the strong FUV radiations. The assembly of a typical first galaxy proceeds via cold and dense flows penetrating deep to the center, where the supersonic streams collide each other to develop a hot and dense shocked gas. In such dense shocked layer, H_2 molecules are collisionally dissociated and thus supermassive clouds are formed. Thereafter, the supermassive cloud collapses isothermally by the atomic cooling (Lyα and various continuum emissions). The range of post-shock conditions for SMS formation can be expressed as $T \gtrsim 6000$ K $(n_{\rm H}/10^4\ {\rm cm^{-3}})^{-1}$ for $n_{\rm H} \lesssim 10^4\ {\rm cm^{-3}}$ and $T \gtrsim 5000 - 6000$ K for $n_{\rm H} \gtrsim 10^4\ {\rm cm^{-3}}$. Moreover, metal enrichment does not affect the above condition for metallicity below $\sim 10^{-3}\ Z_\odot$ if metals are in the gas phase.

Next, we investigate the fate of a supermassive cloud using the three-dimensional hydrodynamical simulations. We find the cloud can collapse runaway and without efficient fragmentation even if the cloud has turbulent motions. Though the H_2 fractions are rapidly enhanced by the three-body reaction ($3{\rm H} \rightarrow {\rm H_2} + {\rm H}$), the H_2 cooling (both of line and continuum emission) never play a significant role for the thermal evolution at the central region. When the central region becomes optically thick, single hydrostatic core (i.e., protostar) is formed. The formed protostar grows via rapid accretion fed the dense filamentary flows. The accretion rate is so high ($\dot{M}_{\rm acc} \sim 3\ M_\odot\ {\rm yr}^{-1}$) that the protostar is expected to evolve up to a supermassive star ($\gtrsim 10^5\ M_\odot$) within its lifetime

Finally, we solved the stellar structure growing at the rate of $\gtrsim 0.01\ M_\odot\ {\rm yr}^{-1}$. Under rapid accretion, the stellar radius continues to increases monolithically with the stellar mass following $R_* \propto M_*^{1/2}$. The stellar interior inhomogeneously contracts by losing the thermal energy. The maximum of the stellar radius is $R_* \simeq 4 \times 10^4\ R_\odot \sim 10^2$ AU for $M_* \sim 10^4\ M_\odot$. With this very large radius, the stellar effective temperature is less than 10^4 K even after the protostar becomes supermassive. Strong UV feedback, which could limit the mass accretion onto the star, is thus unlikely to operate in this case. Moreover, we investigate the stability of the accreting protostar against the stelar pulsations. As a result, accreting SMSs become pulsation unstable due to the κ-mechanism, but the resulting mass-loss rates are still much lower than the accretion rates. We conclude that the protostar rapidly grows to a SMS ($\gtrsim 10^5\ M_\odot$) without the strong mass-loss due to the negative feedbacks.