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Black Hole Feedback on the First Galaxies

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Abstract. We study how the first galaxies were assembled under feedback from the accretion onto a central black hole (BH) that is left behind by the first generation of metal-free stars through self-consistent, cosmological simulations. X-ray radiation from the accretion of gas onto BH remnants of Population III (Pop III) stars, or from high-mass X-ray binaries (HMXBs), again involving Pop III stars, influences the mode of second generation star formation. We track the evolution of the black hole accretion rate and the associated X-ray feedback starting with the death of the Pop III progenitor star inside a minihalo and following the subsequent evolution of the black hole as the minihalo grows to become an atomically cooling galaxy. We find that X-ray photoionization heating from a stellar-mass BH is able to quench further star formation in the host halo at all times before the halo enters the atomic cooling phase. X-ray radiation from a HMXB, assuming a luminosity close to the Eddington value, exerts an even stronger, and more diverse, feedback on star formation. It photoheats the gas inside the host halo, but also promotes the formation of molecular hydrogen and cooling of gas in the intergalactic medium and in nearby minihalos, leading to a net increase in the number of stars formed at early times. Our simulations further show that the radiative feedback from the first BHs may strongly suppress early BH growth, thus constraining models for the formation of supermassive BHs.

Keywords: cosmology, galaxies, black hole, feedback
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INTRODUCTION

It has been a longstanding goal to understand the formation of the first galaxies subject to different accompanying feedback effects from the first stars, such as ionizing feedback from individual Pop III stars [e.g., 1, 2], chemical feedback produced by a supernova (SN) explosion [e.g., 3, 4], and radiativea feedback from accreting black holes (BHs) [e.g., 5, 6]. The first stars are expected to form at a redshift $z \sim 15$ inside dark matter minihalos with masses of $\sim 10^6\,M_\odot$ [e.g., 7, 8]. For the characteristic masses of the stars formed out of such metal-free gas, this issue is far from being settled. Recent improved simulations of Pop III star formation suggest that the primordial gas could fragment into two or more distinct cores, possibly resulting in a massive binary, or higher-multiple stellar system, compared to a single isolated Pop III star with the canonical value of $\sim 100\ M_\odot$.

We here briefly summarize our recent study [9], in which we investigated the feedback effects from such stellar-mass BHs by focusing on the question: “How does a stellar black hole, a remnant of a Pop III star, influence the subsequent star formation and in turn the assembly process of the first galaxies?" The first BH feedback may also be

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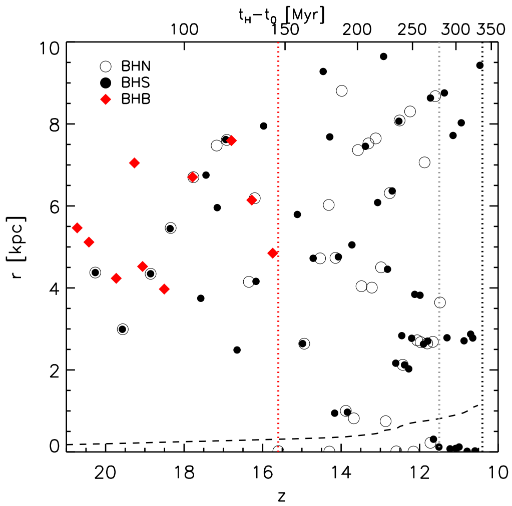

FIGURE 1. Distances between newly formed Pop III stars that are accompanied by H II regions and the BH as a function of redshift from our three simulations. Note that the BHN, BHS and BHB simulations end at different redshifts, corresponding to $z \approx 11.6$, $z \approx 10.4$, and $z \approx 15.8$, respectively (indicated by the vertical dotted lines). We also show the virial radius of the DM halo hosting the active BH or the HMXB (*dashed line*).

expected to have important effects on BH growth. One outstanding question is how the supermassive black holes (SMBHs), observed by the *Sloan Digital Sky Survey* (SDSS) at $z \sim 6$ with masses of $\sim 10^9 M_\odot$ [10], were able to grow within such a short period of time after the Big Bang. A second goal of this study is to provide an improved understanding of whether a stellar BH can grow to become a SMBH in the presence of stellar and BH feedback.

SIMULATIONS

To survey the relevant parameter space, we have carried out three cosmological simulations. As a reference, simulation “BHN" includes stellar radiative feedback from Pop III stars, whereas the subsequent feedback due to BH accretion is not taken into account. The simulation “BHS" includes both the feedback from Pop III stars and from a single isolated BH. Finally, in simulation “BHB" we assume that the Pop III BH remnant has a stellar binary companion, giving rise to a HMXB.

For the simulations presented here, we use a customized version of the combined hydrodynamics and N-body code GADGET2 [11]. We propagate the ionization front around Pop III stars to build up a primordial H II region, using a well-tested ray-tracing algorithm [for details see 12]. We follow Kuhlen & Madau [5] to model the propagation of high-energy photons emitted from the accretion onto a BH in which the accretion rate is estimated by the Bondi & Hoyle model [see 13].

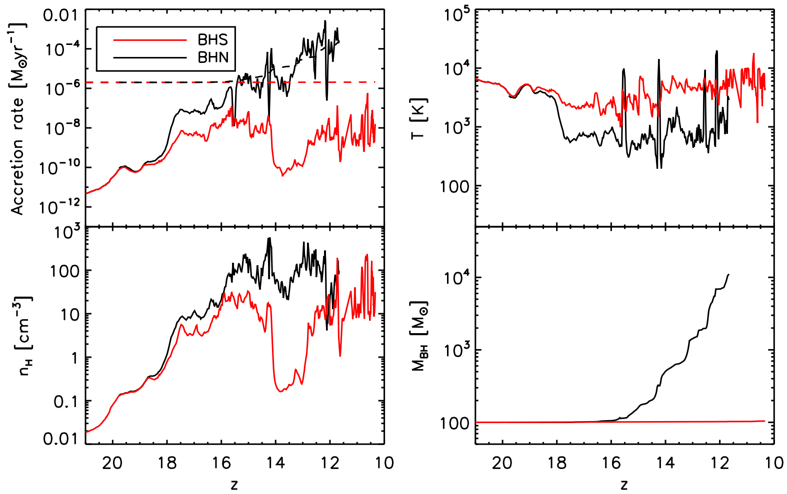

FIGURE 2. BH growth with and without feedback. Shown is the redshift evolution of the BH accretion rate, the density and the temperature of the gas in the immediate vicinity of the BH, as well as the resulting BH masses for simulations BHN (*black*) and BHS (*red*). In the top-left panel, we also indicate the corresponding Eddington-limited accretion rates for the two cases (*dashed lines*).

RESULTS

Figure 1 shows the distance between newly formed Pop III stars and the central BH in the range of redshifts $z = 10 - 20$ from three simulations. A total of ~ 50 Pop III stars have been formed in the BHN and BHS cases, accompanied by individual H II regions. We find that for over 250 Myr after the seed BH formed there has been no further star formation within the host halo in simulation BHS. This is because it takes time for the gas expelled by the BH progenitor star to be reincorporated into the halo, and the modest feedback from the BH prevents the gas from cooling. In simulation BHN, on the other hand, stars inside the host halo continue to form already much earlier, demonstrating that X-ray heating from the accreting BH in simulation BHS implies a strong local negative feedback.

For simulation BHB, the positive feedback is clearly evident far away from the source. This is due to the gas collapse into distant minihalos, facilitated via H_2 cooling promoted by the strong X-ray emission from the HMXB. Locally, on the other hand, star formation is suppressed due to the strong negative feedback from the binary source owing to the photo-evaporation of the gas within the halo. This implies that if an HMXB existed within a minihalo at high redshifts, it would take significantly longer for the halo to reassemble the lost gas, and to eventually evolve into a primordial galaxy.

Figure 2 shows the evolution of the accretion rate onto the BH, the density and temperature of the neighboring gas, as well as the BH mass for simulations BHN and BHS. The accretion rate in the BHN simulation is already comparable to the Eddington value, depicted as dashed lines in Figure 2 (top-left panel), at $z \sim 15.5$, while it is still an order of magnitude lower in the BHS case. Occasionally, star formation takes place very close to the BH, e.g., ~ 1 kpc away at $z \sim 14$. The radiative feedback from this event acts to compound the heating effect from the BH accretion, thus rendering the removal of gas out of the shallow potential well more effective.

The combined stellar and BH radiative feedback results in an accretion rate that is on average 4 orders of magnitude below the Eddington value at $z = 14 - 13$. Even 300 Myr after BH formation, the mass of the BH has increased by only 1.5 % in the BHS simulation, whereas it has grown by two orders of magnitude in the BHN case. This indicates that the feedback from a stellar-mass BH is sufficiently strong to prevent significant growth, suggesting a very important constraint on SMBH formation scenarios. We infer that the radiative feedback from an accreting BH might be partly responsible for the low density of quasars at redshifts $z \sim 6$, by suppressing early BH growth.

CONCLUSIONS

We have studied how the assembly of a primordial galaxy is affected by the radiative feedback from an accreting, isolated stellar-mass BH and an HMXB, which are two possible end products of Pop III star formation. We have shown that locally the feedback from an isolated, accreting BH is very efficient, leading to a strong suppression of the early growth of the seed BH. Without such feedback, the growth rate quickly reaches near-Eddington values. We suggest that the radiative feedback from accreting BHs plays a key role in suppressing early BH growth, thus constraining models for SMBH formation.

The feedback from an efficiently radiating HMXB is very strong locally, and moderately important globally. Locally, the effect on the surrounding primordial gas is to heat it to high temperatures of $\sim 10^4$K, and to fully ionize it. The corresponding strong photo-evaporative outflow suppresses central gas densities, thus preventing any subsequent star formation within the emerging galaxy. Our results imply that once a halo of $\sim 10^6 M_\odot$ harbors an HMXB, the ensuing strong radiative feedback will delay the condensation of gas in the atomic cooling halo, possibly leading to a decrease in the number of first galaxies at a given epoch.

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