Extreme Population III Starbursts and Direct Collapse Black Holes Stimulated by High Redshift Quasars

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ABSTRACT

High redshift quasars emit copious X-ray photons which heat the intergalactic medium to temperatures up to $\sim 10^6$ K. At such high temperatures the primordial gas will not form stars until it is assembled into dark matter haloes with masses of $\sim 10^{11}$ $M_\odot$, at which point the hot gas collapses and cools under the influence of gravity. Once this occurs, there is a massive reservoir of primordial gas from which stars can form, potentially setting the stage for the brightest Population (Pop) III starbursts in the early Universe. Supporting this scenario, recent observations of quasars at $z \sim 6$ have revealed a lack of accompanying Lyman $\alpha$ emitting galaxies, consistent with suppression of primordial star formation in haloes with masses below $\sim 10^{10}$ $M_\odot$. Here we model the chemical and thermal evolution of the primordial gas as it collapses into such a massive halo irradiated by a nearby quasar in the run-up to a massive Pop III starburst. We show that at distances of $\sim 1$ Mpc from a typical quasar the conditions are prime for HD cooling to play a role in the evolution of the gas, possibly resulting in a shift to a lower characteristic stellar mass. Within $\sim 100$ kpc of the highest redshift quasars discovered to date the Lyman-Werner flux produced by the stars in the quasar host galaxy may be high enough to stimulate the formation of a direct collapse black hole (DCBH). Given that metal-enriched outflows are expected to extend out to only $\sim 50$ kpc from high-z quasars, this suggests that there is ample unpolluted primordial gas for the formation of DCBHs and Pop III starbursts. How frequently these objects form can be constrained with the James Webb Space Telescope in the coming years.

Key words: early Universe — cosmology: theory — molecules — X-rays — stars: Population III — quasars

1 INTRODUCTION

The hunt for the first generation of stars, so-called Population (Pop) III stars, is generally carried out following two different approaches. In the first, long-lived extremely metal-poor stars are sought in large surveys of our Galaxy, in order to place constraints on the initial mass function of primordial stars (e.g. Frebel & Norris 2015). In the second, deep observations are made of the distant, high redshift Universe, in order to identify galaxies that may host metal-free star formation (e.g. Inoue 2011; Sobral et al. 2015; Xu et al. 2016). The first approach will only succeed in uncovering Pop III stars if they are sufficiently low-mass that they are still burning their nuclear fuel in the Milky Way today (or in nearby dwarf galaxies; Magg et al. 2018). The second approach will only succeed if Pop III star-hosting galaxies are bright enough to be detected in deep surveys of the early Universe (e.g. Jaacks et al. 2018; Sarmento et al. 2018). With the sensitivity of these surveys on the verge of great improvements, for example with the launch of the James Webb Space Telescope ( JWST; e.g. Gardner et al. 2006; Zackrisson et al. 2012), it is key to make predictions for how Pop III galaxies may be discovered.

The brightest Pop III galaxies are likely to form in the largest dark matter (DM) haloes which harbor metal-free gas in the early Universe. Such galaxies are expected to form in regions where Pop III star formation is delayed until a large halo is assembled, either due to radiative feedback (e.g. O’Shea & Norman 2008; Trenti et al. 2009; Johnson 2010; Safranek-Shrader et al. 2012; Xu et al. 2013) or a violent merger history (Inayoshi et al. 2018). In the case of the former, high host halo masses are achieved when the primordial gas is subject to a stellar ionizing radiation field which maintains its temperature at $\gtrsim 10^4$ K and prevents its collapse until a halo with such a high virial temperature, corresponding to a mass of up to $\sim 10^9$ $M_\odot$, is assembled (e.g. Dijkstra et al. 2004; Noh & McQuinn 2014; Visbal et al. 2017; Yajima & Khochfar 2017).

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While haloes of a billion solar masses are much larger than those thought to host the very first stars at $z \approx 20$ (e.g. Greif 2015), it is possible that even more massive haloes may also host primordial star formation in regions where the gas is heated to even higher temperatures. In particular, the highest temperatures of the intergalactic medium (IGM) in the early Universe are likely to arise in the vicinity of bright quasars powered by accretion of gas onto supermassive black holes at $z \gtrsim 6$ (e.g. Mortlock et al. 2011; Wu et al. 2015; Bañados et al. 2017). The intense photoheating by the copious X-rays emitted from these objects can drive the primordial gas to temperatures of up to $\sim 10^6$ K (e.g. Bolton et al. 2009; Smidt et al. 2017). In such environments, the gas will only collapse into extremely large DM haloes with masses of up to $\sim 10^{11} M_\odot$ (e.g. Barkana & Loeb 2001), setting the stage for the brightest Pop III starbursts in the early Universe.

There is recent observational evidence that star formation is, in fact, suppressed in DM haloes with masses below this range in the vicinity of high redshift quasars. Goto et al. (2017) report a dearth of Lyman $\alpha$ emitting galaxies within several megaparsecs of a luminous quasar at $z = 6.4$, consistent with suppression of star formation in haloes with masses below $\sim 10^{10} M_\odot$ due to the strong X-ray heating of the IGM by the quasar (see also Ota et al. 2018). This finding supports the tantalizing possibility that the strong radiative feedback from high redshift quasars may delay primordial star formation until extremely massive haloes are assembled, suggesting that the conditions for the brightest Pop III starbursts may indeed occur in the neighborhoods of bright high redshift quasars.

Here we study the evolution of primordial gas irradiated by a luminous quasar at high redshift, in order to predict the nature of the primordial objects formed during its collapse. In Section 2 we lay out the methodology of our calculations. In Section 3 we present our basic results illustrating the evolution of irradiated gas, while in Section 4 we explore the nature of the objects that are formed in its collapse. Finally, we conclude in Section 5 with a brief summary of our findings.

## 2 METHODOLOGY

The basic scenario that we consider is illustrated schematically in Figure 1. On the left, a quasar at high redshift (e.g. $z \gtrsim 6$) emits radiation in three distinct wavebands that impact the evolution of the primordial gas collapsing into the massive DM halo, on the right, that sits at a distance $d$ from the quasar. A portion of this radiation is emitted during the accretion process of the central black hole and a portion is from the stellar population in the quasar host halo. In addition, some fraction of the metals produced by the stars inhabiting the host halo are assumed to be entrained in a galactic wind driving an outflow.

The accreting black hole powering the quasar emits high energy X-ray radiation, most of which escapes its host galaxy, although a small portion is converted into Lyman-Werner (LW) $H_2$-dissociating radiation within the host galaxy. Here we assume that the X-rays which escape the host galaxy are monoenergetic at 1 keV, which is in the range in which most X-ray energy has been observed to escape from high-$z$ quasars (e.g. Nanni et al. 2017). For the flux of LW radiation $J_{21, BH}$ at the location of the target primordial halo that is produced due to reprocessing of the radiative energy emitted in the accretion process, as well as due to diffuse emission in the host galaxy, we assume a simple scaling that has been derived from cosmological radiation hydrodynamics calculations (Barrow et al. 2018):

$$J_{21, BH} = 80 \left( \frac{M_{BH}}{10^8 M_\odot} \right) \left( \frac{E_{Edd}}{1} \right) \left( \frac{d}{1 \text{ Mpc}} \right)^{-2},$$  \hspace{1cm} (1)

where $d$ is the distance between the quasar and the target primordial halo (as shown in Figure 1), $M_{BH}$ is the mass of the black hole powering the quasar, and $E_{Edd}$ is the ratio of the X-ray luminosity to the Eddington luminosity. Finally, the units of $J_{21, BH}$ are the standard $10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2}$

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1 We also note that Smidt et al. (2017) find good agreement with the available data on the Mortlock et al. (2011) quasar at $z = 7.1$ by adopting such a monoenergetic X-ray spectrum in a fully cosmological radiation hydrodynamics calculation.
Hz$^{-1}$ sr$^{-1}$. The X-ray energy that escapes the quasar host halo propagates into the intergalactic medium (IGM), where it heats the primordial gas to high temperatures, as shown in Figure 2.

The stellar population in the quasar host galaxy is assumed to contribute to the LW flux impinging on the target primordial halo, as well as to a flux of optical and infrared radiation at energies $\geq 0.75$ eV that can destroy H$^-$, an important precursor to the formation of H$_2$ in the primordial gas. The LW flux $J_{21,\ast}$ produced by the stellar population is expressed in terms of the stellar mass $M_\ast$ in the quasar host halo, as follows (Johnson et al. 2013):

$$J_{21,\ast} = 60 \left( \frac{M_\ast}{10^{10} M_\odot} \right) \left( \frac{d}{1 \text{ Mpc}} \right)^{-2}.$$  

(2)

This rate has been chosen to correspond to an effective stellar temperature of $T_\ast = 3 \times 10^4$ K, in line with the cosmological average stellar properties at $z \sim 6$ presented in Agarwal & Khochfar (2015). Also following these authors, we have adopted this effective stellar temperature in evaluating the rate of H$^-$ destruction by optical and infrared radiation, although in Section 3 we explore the impact on our results of assuming either older (cooler) or younger (hotter) stellar populations (e.g. Shang et al. 2010).

To model the evolution of the primordial gas as it collapses into the massive primordial target halo (shown in right in Figure 1), we use these radiative fluxes in the one-zone primordial chemistry code adopted in Johnson & Dijkstra (2017). To properly incorporate the effects of X-rays in this model, we have made the following four modifications. (1) We calculate the rate of photoinization of both hydrogen and helium species, using the cross sections presented in Osterbrock & Ferland (2006). (2) We account for the partitioning of photoelectron energy into secondary ionizations and collisional heating, as described by Shull & van Steenberg (1985). (3) We adopt an approximate treatment for the local attenuation of the X-ray flux in the target primordial halo, following Johnson et al (2014). (4) We account for Compton heating of the primordial gas due to X-rays.

As we show in the next Section, our results are in basic agreement with those gleaned from the similar framework presented in Inayoshi & Omukai (2011) and in the cosmological calculations presented in Regan et al. (2016), although in many cases the X-ray fluxes that we consider are much higher than those considered by these authors.

3 EVOLUTION OF STRONGLY IRRADIATED PRIMORDIAL GAS

Given the extreme radiative environment in the vicinity of a luminous quasar in the early Universe, the evolution of the primordial gas exposed to this radiation is strongly dependent on its proximity to the quasar. In addition, the chemistry of the primordial gas is impacted in a complex manner by the various types of radiation that are emitted from the accreting black hole and its surrounding host galaxy. In particular, while the LW radiation and the optical/infrared radiation generally act to suppress the abundance of the key molecular coolant H$_2$, the intense X-ray radiation acts to produce free electrons which stimulate its formation (e.g. Glover 2003).

Figure 2. Temperature of the primordial gas (left axis), as a function of distance $d$ from quasars powered by Eddington accretion onto black holes of three distinct masses: $10^8$, $10^9$ and $10^{10} M_\odot$. The gas is assumed to be at the cosmic mean density at $z = 6$. The kinks in the curves are due to recombination of helium and hydrogen ions and the additional cooling that they provide. Also shown is the minimum halo mass required for the primordial gas to collapse (right axis) to form either stars or a DCBH.

Figure 3 shows the evolution of the primordial gas as it collapses to high density in a massive primordial DM halo exposed to the radiation produced by a quasar powered by Eddington accretion onto a $10^8 M_\odot$ supermassive black hole within a host galaxy containing $10^{10} M_\odot$ in stars. While the gas is initially at very high temperatures when it is at the density of the IGM prior to its collapse, as shown in Figure 2, once it is bound in a sufficiently massive DM halo it is able to collapse to high density and its temperature then drops to the $\sim 10^4$ K floor set by atomic hydrogen cooling. Then, depending on its distance from the quasar, the temperature drops by up to another two orders of magnitude due to molecular cooling by H$_2$. While the free electron fraction is elevated due to photoinization of hydrogen and helium species by the X-rays, leading to the catalyzed formation of H$_2$ molecules, the LW and optical/infrared radiation emitted from the quasar host galaxy also strongly suppress the H$_2$ fraction. The result is that, closer to the quasar source, the gas remains hotter at the highest densities than it is farther away.

The net impact of the X-ray flux on the thermal evolution of the gas is shown in Figure 4, where the solid lines show the temperature of the gas with the X-ray flux included in the calculation and the dashed lines show it with them excluded. It is clear that while they strongly heat the gas at low densities, the X-rays also have the impact of enhancing molecular cooling at high densities (e.g. Aykutalp et al. 2014; Inayoshi & Tanaka 2015; Latif et al. 2015; Glover 2016). Their effect is strongest closest to the quasar source, where in their absence the gas temperature remains elevated at $\sim 10^4$ K at a distance of 100 kpc, signifying a very strong suppression of H$_2$ formation. At larger distances from the quasar source, where the gas is able to cool due to the radiation from H$_2$ molecules, it is also possible for the coolant HD to play a role in the thermal evolution of the gas, as shown in Figure 5. As the gas temperature drops to lower values with increasing distance.
from the quasar source, HD cooling becomes stronger, as reflected in the higher HD fractions at larger distances in the bottom-right panel of Figure 3. This is consistent with previous work showing that HD cooling can be triggered in primordial gas with an elevated free electron fraction (e.g. Nagakura & Omukai 2005; Johnson & Bromm 2006; Nakauchi et al. 2014). Due to the lower temperatures to which the gas is able to cool, in part due to HD cooling, farther from the quasar source, the fragmentation scale in the primordial gas is likely smaller and the characteristic initial mass function of stars that form may be shifted to lower masses (e.g. Uehara & Inutsuka 2000; Ripamonti 2007; McGreer & Bryan 2008).

While we have assumed a cosmological average stellar population for the quasar host galaxy in our results presented thus far, in Figure 6 we show the thermal evolution of the gas irradiated by both an older and a younger stellar population, corresponding to characteristic stellar radiation temperatures of $T_\star = 10^4$ and $10^5$ K, respectively. Principally due to the elevated rate of photodetachment of H$^-$ by infrared and optical photons, an older stellar population clearly delays the cooling of the gas and in some cases prevents it from cooling to temperatures much below $10^4$ K, consistent with previous results (e.g. Wolcott-Green et al. 2012, 2017; Sugimura et al. 2014; Agarwal & Khochfar 2015; Latif et al. 2015). In contrast, the gas evolves similarly to our fiducial case with a younger, hotter stellar population in the quasar host halo.

## 4 CONDITIONS FOR DIRECT COLLAPSE BLACK HOLE FORMATION

The final fate of the quasar-irradiated primordial gas in a massive DM halo is strongly dependent on the temperature to which it cools as it collapses, as this dictates the scale on which gravitational fragmentation occurs. In general, if the gas remains hotter during its collapse then it is likely to fragment into stars with a mass function shifted to higher masses. In extreme cases in which molecular cooling is strongly suppressed, the gas may remain at temperatures of $\approx 10^4$ K, leading to the formation of supermassive stellar objects (e.g. Begelman 2010; Hosokawa et al. 2013; Schleicher et al. 2013; Haemmerlé et al. 2018) with masses of $10^4 - 10^6 M_\odot$ which promptly collapse into so-called direct collapse black holes (DCBHs; for reviews see Volonteri 2012; Latif & Ferrara 2016; Valiante et al. 2017; Smith et al. 2017). Here we explore the conditions required for the formation of DCBHs in primordial halos irradiated by quasars.

As shown in the previous Section, it is possible for the primordial gas to remain at the high temperatures required for DCBH formation if the radiative flux from the quasar is sufficiently strong. Table 1 shows the maximum distance...
$d_{\text{DCBH}}$ from a quasar powered by Eddington accretion out to which DCBH formation can occur, for various masses $M_{\text{BH}}$ of the black hole powering the quasar and across a range of temperatures characterizing the stellar population in the quasar host galaxy. For our fiducial case with $T_*=3 \times 10^4 \text{ K}$, we find that DCBH formation may occur within 50 kpc of a quasar powered by Eddington accretion onto a $10^8 M_{\odot}$ black hole, while it may occur out to 500 kpc in the extreme case of one powered by a $10^{10} M_{\odot}$ black hole. In general, the values we find for $d_{\text{DCBH}}$ increase with decreasing stellar radiation temperature, implying that DCBHs can form farther out from quasars hosting older stellar populations.

While Table 1 shows results for a fiducial choice of $M_*/M_{\text{BH}} = 100$ for the stellar to black hole mass in the source quasar, it is important to note that this ratio can take on smaller values particularly in the early Universe when there has been little time for star formation around the rapidly accreting black holes powering quasars. In particular, Venemans et al. (2017a,b) find evidence for values as low as $M_*/M_{\text{BH}} \sim 20$ for the highest redshift quasars. Furthermore, in some scenarios for the earliest stages of growth of high-$z$ quasars, the central black hole mass can be even larger relative to that of the stellar population (e.g. Agarwal et al. 2013). Table 2 shows the values of $d_{\text{DCBH}}$ that we find for various ratios of the stellar to black hole mass in the quasar host halo. In general, given the contribution that the stellar component makes to the production of $\text{H}_2$-dissociating LW radiation, we find that DCBH formation can occur out to larger distances for a larger stellar population, at a given value of the central black hole mass. The results shown in Table 2 are captured well by a single fitting formula which expresses $d_{\text{DCBH}}$ in terms of the black hole mass $M_{\text{BH}}$ and stellar mass $M_*$ in the quasar host halo:

$$d_{\text{DCBH}} \simeq 30 \text{ kpc} \left( \frac{M_{\text{BH}}}{10^9 M_{\odot}} \right)^{0.5} \left( \frac{M_*}{M_{\text{BH}}} \right)^{0.4},$$

where this is valid under the assumption of Eddington accretion onto the black hole and given our fiducial case of a $z \sim 6$ cosmological average stellar population with a characteristic temperature of $T_* \sim 3 \times 10^4 \text{ K}$. Outside of $d_{\text{DCBH}}$ we expect that the gas will cool to sufficiently low temperatures that a cluster of Pop III stars is likely to form, instead of a DCBH.

While the radiation emitted from high-$z$ quasars may provide the conditions for the formation of these objects, such quasars are also known to emit metal-enriched outflows which pollute the IGM, as shown schematically in Figure 7. These metals, if mixed with the collapsing primordial gas, will act to preclude the formation of Pop III stars and DCBHs. At an average velocity of 100 km s$^{-1}$ (e.g. Girichidis et al. 2016), the outflow would progress at most $\simeq 100$ kpc within the age of the Universe at $z=6$. This is, in fact, broadly consistent with the results of a cosmological radiation hydrodynamics simulation (Smidt et al. 2017) of the formation of a $z=7.1$ quasar matching the observable properties of the Mortlock et al. (2011) quasar, in which the metal-enriched region extends out to $\simeq 50$ kpc from the compact quasar host galaxy.\(^2\) In addition, this is also in line with the $\simeq 50$ kpc extent of the outflow inferred for a bright...
are comparable to those we find for z = 6.4 quasar by Cicone et al. (2015). As these distances are set to be tested in the upcoming years with the launch of JWST, among other next generation facilities that will support bright quasars in the early Universe.

The possible final outcomes of the collapse of the gas that we find are shown schematically in Figure 7. The intense LW radiation that is emitted from quasar host galaxies suppresses the cooling of the primordial gas as it collapses, thus satisfying the requirements for the formation of DCBHs in close proximity to high-z quasars. Farther out, bright Pop III starbursts are instead likely to occur, with the mass function of stars likely shifting to lower masses farther from the quasar, in part due to the action of HD cooling and in part due to the more intense heating of the gas by X-rays closer to the quasar (see also e.g. Hocuk & Spaans 2010).

It is key that predictions for the sites of primordial star and seed black hole formation be put forward now, as they are set to be tested in the upcoming years with the launch of the JWST, among other next generation facilities that will peer deeper than ever into the distant early Universe. This work provides a clear prediction that the brightest Pop III starbursts could be located within ~ 1 Mpc of bright quasars at z > 6, and that DCBHs may be formed in even closer proximity to them. While these primordial objects are likely rare, it follows from this prediction where they should be sought: near bright quasars in the early Universe, perhaps even around some that have already been discovered.

### 5 SUMMARY

We have explored the evolution of the primordial gas as it is exposed to the extreme radiation emitted from high-z quasars powered by rapidly accreting supermassive black holes. As shown in Figure 2, we confirm that the temperature of the gas is raised to values of up to ~ 10^8 K due to the intense X-ray flux, with the implication that the gas will only collapse once it has been incorporated in DM haloes with masses up to ~ 10^{11} M⊙. Such large haloes would provide extremely large mass reservoirs of gas from which Pop III stars could form, setting the stage for the brightest primordial starbursts in the early Universe.

Table 1. Maximum distance d_{DCBH} (in kpc) from host quasars powered by black holes with masses M_{BH} in which DCBH can form, for various values of the effective temperature T_e of the stellar population in the quasar host halo. Eddington accretion is assumed for the BH in the source quasar in all cases shown here, as is an effective stellar temperature of T_e = 3 \times 10^4 K.

| M_{BH} [M⊙] | T_e = 10^4 K | T_e = 3 \times 10^4 K | T_e = 10^5 K |
|-------------|-------------|-------------|-------------|
| 10^8        | 300         | 50          | 20          |
| 10^9        | 1000        | 200         | 70          |
| 10^{10}     | 3000        | 500         | 200         |

Table 2. Maximum distance d_{DCBH} (in kpc) from host quasars powered by black holes with masses M_{BH} in which DCBH can form, for various ratios of the stellar to black hole mass (M_* / M_{BH}) in the quasar host halo. Eddington accretion is assumed for the BH in the source quasar in all cases shown here.

| M_{BH} [M⊙] | M_* / M_{BH}=1 | M_* / M_{BH}=10 | M_* / M_{BH}=100 |
|-------------|----------------|----------------|------------------|
| 10^8        | 10             | 20             | 50               |
| 10^9        | 30             | 70             | 200              |
| 10^{10}     | 100            | 200            | 500              |
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