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Enhanced direct collapse due to Lyman α feedback

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ABSTRACT

We assess the impact of trapped Lyman α cooling radiation on the formation of direct collapse black holes (DCBHs). We apply a one-zone chemical and thermal evolution model, accounting for the photodetachment of H^- ions, precursors to the key coolant H_2, by Lyman α photons produced during the collapse of a cloud of primordial gas in an atomic cooling halo at high redshift. We find that photodetachment of H^- by trapped Lyman α photons may lower the level of the H_2-dissociating background radiation field required for DCBH formation substantially, dropping the critical flux by up to a factor of a few. This translates into a potentially large increase in the expected number density of DCBHs in the early Universe, and supports the view that DCBHs may be the seeds for the BHs residing in the centers of a significant fraction of galaxies today. We find that detachment of H^- by Lyman α has the strongest impact on the critical flux for the relatively high background radiation temperatures expected to characterize the emission from young, hot stars in the early Universe. This lends support to the DCBH origin of the highest redshift quasars.

Key words. radiative transfer – cosmology: theory – dark ages, reionization, first stars – molecular processes – black hole physics – quasars: supermassive black holes

1. Introduction

The direct collapse scenario for black hole (BH) formation in the early Universe has received much attention in recent years, in particular for its ability to explain the formation of BHs with masses $\gtrsim 10^9\ M_\odot$ within the first billion years of cosmic history (e.g. Mortlock et al. 2011; Wu et al. 2015). The key ingredients for the formation of the massive ($\sim 10^5\ M_\odot$) seed BHs in this theory are (1) primordial gas collapsing into an atomic cooling dark matter halo and (2) a sufficiently low fraction of H_2 molecules in the gas to prevent cooling below the $\sim 10^4$ K cooling limit of atomic hydrogen (for reviews see Volonteri 2012; Haiman 2013; Johnson & Haardt 2016; Latif & Ferrara 2016).

The main ways that are envisioned for keeping the primordial gas devoid of molecules is photodissociation of H_2 due to so-called Lyman-Werner (LW) radiation at energies 11.2–13.6 eV and photodetachment of the H^- ion, which is an intermediary in the formation of H_2 (e.g. Bromm & Larson 2004), by photons with energies >0.76 eV (e.g. Chuzhoy et al. 2007). The relative importance of each of these processes has been found to be strongly dependent on the spectrum of the incident radiation (e.g. Shang et al. 2010; Sugimura et al. 2014; Glover 2015; Agarwal et al. 2015; Latif et al. 2015; Wolcott-Green et al. 2016), presumably produced by a nearby star-forming galaxy (e.g. Dijkstra et al. 2008; Agarwal et al. 2012; Visbal et al. 2014; Regan et al. 2016a).

An additional source of radiation which contributes to the photodetachment of H^- and so limits the formation rate of H_2 is the trapped Lyman α cooling radiation that is emitted from the collapsing atomic gas in the halo itself (Spaans & Silk 2006; Schleicher et al. 2010). Here we explore the impact that this trapped radiation has on the production of H_2 molecules in the gas and, in turn, on its ability to cool below the $\sim 10^4$ K required for direct collapse black hole (DCBH) formation. In the next section, we outline the one-zone chemical and cooling model that we employ for our study and we describe our approach to modeling the photodetachment of H^- by Lyman α cooling radiation. In Sect. 3 we present the basic results of our calculations, and in Sect. 4 we explore the impact of Lyman α feedback on the critical LW flux required for DCBH formation. Finally, we give our conclusions and provide a brief discussion of our results in Sect. 5.

2. Feedback from Lyman α cooling radiation

For our study, we begin with the same one-zone model for the collapse of the primordial gas as presented in Johnson & Bromm (2006), which is very similar to other one-zone models that have been routinely applied to DCBH formation (e.g. Omukai et al. 2005, 2008; Schleicher et al. 2010; Agarwal et al. 2016a). The model assumes that the density of the primordial gas increases on the free-fall timescale, and the non-equilibrium chemical and thermal evolution of the collapsing gas is calculated. All of the pertinent primordial chemical species are included, as are all of the pertinent radiative processes.

While the reader is referred to Johnson & Bromm (2006) for more details, here we describe the key ingredients in the model that we draw on for our study of the direct collapse scenario. One important update to this code has been the adoption of the H_2 self-shielding prescription presented in Wolcott-Green et al. (2011; see also Hartwig et al. 2015; Wolcott-Green et al. 2016), which replaced the simpler prescription presented in Bromm & Loeb (2003). We have also updated the collisional dissociation rate of H_2 to that presented in Martin et al. (1996), which is now the commonly adopted rate (e.g. Shang et al. 2010; Agarwal et al. 2016a). The model includes the main cooling processes that are relevant for the direct collapse scenario, which are atomic hydrogen line cooling and molecular (H_2) line cooling (e.g. Cen 1992; Abel et al. 1997). In addition, the model tracks the non-equilibrium chemistry of the primordial gas and the formation of H_2 molecules, the main channel for which is the following two reactions:

$$H + e^- \rightarrow H^- + \gamma \tag{1}$$

$$H^- + H \rightarrow H_2 + e^-, \tag{2}$$

where e^- is a free electron and γ is a photon. Given that H^- is the main precursor to H_2, the photodetachment of H^- is a key reaction to track in order to accurately calculate the formation rate of H_2. Thus, we track the photodetachment of H^- as well as the photodissociation of H_2 in our model, adopting the rates presented in Shang et al. (2010) as functions of the temperature of the radiation field[1].

We solve additional equations in order to assess the impact of photodetachment of H^- by Lyman α photons. To begin, we make the simple assumption that the luminosity of Lyman α cooling emission in the cloud balances the rate of gravitational potential energy release during the collapse of the cloud (e.g. Dijkstra et al. 2016a,b). This is a sound approximation, as it has been shown in numerous cosmological simulations that the collapse of primordial gas in atomic cooling halos is roughly isothermal and occurs on the free-fall timescale (e.g. Wise et al. 2008; Regan & Haehnelt 2009). Thus, we adopt the following simple expression for the Lyman α luminosity:

$$L_{\mathrm{Ly}\alpha} = \frac{GM_{\mathrm{cloud}}^2}{r_{\mathrm{cloud}}}\frac{1}{t_{\mathrm{ff}}}, \tag{3}$$

where $t_{\mathrm{ff}} = (3\pi/32G\rho)^{\frac{1}{2}}$ is the free-fall time, where G is Newton's constant and ρ is the density of the collapsing gas. Here $M_{\mathrm{cloud}} = 10^6\ M_\odot$ is the typical mass of the central gas cloud collapsing in an atomic cooling halo (e.g. Wise et al. 2008; Johnson et al. 2011, 2014; Latif et al. 2013; Choi et al. 2013). Assuming a uniform cloud density, which is appropriate for our simplified one-zone calculations, this implies a cloud radius of $r_{\mathrm{cloud}} = 30$ pc $(n/10^2\ \mathrm{cm^{-3}})^{-1/3}$ where n is the number density of hydrogen nuclei. As the gas cools, this is the characteristic length scale over which Lyman α photons must diffuse in order to escape the cloud.

The diffusion of Lyα photons out of the cloud enhances the energy density in Lyα photons by an amount that depends on the cloud column density, N_{H}. The total line center optical depth to Lyα is given by $\tau_{\mathrm{Ly}\alpha} = 5.9 \times 10^6 \left(\frac{N_{\mathrm{H}}}{10^{20}\ \mathrm{cm^{-2}}}\right)\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-\frac{1}{2}}$, where T is the temperature of the gas and the column density of hydrogen atoms is $N_{\mathrm{H}} = r_{\mathrm{cloud}}n$ (e.g. Osterbrock & Ferland 2006). Following Adams (1975; see also Smith et al. 2017 for an updated discussion), the pathlength traversed by the photons in escaping the cloud is enhanced by a factor $\mathcal{M}_{\mathrm{F}} \sim (a_{\mathrm{v}}\tau_{\mathrm{Ly}\alpha})^{\frac{1}{3}}$, where $a_{\mathrm{v}} = 4.7 \times 10^{-4}\ (T/10^4\ \mathrm{K})^{-\frac{1}{2}}$ is the Voigt parameter. We estimate the total energy density in Lyα radiation, u_α, to be

$$u_\alpha = \mathcal{M}_{\mathrm{F}}\frac{L_{\mathrm{Ly}\alpha}r_{\mathrm{cloud}}}{V_{\mathrm{cloud}}c}, \tag{4}$$

where V_{cloud} denotes the volume of the cloud, and $\mathcal{M}_{\mathrm{F}}$ equals

$$\mathcal{M}_{\mathrm{F}} \sim 60\left(\frac{n}{10^2\ \mathrm{cm^{-3}}}\right)^{2/9}\left(\frac{M}{10^6\ M_\odot}\right)^{1/9}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1/3}. \tag{5}$$

Assuming that the Lyman α radiation field is isotropic within the cloud due to the large optical depth to scattering, we can then approximate the photodetachment rate R_{detach} of H^- ions by Lyman α photons as

$$R_{\mathrm{detach}} = \sigma_{\mathrm{H^-}}\mathcal{M}_{\mathrm{F}}\frac{L_{\mathrm{Ly}\alpha}}{E_{\mathrm{Ly}\alpha}}\frac{3}{4\pi r_{\mathrm{cloud}}^2}\mathcal{B}, \tag{6}$$

where the cross section for this process is $\sigma_{\mathrm{H^-}} = 5.9 \times 10^{-18}\ \mathrm{cm^2}$ and $E_{\mathrm{Ly}\alpha} = 10.2$ eV is the energy of a Lyman α photon (e.g. de Jong 1972; Shapiro & Kang 1987). As the dependence on the optical depth to scattering shows, this rate is elevated due to the many scatterings that Lyman α photons make in passing out of the cloud. Finally, $\mathcal{B}$ accounts for the fact that spatial diffusion of Lyα photons does not necessarily uniformly enhance the Lyα intensity throughout the cloud, especially when Lyα emission is concentrated more towards the center of the cloud (see Fig. A.1). In Appendix A we show that $\mathcal{B}$ can be as large as $\mathcal{B} \sim 10$ toward the center of the cloud, which is where the DCBH forms. Throughout, we will investigate the impact of varying $\mathcal{B}$ within the range $\mathcal{B} = 1-10$.

Combining the above equations, we obtain the following expression for the photodetachment rate as a function of cloud temperature, mass and density:

$$R_{\mathrm{detach}} \simeq 10^{-8}\ \mathrm{s^{-1}}\left(\frac{M_{\mathrm{cloud}}}{10^6\ M_\odot}\right)^{\frac{10}{9}}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-\frac{1}{3}}\left(\frac{n}{10^2\ \mathrm{cm^{-3}}}\right)^{\frac{31}{18}}\left(\frac{\mathcal{B}}{2}\right). \tag{7}$$

This is the equation that we include in our calculations in order to assess the role that Lyman α feedback plays in the formation of DCBHs.

3. Basic results

Here we show our results for two sets of calculations, one in which the effect of H^- detachment by Lyman α photons is included and another in which it is neglected. In both cases, we also include the effect of a background LW radiation field, which is assumed to only contribute to the photodissociation of H_2 molecules and not to the detachment of H^- ions. In the next Section, we explore how the inclusion of the photodetachment rate due to the background radiation impacts the evolution of the collapsing gas. Finally, here we only consider cases with $\mathcal{B} = 1$, corresponding to the simplest case of uniform Lyman α emission from the collapsing cloud. We explore cases with higher $\mathcal{B}$ values, corresponding to strongly centralized emission, in the next section.

Figure 1 shows the evolution of the H_2 fraction of the gas, as a function of density, both with and without the above equations for Lyman α photodetachment included. The three sets of curves correspond to different values of the LW background radiation field J_{21}, which is expressed in the standard units of 10^{-21} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}. As expected, the H_2 fraction is steadily depressed as the level of the background radiation increases. The impact of Lyman α photodetachment is also evident, resulting in the peak H_2 abundances dropping by orders of magnitude in the cases with relatively high background radiation levels $J_{21} > 100$.

[1] While H_2^+ is also a precursor to H_2 formation in the primordial gas, the rate of H_2 formation via this channel is much lower than that through the H^- channel for the relatively hot radiation spectra ($\gtrsim 10^4$ K) that are of interest here (see e.g. Sugimura et al. 2016). For this reason, we neglect the radiative destruction of H_2^+ in our modeling.

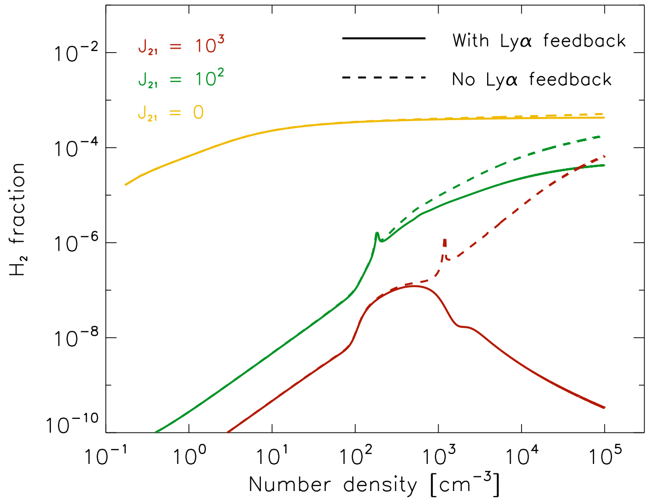

Fig. 1. Evolution of the H_2 molecule fraction as a function of the number density of hydrogen nuclei, with (solid lines) and without (dashed lines) accounting for the effect of photodetachment of H^- ions by Lyα photons. The colors denote calculations assuming different background radiation fields, as labeled, which are assumed only to dissociate H_2 molecules. In all cases shown here $\mathcal{B} = 1$, corresponding to uniform Lyman α emission within the collapsing cloud.

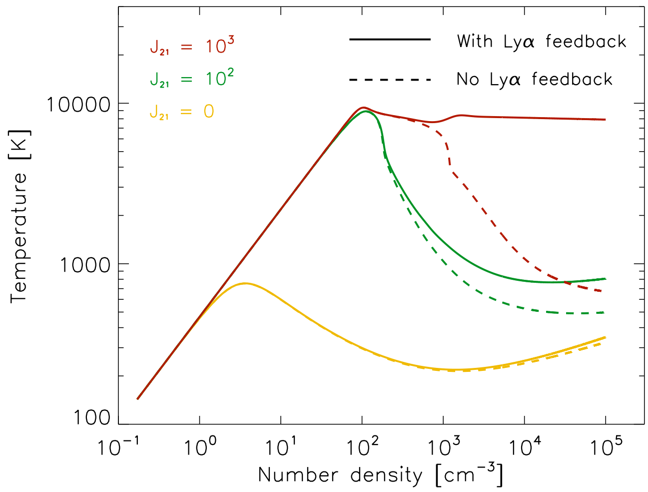

Fig. 2. Evolution of the gas temperature as a function of the number density of hydrogen nuclei, with (solid lines) and without (dashed lines) accounting for the effect of photodetachment of H^- ions by Lyα photons. The colors denote calculations assuming different background radiation fields which are assumed only to dissociate H_2 molecules. With no photodetachment the temperatures remain too low for DCBH formation in all cases, but with this effect included DCBH formation can occur for a background radiation field with $J_{21} \sim 10^3$. As in Fig. 1, here $\mathcal{B} = 1$, corresponding to uniform Lyman α emission within the collapsing cloud.

The thermal evolution of the gas in these same sets of calculations is shown in Fig. 2[2]. Due to the depressed H_2 fraction, molecular cooling is less effective with higher levels of the background radiation field. However, in all cases shown here the gas is still able to cool to $\lesssim 10^3$ K when H^- detachment is not included in the calculation. With this effect included, the cooling of the gas is suppressed at high density, resulting in much

[2] Note that we recover the canonical cooling behavior of the gas for the case with no background radiation ($J_{21} = 0$) and no H^- photodetachment (e.g. Bromm & Larson 2004; Greif 2015), as expected since we are employing effectively the same code as in previous studies of such processes (Johnson & Bromm 2006).

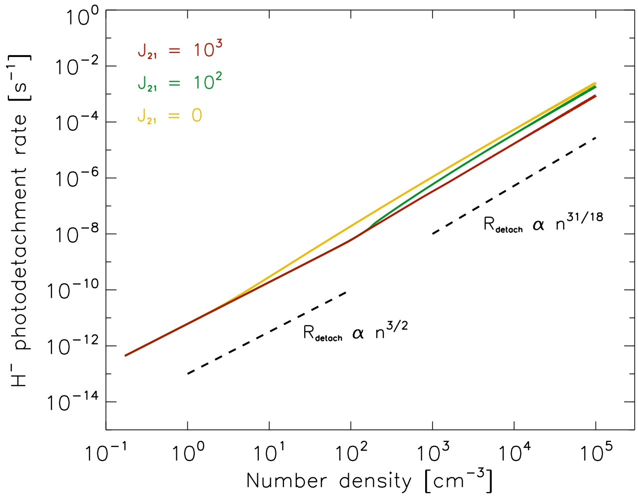

Fig. 3. Rate of H^- photodetachment by Lyα cooling radiation (Eq. (7)), for the same calculations shown in Figs. 1 and 2. The photodetachment rate is slightly higher for lower levels of the background radiation J_{21} due to the temperature dependence of the cross section for Lyman α scattering. At low densities the gas evolves adiabatically, leading to the scaling $R_{\rm detach} \propto n^{3/2}$, whereas at higher densities the scaling is better approximated assuming the gas is isothermal, leading to the scaling $R_{\rm detach} \propto n^{31/18}$. Note that, in all cases, the photodetachment rate rises above the critical rate of $\sim 10^{-5}$ s^{-1} found in calculations assuming a constant background rate and a weak H_2-dissociating radiation field by Agarwal et al. (2016a).

higher temperatures. Importantly, we find that with photodetachment included, the temperature remains high enough for DCBH formation in the case with $J_{21} = 10^3$. Thus, H^- detachment by Lyman α photons has the effect of lowering the critical value of the background radiation level required for the formation of DCBHs.

To more fully elucidate the impact of photodetachment, the photodetachment rates in our calculations, as a function of the cloud density, are shown in Fig. 3. The density and time dependence of the photodetachment rate makes comparison with previous determinations of the critical rate of photodetachment for DCBH formation difficult (e.g. Sugimura et al. 2014; Agarwal et al. 2016a; Wolcott-Green et al. 2016), as constant photodetachment rates have typically been assumed. However, it is clear that the photodetachment rates we find rise well above the critical value of $\sim 10^{-5}$ s^{-1} found, for instance, by Agarwal et al. (2016a) for the case of a weak H_2-dissociating radiation field. Thus, in this sense, our results are consistent with, and can be understood in the context of, previous work. Noting from Fig. 2 that the gas evolves roughly adiabatically up to $n \sim 10^2$ cm^{-3} such that $T \propto n^{2/3}$, the scaling $R_{\rm detach} \propto n^{3/2}$ provides a good match to our calculations, as shown in Fig. 3. At higher densities an isothermal scaling of $R_{\rm detach} \propto n^{31/18}$ provides a better fit, as is also shown in the figure. We next turn to assessing the impact of Lyman α feedback on the value of the critical LW flux required for DCBH formation.

4. The Impact on the critical Lyman-Werner flux

Here we consider how our results change when including the H^- photodetachment rate due to the background radiation. To do so, we carry out the same calculations as shown in Fig. 2, but now including also the H^- detachment rate due to the background radiation field. We adopt the rates presented in Shang et al. (2010) assuming simple blackbody spectra at $T_{\rm rad} = 10^4$ and 10^5 K, and we evaluate the critical LW flux $J_{21,\rm crit}$ that is

Table 1. Calculated values of the critical LW radiation.

T_{rad} [K]	Lyα feedback ($\mathcal{B} = 1$)	Lyα feedback ($\mathcal{B} = 10$)	No Lyα feedback
10^4	24	22	26
10^5	900	200	1100

Notes. Our calculated values of the critical LW radiation field $J_{21,crit}$ required for DCBH formation, for two different background radiation temperatures, with and without accounting for the impact of photodetachment of H^- by Lyman α cooling radiation, which is assumed to be either uniform ($\mathcal{B} = 1$) or strongly centrally concentrated ($\mathcal{B} = 10$). While the photodetachment rate due to the background radiation is relatively high already when T_{rad} is relatively low, the detachment rate due to Lyman α feedback comes to dominate the rate due to the background when T_{rad} is high, in particular at high gas densities (see Fig. 3).

required to maintain the gas at $\sim 10^4$ K, leading to the formation of a DCBH.

Our results are presented in Figs. 4 and 5, and are summarized in Table 1. As shown in the left panels of Figs. 4 and 5, for a relatively low background radiation temperature of $T_{rad} = 10^4$ K the additional suppression of H_2 cooling due to Lyman α feedback is relatively small, as the LW flux required to maintain the gas at $\simeq 10^4$ K at a density of $n \sim 10^5$ cm^{-3} is $J_{21,crit} \simeq 26$ neglecting the effect and $J_{21,crit} \simeq 22{-}24$, depending on the geometry of the Lyman α emission (i.e. for $\mathcal{B} = 1{-}10$), when accounting for it. However, as shown in the right panels of Figs. 4 and 5, for a larger background radiation temperature of $T_{rad} = 10^5$ K accounting for Lyman α feedback results in a much larger drop in the critical flux from $J_{21,crit} \simeq 1.1 \times 10^3$ to $\simeq 200{-}900$, depending on the geometry of the Lyman α emission. Thus, for the spectra expected from hot, young stars in the early Universe, the impact of Lyman α feedback may be especially important. As shown in Fig. 3 and in Eq. (7), it is detachment rates due to Lyman α feedback at high densities, which are higher than the detachment rate due to the background radiation field, that result in a lower critical LW background flux.

It is important to note the reason for the much larger difference in the critical flux in the case of the higher background radiation temperature. This is ultimately due to the much lower rate of H^- photodetachment, relative to the H_2 photodissociation rate, for the higher temperature background radiation field. Specifically, the photodetachment rate at a given value of J_{21} is some four orders of magnitude lower for a background temperature of 10^5 K than it is for one of 10^4 K (Shang et al. 2010). This implies that the rate of photodetachment by Lyman α photons, which is independent of the spectrum of the background radiation field, is much higher relative to the rate due to the background radiation for the hotter spectrum than it is for the colder one. This leads directly to the much larger drop in the critical value of J_{21} due to Lyman α feedback that we find for the hotter background spectrum than for the colder one.

The values we find for the critical LW flux ($J_{21,crit}$) in the cases neglecting Lyman α feedback are broadly consistent with the values found by previous authors (see e.g. Omukai et al. 2008; Sugimura et al. 2014; Latif et al. 2015; Hartwig et al. 2015; Agarwal et al. 2016a,b; Glover 2016), although they are different in detail due to differences in the models adopted in these studies (see also Glover 2015 on rate coefficient uncertainties). As shown in Table 1, however, we can conclude from our calculations that the impact of Lyman α feedback can be strong and, importantly, results in a particularly large drop in the critical LW background flux required for DCBH formation for background radiation temperatures characteristic of young, hot stars in the early Universe (e.g. Tumlinson et al. 2001; Bromm et al. 2001; Oh et al. 2001; Schaerer 2002).

Recent analyses have pointed out that it is more accurate to go beyond J_{crit}, and quantify the requirements for direct collapse in terms of both the photodetachment rate of H^- and the photodissociation rate of H_2 (e.g. Sugimura et al. 2014; Agarwal et al. 2016a; Wolcott-Green et al. 2016). These works show that once $R_{detach} \gtrsim 10^{-7}$ s^{-1}, the photodissociation rate that is required for direct collapse decreases rapidly. Our calculations indicate that the constraint $R_{detach} \gtrsim 10^{-7}$ s^{-1} is reached for $\log[n/\mathrm{cm}^{-3}] \gtrsim 2.5$, implying that the thermal evolution of the gas at these high densities becomes strongly impacted by Lyman α feedback.

5. Discussion and conclusions

We have applied a one-zone chemical and thermal evolution model to investigate the role that trapped Lyman α cooling radiation, generated during the collapse of atomic cooling halos, has in suppressing molecular cooling. We find that, while this feedback from Lyman α emission is not strong enough on its own to suppress H_2 cooling, it does have the effect of lowering the intensity of the background LW radiation level that is required for the formation of DCBHs. While our modeling is simplified, the effect can be pronounced, potentially dropping the critical LW flux by up to a factor of a few for the background radiation temperatures expected to be produced by young, hot stars in the early Universe.

One implication of our results is that the number density of DCBHs may be higher than previously anticipated based on calculations neglecting H^- detachment by cooling radiation. Previous works have shown that the number density of DCBHs increases roughly as $J_{21,crit}^{-4}$ (Dijkstra et al. 2008, 2014; Inayoshi & Tanaka 2015; Chon et al. 2016), which suggests that the impact of H^- detachment by Lyman α photons results in a large increase of up to a factor of order 10^2 in the number density of DCBHs in regions of the early Universe illuminated by bright, young stellar populations. This is important, as DCBH formation may have to occur relatively early in the epoch of galaxy formation, when stellar populations are still young, in order to be the seeds for the highest-redshift quasars. The lower values of $J_{21,crit}$ implied by our results also mean that overall higher rates of DCBH formation may be realized, perhaps high enough for DCBHs to account for the BHs residing in the centers of a fraction of normal galaxies today (e.g. Habouzit et al. 2016). We do note, however, that perhaps the most likely sources of the LW radiation that leads to DCBH formation are metal-enriched stellar populations which are likely to emit radiation with characteristic temperatures intermediate between the 10^4 and 10^5 K that we have considered here (e.g. Agarwal et al. 2012; Johnson et al. 2013). The precise enhancement of the DCBH formation rate that is due to Lyman α feedback will clearly depend on the spectra of the sources producing the LW radiation, and it is possible that if the spectra are sufficiently soft then the impact of this feedback may be limited.

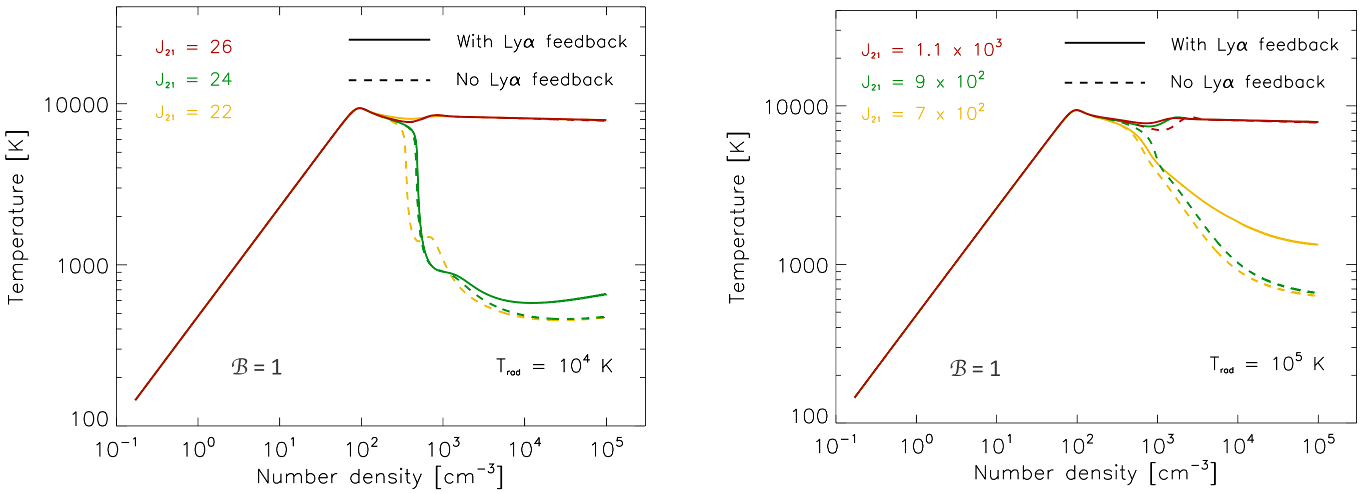

Fig. 4. Just as Fig. 2, but now with photodetachment of H^- ions by the background radiation field, assumed to be described by a blackbody spectrum with a temperature of $T_{rad} = 10^4$ K (*left panel*) and 10^5 K (*right panel*), included. The values of J_{21} shown in each panel bracket the critical values required to maintain the temperature at $\sim 10^4$ K at a density of 10^5 cm^{-3} that are inferred both with and without Lyman α feedback included, as summarized in Table 1. The case shown here assumes $\mathcal{B} = 1$, corresponding to uniform Lyman α emission within the collapsing cloud.

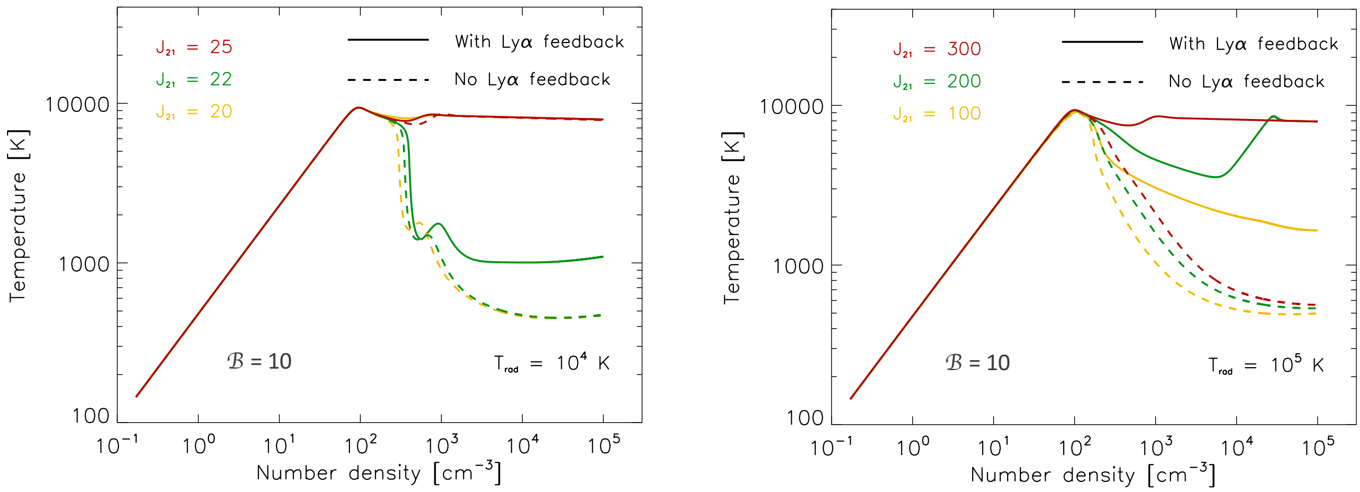

Fig. 5. Just as Fig. 4, but now with a Lyman α flux enhancement $\mathcal{B} = 10$, an extreme case expected for strongly centralized Lyman α emission.

The extremely bright Lyman α emitter known as CR7 is an intriguing candidate for a high-redshift quasar that may be powered by accretion onto a DCBH (Sobral et al. 2015). Recent modeling efforts have demonstrated that a nearby galaxy may well have produced a high enough level of LW radiation to induce the formation of a DCBH in this galaxy and that the nebular emission could be explained by an accreting BH with a mass consistent with formation as a DCBH (e.g. Pallottini et al. 2015; Agarwal et al. 2016c; Hartwig et al. 2016; Smidt et al. 2016; Smith et al. 2016; Dijkstra et al. 2016a)[3]. In suggesting that the critical LW flux may be lower than previously thought, our results lend support to DCBH scenario for the origin of CR7. We note that this is also consistent with recent work suggesting that a massive cluster of Population III stars, an alternative explanation for the origin of CR7 (e.g. Sobral et al. 2015; Visbal et al. 2016; see also Johnson 2010), is dubious since it is unknown how a sufficiently high mass of Population III stars could be assembled rapidly enough to explain the observed extremely bright emission (e.g. Hartwig et al. 2016; Yajima & Khochfar 2016; Xu et al. 2016; Visbal et al. 2017).

We note that we have neglected the 2-photon and other hydrogen line emission that is produced at very high densities ($\gtrsim 10^6$ cm^{-3}) where Lyman α photons can be destroyed before escaping the collapsing cloud (e.g. Schleicher et al. 2010; Dijkstra et al. 2016b). While not resonant emission lines, these photons are energetic enough to detach H^- and, in fact, the cross section for this process is greater at these photon energies than for Lyman α photons (e.g. de Jong 1972). Thus, neglecting this emission may also lead to a slight overestimate of the critical LW flux.

We note also, though, that we have neglected the absorption of Lyman α photons by H_2 molecules, as described in Neufeld (1990; see also Dijkstra et al. 2016b). However, we estimate that this results in a reduction in the Lyman α flux of, at most, a factor of two at the column densities ($N_H \sim 10^{23}$ cm^{-2}) and the low H_2 fractions ($f_{H2} \sim 10^{-7}$) that occur with an elevated background radiation field. In addition, the LW photons produced in

[3] We note that recent observations of CR7 suggest that the bright Lyman α source may be enriched to some degree with heavy elements (Bowler et al. 2016), suggesting that it is somewhat evolved if it did intially host the formation of a DCBH (see e.g. Aykutalp et al. 2014; Agarwal et al. 2017).

the subsequent radiative decay of the H_2 molecules are also able to detach H^-. Thus, we do not expect that accounting for this effect would strongly impact our conclusions.

Our results also carry implications for the impact of X-rays on the collapse of gas in atomic cooling halos, which numerous authors have shown is to produce free electrons which catalyze H_2 formation, resulting in an increase in the critical flux $J_{21,\mathrm{crit}}$ (e.g. Inayoshi & Omukai 2011; Inayoshi & Tanaka 2015; Latif et al. 2015; Glover 2016; Regan et al. 2016b). We note, in particular, that our results for the critical LW flux for DCBH formation are in reasonable agreement with those of Glover (2016) for the case neglecting X-ray feedback. While X-rays may have the effect of raising the critical flux by up to two orders of magnitude in the absence of Lyman α feedback for a hard spectrum (Glover 2016), another impact of X-rays is to enhance the Lyman α emission within the halo (e.g. Dijkstra et al. 2016a). As we have shown, this should result in an enhanced rate of H^- photodetachment that will again lower the critical flux.

Finally, we note that atomic cooling halos which grow rapidly, due to mergers or due to growth in high density environments, likely produce Lyman α cooling radiation at a higher rate than assumed in our calculations. This more intense emission leads, in turn, to larger photodetachment rates and lower values for the critical externally-produced LW flux required for DCBH formation. As the earliest supermassive black holes form in relatively rare, overdense regions, this implies that Lyman α feedback may play an especially strong role in paving the way for the formation of the DCBH seeds of the earliest bright quasars (e.g. Mortlock et al. 2011; Wu et al. 2015). Future work incorporating the feedback effect of Lyman α radiation on the chemical evolution of atomic cooling halos in 3D cosmological simulations will further elucidate the role that this process plays in determining the overall rate of DCBH formation.

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Appendix A: Radial dependence of Lyα trapping

In one-zone models, the physical conditions of the collapsing gas cloud are described completely by its temperature and density. When we interpret one-zone models as clouds of uniform density in which Lyα emission is produced uniformly (as we did when deriving Eq. (7), the energy density in Lyα photons is enhanced almost uniformly throughout the cloud (see discussion below and Fig. A.1). The spatial diffusion of Lyα photons out of the cloud introduces only small gradients in the Lyα energy density. However, larger gradients exist if Lyα is not emitted uniformly throughout the cloud, as is generally the case in more realistic scenarios, in which we expect Lyα cooling to increase towards the center of the cloud.

Here we compute the radial dependence of the Lyα energy density in a suite of spherical gas clouds. We vary the HI column density of the cloud and where Lyα is emitted, and compute $\mathcal{B}$ by comparing this energy density to our estimate for u_α given by Eq. (4). Lyα transfer through static, spherical clouds of uniform density can generally be solved analytically for large line-center optical depths τ_0. Dijkstra et al. (2006) derive expressions for the (angle-averaged) Lyα intensity J as a function of radius r and frequency x in a spherical cloud of radius $R_{\rm cl}$ (see their Eq. (C12)). For a central Lyα point source (at $r_{\rm s} = 0$) their expression for the total (integrated over frequency) intensity simplifies to

$$J(r/R) = A \sum_{n=1}^{\infty} \int_{-\infty}^{\infty} {\rm d}x \left(\frac{R}{r}\right) \sin p_n \exp\left(\frac{-\lambda_n|\sigma(x)|}{\kappa_0}\right), \quad (A.1)$$

where A is a normalization constant, and

$$p_n = \pi n \left(\frac{r}{R}\right)\left(1 - \frac{2}{3\tau_0\phi(x)}\right) \quad (A.2)$$

$$\frac{\lambda_n}{\kappa_0} = \frac{\pi n}{\tau_0}\left(1 - \frac{2}{3\tau_0\phi(x)}\right) \quad (A.3)$$

$$\sigma = \sqrt{\frac{2\pi}{27}}\frac{x_3}{a_v}. \quad (A.4)$$

We obtain $\mathcal{B}$ by dividing the energy density $u_\alpha(r/R) = 4\pi J(r/R)/c$ to u_α given by Eq. (4).

Figure A.1 shows $\mathcal{B}$ as a function of r/R for the analytic model (*thick grey line*). This line is independent of τ_0 provided that $a_v\tau_0 \gtrsim 10^3$. We overplot 3 lines with different colors, which we obtained from Monte Carlo simulations of the Lyα radiative transfer. The blue, red, and black lines represent the cloud when its density is $n = 10^2$, 10^3, and 10^4 cm^{-3}, respectively. First, we note that (not shown here) the total *average* trapping time we found for Lyα photons in the Monte Carlo simulation agreed well with our estimate used for Eq. (4). Figure A.1 shows clearly that $\mathcal{B} > 1$ at $r < 0.6\,R_{\rm cl}$, and that $\mathcal{B} > 10$ at $r < 0.2\,R_{\rm cl}$. That is, in the case of a central Lyα source, photodetachment of H^- by Lyα is signficantly more important for the inner $\sim 10^4\,M_\odot$ of gas than in the exterior regions. Clearly, the case of a central point source represents an extreme case of centrally enhanced Lyα emission, and we consider the values of $\mathcal{B}$ that we obtain for these models to represent upper limits.

For completeness, the *black line* shows $\mathcal{B}$ obtained from our Monte Carlo simulations in which Lyα photons are produced uniformly throughout the cloud. For clarity, we have only shown the case $n = 10^2$ cm^{-3}, but we have verified that the curve does not change for higher densities. The Lyα energy density is enhanced close to uniformly throughout the cloud, and at a level that is in good agreement with Eq. (4).

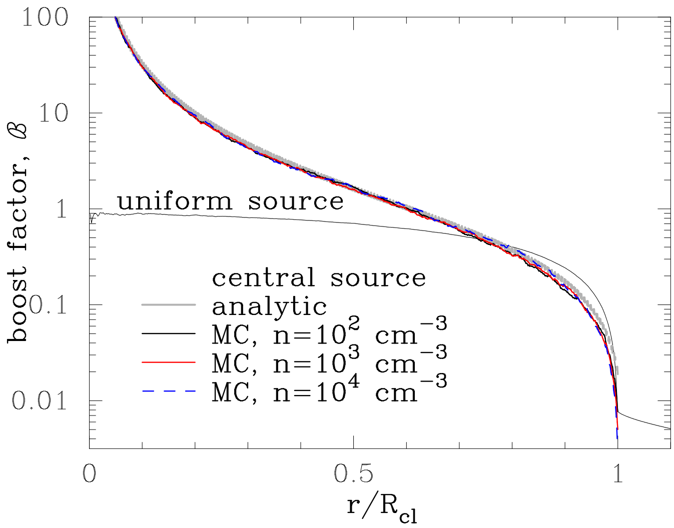

Fig. A.1. Lines: radial dependence of the boost factor $\mathcal{B}$ for a central Lyα point source surrounding a uniform gas cloud of density $n = 10^2$ cm^{-3} (black), $n = 10^3$ cm^{-3} (red), and $n = 10^4$ cm^{-4} (blue). When normalized to the cloud radius R, $\mathcal{B}(r/R)$ does not depend on n. The grey line shows analytic solution from Dijkstra et al. (2006). The black line shows a case in which Lyα is produced uniformly throughout the cloud, and $\mathcal{B} \sim 1$, which shows that the calculations presented in the paper are quite accurate if Lyα is emitted uniformly throughout the cloud.