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# Accretion onto the first stellar mass black holes

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## ABSTRACT

The first stars, forming at redshifts $z > 15$ in minihalos with $M \sim 10^{5-6} M_\odot$ may leave behind remnant black holes, which could conceivably have been the "seeds" for the supermassive black holes observed at $z \lesssim 7$. We study remnant black hole growth through accretion, including for the first time the radiation emitted due to accretion, with adaptive mesh refinement cosmological radiation-hydrodynamical simulations. The effects of photo-ionization and heating dramatically affect the large-scale inflow, resulting in negligible mass growth. We compare cases with accretion luminosity included and neglected to show that accretion radiation drastically changes the environment within 100 pc of the black hole, increasing gas temperatures by an order of magnitude. Gas densities are reduced and further star formation in the same minihalo is prevented for the two hundred million years we followed. Without radiative feedback included most seed black holes do not gain mass as efficiently as has been hoped for in previous theories, implying that black hole remnants of Pop III stars in minihalos are not likely to be miniquasars. Most importantly, however, our calculations demonstrate that if these black holes are indeed accreting close to the Bondi-Hoyle rate with ten percent radiative efficiency they have a dramatic local effect in regulating star formation in the first galaxies. This suggests a novel mechanism for massive black hole formation – stellar-mass black holes may have suppressed fragmentation and star formation after falling into halos with virial temperatures $\sim 10^4$ K, facilitating intermediate mass black hole formation at their centers.

*Subject headings:* cosmology: theory — galaxies: formation — black hole physics

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## 1. INTRODUCTION

The first stars in the universe may have left a population of black holes as their remnants. This possibility demands we understand how radiative feedback would have affected their environment and regulated accretion. Luckily, there is a relative amount of theoretical consensus regarding the nature of first star formation, offering a solid foundation for further investigation into their black hole remnants.

The first stars probably formed at redshifts $z > 15$ in minihalos with mass $10^{5-6} M_\odot$, and were likely massive, with $30 \lesssim M_*/M_\odot \lesssim 300$ (Abel et al. 2002; Bromm et al. 2002). They influenced subsequent structure formation through their UV radiation heating the surrounding gas and initiating reionization (Whalen et al. 2004; Kitayama et al. 2004; Alvarez et al. 2006; Johnson & Bromm 2007; Abel et al. 2007; Yoshida et al. 2007; Wise & Abel 2007, 2008). If these population III (Pop III) stars were less massive than 140 $M_\odot$ or more massive than 260 $M_\odot$, they likely would collapse to form a black hole at the end of their lifetime (Heger et al. 2003).

The presence of these black holes could have had dramatic consequences. If a 100-$M_\odot$ black hole is radiating at the Eddington limit with ten per cent radiative efficiency, beginning at $z > 20$, it will attain a final mass at $z = 6.4$ of greater than $10^9 M_\odot$, implying that accretion onto these black holes is a viable explanation for the $z \gtrsim 6$ quasars (e.g., Haiman & Loeb 2001; Volonteri & Rees 2006). Such efficient accretion would mean that "miniquasars" may have been abundant during reionization.

Feedback from black hole accretion is a very active field, focusing mainly on its relationship to galaxy formation (e.g., Silk & Rees 1998; Ciotti & Ostriker 2001). A typical approach is that described by Springel et al. (2005), where some fraction of the rest-mass energy accreted onto the black hole is deposited as thermal energy within a finite volume of surrounding matter as an additional term in the energy equation. This technique was recently used by Li et al. (2007) and Pelupessy, Di Matteo, & Ciardi (2007) to study the growth of Pop III remnant black holes. While giving insight into the *late time* growth of the seed black holes, these simulations by design do not address the earliest phases of accretion.

In this *Letter* we focus on the evolution of remnant black holes immediately following the death of their progenitor Pop III stars. Our simulations account for the ionizing radiation from the Pop III star itself, which photoevaporates the gas within its host halo. Because the simulations are run from cosmological initial conditions, we can follow the fate of the black hole as it encounters cold, dense gas from nearby halos, as well as the recombining gas in the relic H II region. We model the ionizing radiation from accretion onto the black hole by full radiative transfer coupled to the hydrodynamics, revealing how it regulates black hole growth and alters the nearby environment. We present our simulation method in §2 and our results in §3. We conclude with a discussion in

§4. We will present the results of two otherwise identical simulations runs, one in which ionizing radiation from the accretion is included (“feedback”), and one in which it is not (“no feedback”). The simulations with no feedback were first presented in Alvarez et al. (2008).

## 2. Method

We use the code Enzo[1] (O’Shea et al. 2004) to simulate the formation of the first star within a periodic volume 250 comoving kpc on a side. The dark matter particle mass within the central $\sim 90$ comoving kpc, where refinement is allowed to proceed adaptively, is $30 M_\odot$. A fully-formed 100 $M_\odot$-star is assumed to form when the overdensity is $5 \times 10^5$ and the molecular hydrogen mass fraction is greater than $5 \times 10^{-4}$. The star is assigned an ionizing photon luminosity of $1.2 \times 10^{50}$ s$^{-1}$ and shines for its main sequence lifetime of 2.7 Myr. Adaptive ray-tracing is used for the radiative transfer of ionizing radiation, which is coupled to the hydrodynamics via the energy equation and integrated into Enzo’s primordial chemistry solver. We use the fitting formula provided by Shull & van Steenberg (1985) to take account of secondary ionizations. For more details on the simulation set up and method, see Abel et al. (2007) (the set up is just the same as there, but with a different set of random modes for the initial conditions). After the lifetime of the star, its radiation is turned off and it is assumed to collapse directly to a black hole with the same mass, position, and velocity as the progenitor. We track the position of the black hole as the relic HII region evolves for 210 Myr from $z \sim 18$ to $z \sim 11$.

We base our model for the spectrum of accreting gas on an approximate form of the multicolor disk + power-law model adopted by Kuhlen & Madau (2005). We take $L_\nu \propto \nu$ for $h\nu <$ 200 eV, $L_\nu \propto \nu^{-1}$ for 200 eV $< h\nu <$ 10 keV, and $L_\nu = 0$ for $h\nu >$ 10 keV. This implies a mean photoelectron energy of 460 eV, which we take as our monochramatic ionizing photon energy. $H_2$ dissociating radiation is treated in the optically-thin limit, with Lyman-Werner-band luminosity obtained from our adopted spectrum. While admittedly crude, our model is adequate in this context, where we focus on the larger scale environment on 1-1000 pc scales. Neglecting soft ionizing radiation is conservative because of the much higher opacity at those wavelengths – its inclusion would increase negative feedback effects even further. The normalization of the total luminosity is obtained by assuming that ten per cent of the rest mass energy of matter falling in is converted to radiation, and the accretion rate is determined from the Bondi-Hoyle (Bondi & Hoyle 1944; Bondi 1952) formula, $\dot{M}_{BH} = 4\pi G^2 M^2 \rho/(c_s^2 + v_{\rm rel}^2)^{3/2}$, where $c_s$ is the sound speed of the gas and $v_{\rm rel}$ is the velocity of the black hole relative to nearby gas. The Bondi radius, $r_{\rm B} \simeq 0.1$ pc $(M_\bullet/100 M_\odot)(3000\ {\rm K}/T)$, is close to our resolution limit, indicating the local conditions at the black hole are appropriate for

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[1] http://lca.ucsd.edu/projects/enzo

determining the accretion rate. Snapshots of the simulation are shown in Figs. 1 and 2.

## 3. Results

The black hole is tightly bound to the center of the dark matter minihalo in which its progenitor formed for the duration of the simulation. Its path through density-temperature space is shown in Fig. 3, in cases with and without feedback from accretion included. Also plotted are lines of constant Bondi accretion rate in units of the Eddington accretion rate, $\dot{M}_{\rm Edd} = 4\pi G M m_p (1-\epsilon)/(\epsilon \sigma_T c)$, where the radiative efficiency is set to $\epsilon = 0.1$. For $M = 100\, M_\odot$, the Eddington accretion rate is $\simeq 2 \times 10^{-6} M_\odot$ yr$^{-1}$.

Initially, the black hole is bathed in hot, ionized gas, with a temperature $\sim 10^4$ K and hydrogen number density $\sim 1$ cm$^{-3}$. The photoevaporative wind from the first star continues outward under its own inertia with a velocity $\sim 10$ km s$^{-1}$. The black hole eventually encounters a nearby halo with which its own host halo is merging, after which the evolution depends on whether or not radiative feedback due to accretion is included. Without feedback included, the path through density-temperature space oscillates between cold dense gas close to the neighboring halo's center, to the warmer more rarefied gas in the ambient relic H II region, due to the orbital motion of the merging halos. With feedback included, however, the black hole stays in relatively low-density, high-temperature gas for the entire time, partially ionizing and heating gas within tens of pc (Fig. 4).

Shown in Fig. 5 are distance to the nearest high density peak ("clump"), the heating time at the clump, and accretion rate (in units of $\dot{M}_{\rm Edd} \simeq 2 \times 10^{-6}\ M_\odot$yr$^{-1}$) . This figure illlustrates the in-spiralling motion of the clump and black hole as their host halos merge. When the clump approaches, the accretion rate rises, accompanied by a shorter heating timescale. Before the clump approaches the black hole for even the first time, the heating timescale becomes shorter than the sound crossing time at the Bondi radius (dotted line in top panel of Fig. 5), and photoevaporation ensues. For a radiative efficiency of ten percent, self-regultation of accretion onto black holes within minihalos occurs at accretion rates some four to five orders of magnitude below the Eddington rate, to a few times $10^{-11} M_\odot$yr$^{-1}$.

## 4. Discussion

We have presented results from a simulation of radiative feedback from accretion onto a remnant black hole of an early Pop III star. This feedback makes it even more difficult for the black hole to encounter cold, dense gas, further depleting the reservoir of gas available for accretion. Including radiative feedback lowers peak accretion rates from $\sim 10^{-7} M_\odot \mathrm{yr}^{-1}$ to a few times $10^{-11} M_\odot \mathrm{yr}^{-1}$, indicating that radiative feedback is very efficient at halting accretion. Furthermore, the feedback is sufficiently strong to prevent further cooling and star formation within its host minihalo, inhibiting star formation in the halo over the 200 million years we have evolved it.

These results are in agreement with previous work, which indicated that massive Pop III stars forming in minihalos with mass $\sim 10^6 M_\odot$ photoevaporate the halo gas from the inside out, leaving any remnant black hole starved, at least momentarily, of accreting material (Whalen et al. 2004; Kitayama et al. 2004; O'Shea et al. 2005). In particular, Johnson & Bromm (2007) showed that this photevaporation was likely to delay significant accretion for on the order of 100 million years, creating an early "bottleneck" in the black hole's growth. Our results imply that the situation is likely to be even more drastic, because radiative feedback is so effective at preventing gas from reaching the center of the halo, even without taking into account the effect of lower mean free path photons or radiation pressure (e.g., Haehnelt 1995; Dijkstra & Loeb 2008; Milosavljevic et al. 2008).

The possibility that accretion onto black holes in minihalos could power miniquasars (Kuhlen & Madau 2005) and even lead to supermassive black hole formation (Madau et al. 2004; Tanaka & Haiman 2009) has received a great deal of attention lately. Radiation from such a population of miniquasars could have significantly increased the ionizing photon budget of the universe and extended the reionization process and altered its topology (Ricotti & Ostriker 2004; Madau et al. 2004). They could also change the pattern of 21-cm fluctuations before reioinization, as pointed out by Chuzhoy et al. (2006) and Chen & Miralda-Escude (2006). The strong feedback effects and low accretion rates we find here indicate that black hole remnants of Pop III stars that formed in minihalos will have difficulty accreting quickly enough to grow into the supermassive black holes powering the quasars recently discovered at $z > 6$. Specifically, we find that remnant black holes of Pop III stars were not likely to have accreted efficiently *while in minihalos*. Statistical merger-tree based models of black hole growth in minihalos such as those of Madau et al. (2004) and Tanaka & Haiman (2009) may need to be revised to take this finding into account. Because we do not have the dynamic range necessary to follow the merger history of the host minihalo to the point where atomic cooling becomes important (i.e. a virial temperature $\gtrsim 10^4$ K), we have not ruled out the possibility that Pop III remnant black holes as modelled here could accrete efficiently at that point."

What is the likely fate of a Pop III remnant black hole that formed in a minihalo after it falls into a larger, metal-free atomic cooling halo with $T_{\mathrm{vir}} \gtrsim 10^4$ K? Although our simulations could not address this question directly, our results hint at an interesting new possibility. In particular, we find these black holes are likely to maintain a strong negative feedback effect on star formation within tens of pc. Because these remnant black holes are expected to occupy the inner regions of the atomic cooling halos they fall into, they should continue to prevent star formation within the central 10-100 pc, which could contain a gaseous reservoir of perhaps $10^5$ to $10^6$ $M_\odot$, perhaps allowing that gas to collapse further into a massive central black hole as described in, e.g., Bromm & Loeb (2003) and Begelman et al. (2006). Rather than preventing fragmentation by external radiation (e.g., Dijkstra et al. 2008; Shang et al. 2009) or turbulent support Begelman & Shlosman (2009), our results imply yet another path to massive black hole formation in metal-free atomic cooling halos: suppression of fragmentation by black hole feedback *from within*.

This new hypothesis has yet to be tested by cosmological simulations that follow the formation history of an atomic cooling halo, including feedback from all the star and black hole formation that took place in its minihalo progenitors. In addition, the presence of metals and dust would complicate the picture even further, perhaps making suppression of star formation more difficult. We are currently working to answer these questions by including these effects in calculations like those of Wise, Turk & Abel (2007) and Wise & Abel (2008), which will be the subject of future work.

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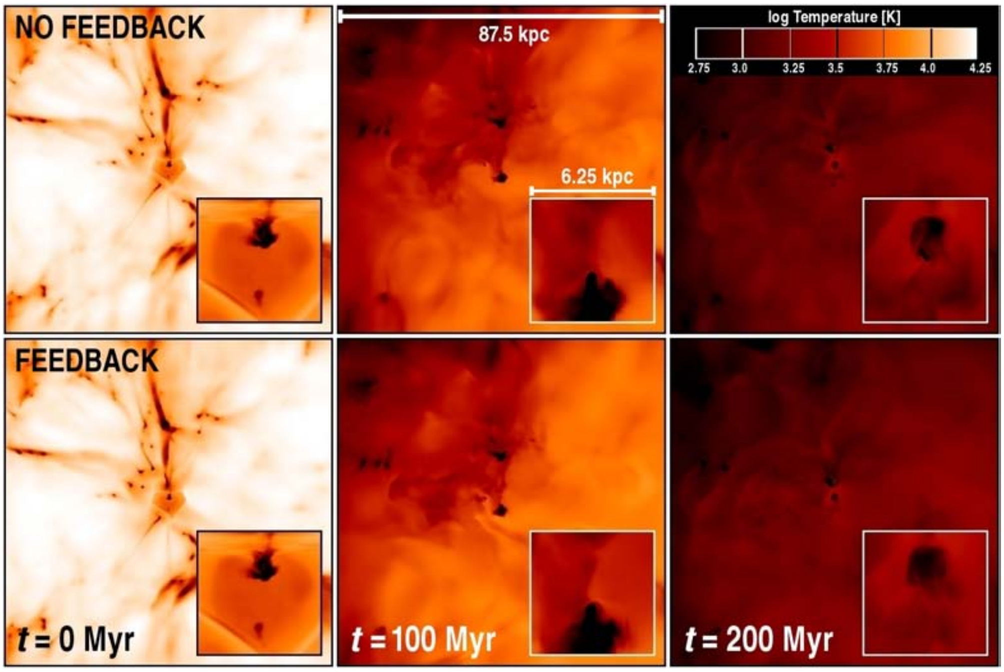

Fig. 1.— Density-squared weighted rojections of temperature in cubic regions 87.5 (large panels) and 6.25 (insets) comoving kpc on a side, centered on the position of the black hole at 0 (left – $z \sim 18$) 100 (center – $z \sim 14$) and 200 (right – $z \sim 11$) Myr after the formation of the black hole. Top row is without feedback, and bottom row is with feedback. While the large scale structure of the volume is hardly affected by the feedback, the insets, on scales of approximately 300 proper pc, show a substantial heating within the host minihalo by the end of the run.

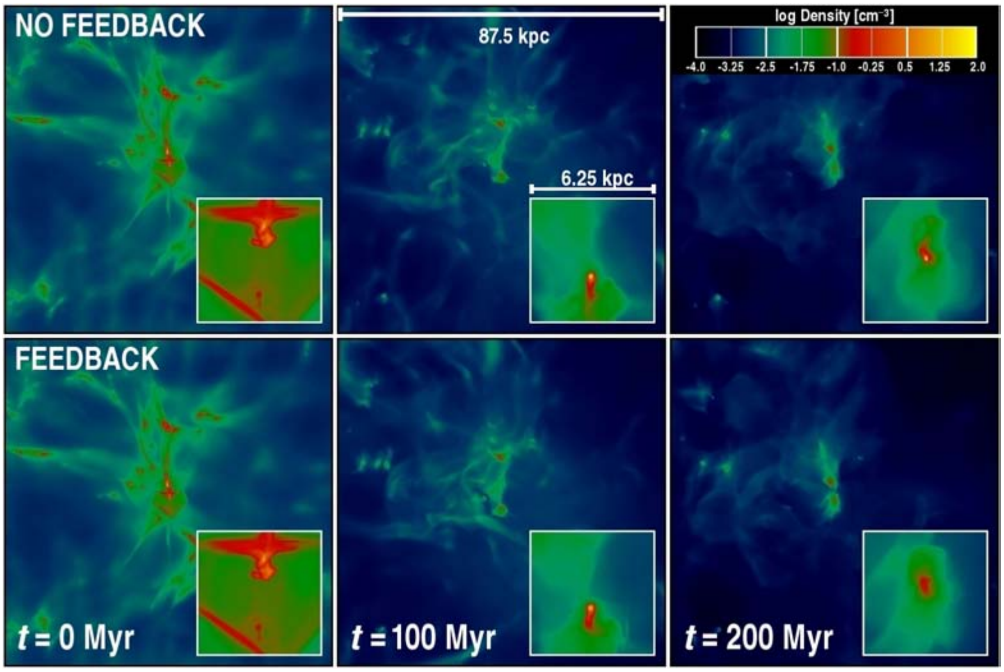

Fig. 2.— Density-squared weighted rojections of density. The sizes of the projections and times are identical to that of Fig. 1. While the large scale structure of the volume is hardly affected by the feedback, the insets, on scales of approximately 300 proper pc, show a substantial density reduction within the host minihalo by the end of the run.

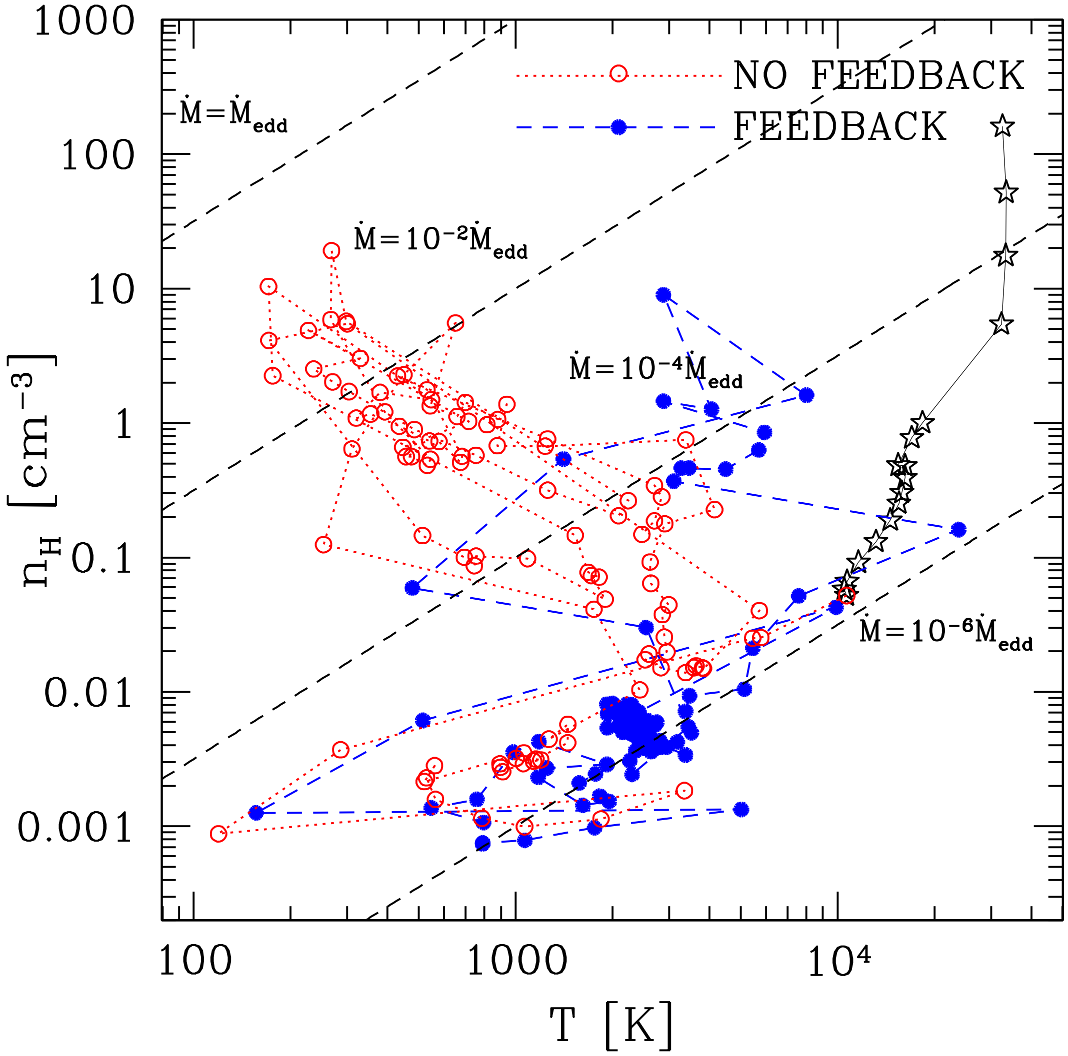

Fig. 3.— Density and temperature at position of black hole along its path (starts at upper right) with (solid) and without (dotted) feedback. The points along the solid line beginning at the top right of the diagram are during the progenitor star's lifetime, and each point thereafter is spaced approximately 2 Myr apart. Also shown as dashed lines are loci of fixed Bondi accretion rate, in units of the mass accretion rate if the black hole were shining at the Eddington luminosity with radiative efficiency, $\epsilon = 0.1$.

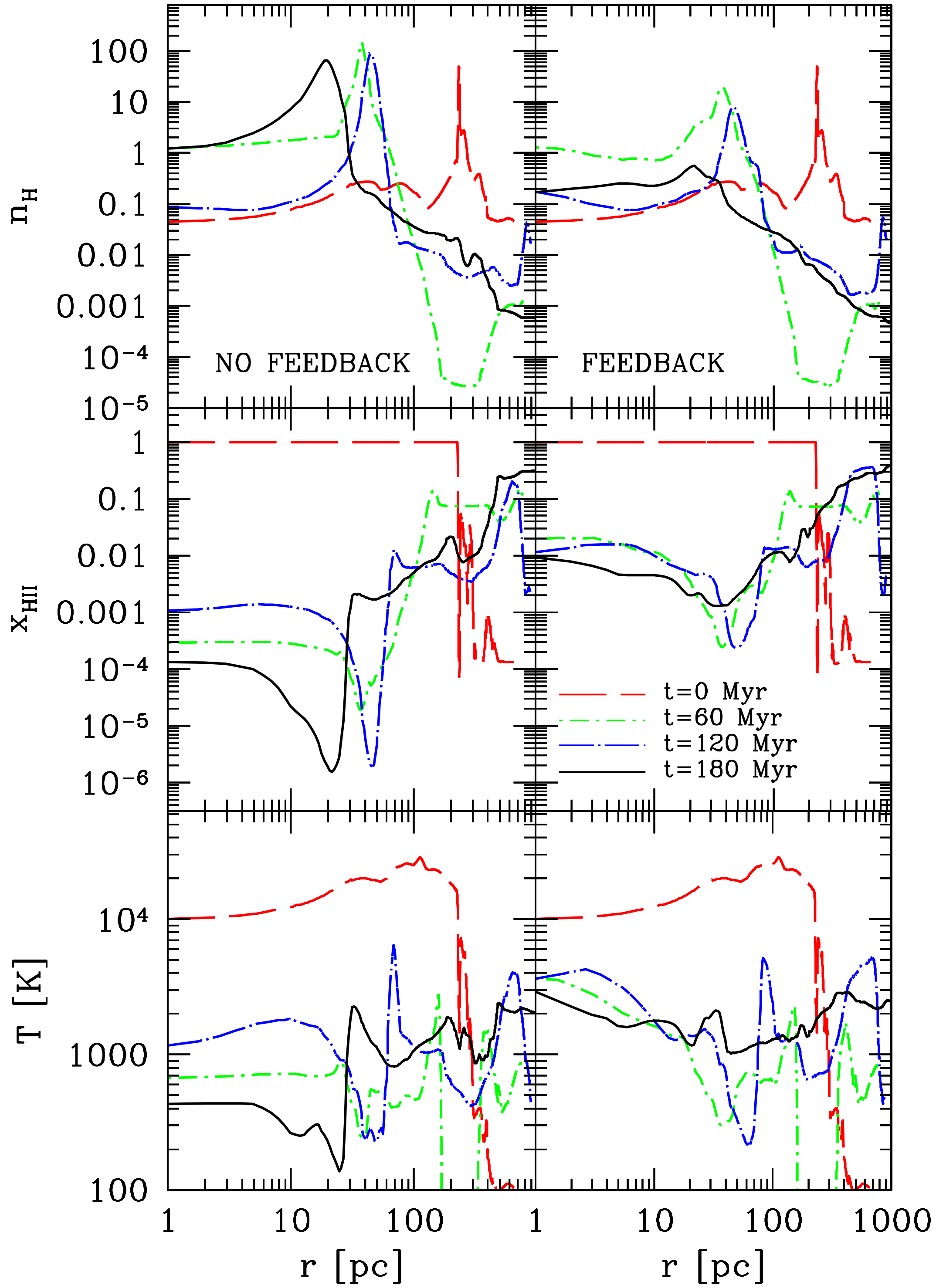

Fig. 4.— Profiles of hydrogen number density (top), ionized fraction (middle), and temperature (bottom), along line connecting the black hole (at $r = 0$) to the highest density point nearby, with (right) and without (left) feedback. The linestyle distinguish times after the black hole is formed. Their times are given in the middle right panel.

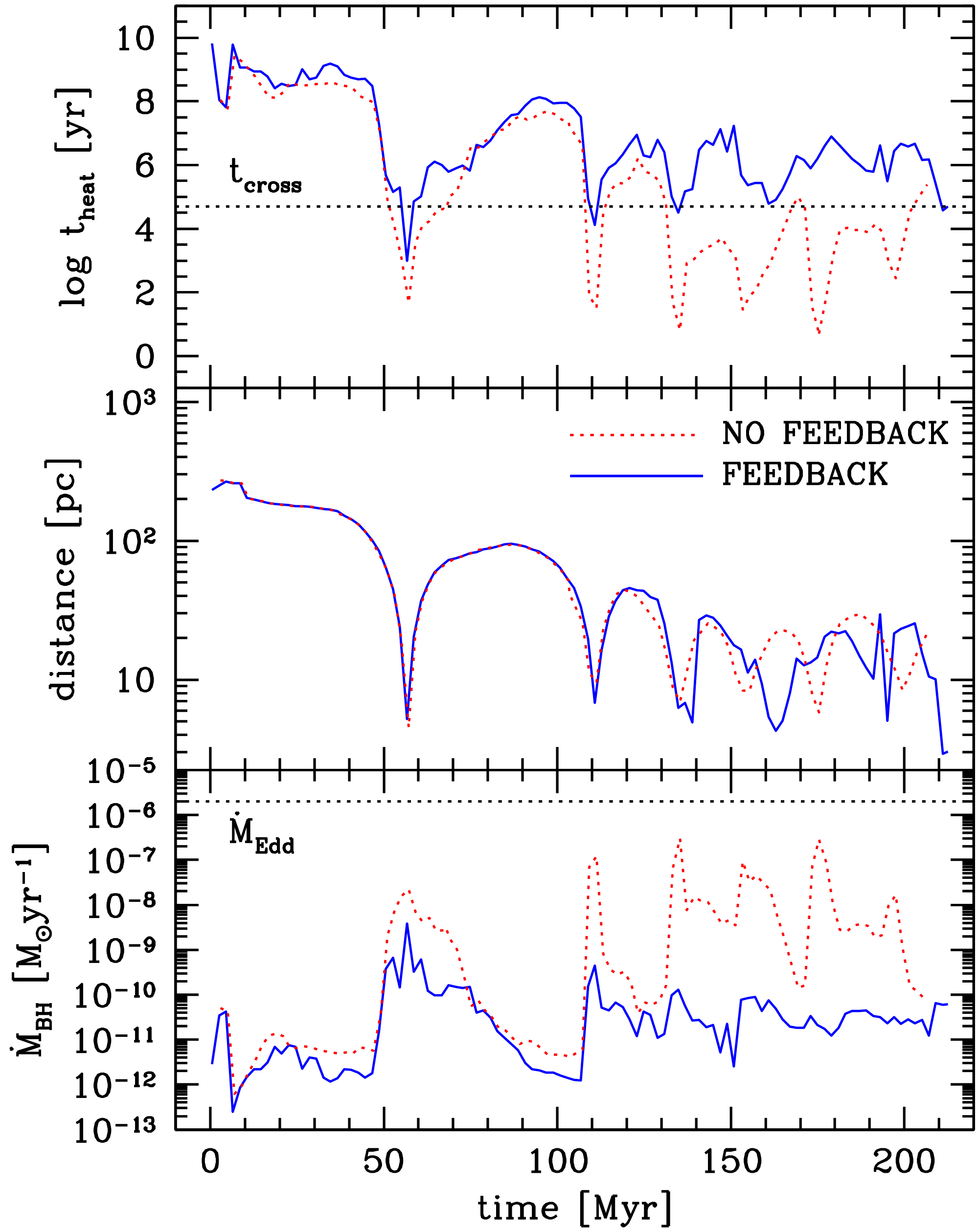

Fig. 5.— Evolution of heating time (top), distance from black hole to clump (middle), and accretion rate (bottom). Solid lines are with feedback, dotted lines are without feedback. The horizontal line in the top panel is the sound crossing time across the Bondi radius at 3000 K ($r_B \sim 0.1$pc), while the one in the lower panel is the Eddington accretion rate for a 100 $M_\odot$ black hole with ten percent radiative efficiency.