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# Supermassive star formation with non-LTE primordial-gas chemistry

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**Abstract.** The remnant black holes (BHs) of supermassive stars formed at $z > 10$ are promising candidates of the seeds for supermassive BHs. They are thought to form in pristine atomic cooling halos in which $H_2$ cooling is totally suppressed by strong external radiation. Here, we obtain the critical FUV specific intensity $J_{21}^{\rm cr}$ (in units of $10^{-21}\,{\rm erg\,s^{-1}\,Hz^{-1}\,sr^{-1}\,cm^{-2}}$) required for supermassive star formation, with non-local thermodynamic equilibrium (non-LTE) primordial-gas chemistry. We consider the non-LTE chemistry with the vibrationally resolved $H_2^+$ kinetics, as well as realistic radiation spectra of galaxies. We find that while the effect of non-LTE $H_2^+$ chemistry is important for soft radiation sources, it is negligible and $J_{21}^{\rm cr} \sim 1000$ for the hard spectra of young and metal-poor galaxies, considered as typical radiation sources in the early Universe.

## 1. Introduction

Discoveries of high-redshift quasars indicate the formation of supermassive black holes (SMBHs) within the first 1 Gyr of the Universe (e.g., Fan et al. 2001; Mortlock et al. 2011). How do those SMBHs form in such a short available time? The remnant BHs of supermassive stars with $\sim 10^5 M_\odot$ is one of the promising candidates for the SMBH seeds (see, e.g., Volonteri 2012; Haiman 2013, for review).

Supermassive stars are thought to form if the $H_2$ cooling is totally suppressed by strong far-ultraviolet (FUV) irradiation in pristine atomic-cooling haloes. The number density of the formation sites strongly depends on the critical FUV specific intensity $J_{21}^{\rm cr}$ (in units of $10^{-21}\,{\rm erg\,s^{-1}\,Hz^{-1}\,sr^{-1}\,cm^{-2}}$) required for their formation (e.g., Dijkstra et al. 2014). Therefore, here we obtain a realistic value of $J_{21}^{\rm cr}$, using a one-zone model of star formation (e.g., Omukai 2001) with detailed primordial-gas chemistry.

## 2. Critical FUV intensity for supermassive star formation

First, to reveal the actual role of $H_2^+$ in supermassive star formation, we study the impact of assuming the LTE population for the vibrational levels of $H_2^+$ in Sugimura et al. (2016). Fig. 1 shows $J_{21}^{\rm cr}$ for the blackbody spectra with $T_{\rm rad}$ obtained by the non-LTE, ground-state and LTE calculations. For our non-LTE calculation, we solve the chemical evolution regarding $H_2^+(v)$ with $v = 0, 1..., 18$ as different species.

Next, we obtain $J_{21}^{\rm cr}$ for realistic radiation spectra of galaxies in Sugimura et al. (2014), as

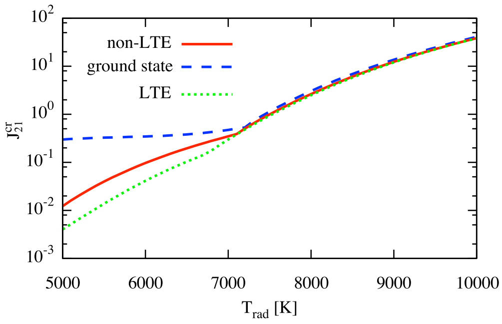


**Fig. 1.** The dependence of $J_{21}^{\rm cr}$ on the temperature of the blackbody spectra. The calculations are done with the different prescriptions for the population of the $H_2^+$ vibrational levels.

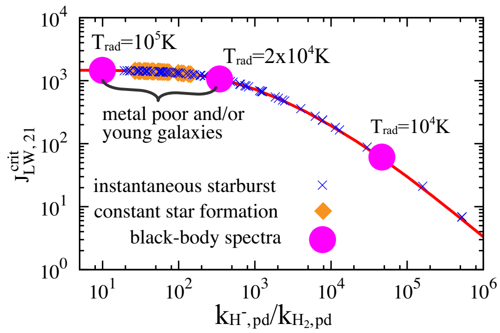


**Fig. 2.** The critical intensity $J_{21}^{\rm cr}$ for each galaxy spectrum model. The horizontal axis represents the hardness of the spectra, given by the ratio of the $H^-$ photodetachment to the $H_2^+$ photodissociation rates.

plotted in Fig. 2. We use the spectra for metal-poor galaxies in Inoue (2011), with the metallicity $Z$ and ages ranged from 0 (Pop III) to $0.2Z_\odot$ (Pop II) and from 1 Myr to 1 Gyr, respectively. We consider instantaneous starburst and constant star formation cases.

## 3. Conclusions

Using a one-zone star formation model (e.g., Omukai 2001), we study the critical radiation intensity $J_{21}^{\rm cr}$ required for supermassive star formation considering the non-LTE chemistry and realistic radiation spectra. The non-LTE chemistry of $H_2^+$ vibrational state has a large impact for soft spectra corresponding to $T_{\rm rad} < 7000\,{\rm K}$, enhancing $J_{21}^{\rm cr}$ by a factor of a few compared to the LTE results. However, typical radiation sources in the early Universe are likely young and metal-poor galaxies with hard spectra, for which we obtain $J_{21}^{\rm cr} \sim 1000$.

Using the $J_{21}$ distribution of Dijkstra et al. (2014) with $J_{21}^{\rm cr} \sim 1000$, we estimate the number density of supermassive stars at $z = 10$ as $\sim 10^{-10}{\rm cMpc}^{-3}$, roughly consistent with the observed SMBH density at $z \sim 6$. To determine whether the supermassive stars are indeed seeds of SMBHs or not, it is necessary to determine the condition for supermassive star formation considering all relevant chemical/physical processes.

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