RAPID GROWTH OF HIGH-REDSHIFT BLACK HOLES
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ABSTRACT

We discuss a model for the early assembly of supermassive black holes (SMBHs) at the center of galaxies that trace their hierarchical buildup far up into the dark halo “merger tree.” Motivated by the observations of luminous quasars around redshift $z \approx 6$ with SMBH masses $\approx 10^9 M_\odot$, we assess the possibility of an early phase of stable supercritical quasi-spherical accretion in the BHs hosted by metal-free halos with virial temperature $T_{\text{vir}} > 10^4$ K. We assume that the first “seed” black holes formed with intermediate masses following the collapse of the first generation of stars in minihalos collapsing at $z \approx 20$ from high-$\sigma$ density fluctuations. In high-redshift halos with $T_{\text{vir}} > 10^4$ K, conditions exist for the formation of a fat disk of gas at $T_{\text{gas}} \approx 5000–10,000$ K. Cooling via hydrogen atomic lines is in fact effective in these comparatively massive halos. The cooling and collapse of an initially spherical configuration of gas leads to a rotationally supported disk at the center of the halo if baryons preserve their specific angular momentum during collapse. The conditions for the formation of the gas disk and accretion onto central black holes out of this supply of gas are investigated, as well as the feedback of the emission onto the host and onto the intergalactic medium. We find that even a short phase of supercritical accretion eases the requirements set by the $z \approx 6$ quasars.

Subject headings: black hole physics — cosmology: theory — galaxies: evolution — quasars: general

1. INTRODUCTION

The strongest constraint on the high-redshift evolution of SMBHs comes from the observation of luminous quasars at $z \approx 6$ in the Sloan Digital Sky Survey (SDSS; Fan et al. 2001). The luminosities of these quasars, well in excess of $10^{47}$ ergs s$^{-1}$, imply that SMBHs with masses $\approx 10^9 M_\odot$ are already in place when the universe is only 1 Gyr old. The highest redshift quasar currently known, SDSS 1148+3251, at $z = 6.4$, has estimates of the SMBH mass in the range $(2–6) \times 10^9 M_\odot$ (Barth et al. 2003; Willott et al. 2003). Among the seed BHs proposed, the less exotic (e.g., Population III star remnants and gravitationally collapsed star clusters) are in the range $10^2–10^4 M_\odot$, forming at $z = 30$ or less.

To grow such seeds up to $10^9 M_\odot$ requires an almost continuous accretion of gas, assuming Eddington accretion and a standard thin-disk radiative efficiency for a Schwarzschild black hole, $\epsilon \approx 0.1$. However, if accretion is via a gaseous thin disk, the alignment of a SMBH with the angular momentum of the accretion disk tends to efficiently spin holes up (Volonteri et al. 2005), and radiative efficiencies can therefore approach 30% (assuming a “standard” spin-efficiency conversion). The accretion of mass at the Eddington rate causes the BH mass to increase in time as

$$M(t) = M(0) \exp \left( \frac{1 - \epsilon}{\epsilon} \frac{t}{t_{\text{edd}}} \right),$$

where $t_{\text{edd}} = 0.45$ Gyr. Given $M(0)$, the higher the efficiency, the longer it takes for the BH to grow in mass by (for example) 20 e-foldings (Shapiro 2005).

Yu & Tremaine (2002), Elvis et al. (2002), and Marconi et al. (2004) compared the local MBH mass density to the mass density accreted by luminous quasars, showing that quasars have a mass-to-energy conversion efficiency $\epsilon \approx 0.1$ (an argument originally proposed by Soltan 1982). This high average radiative efficiency, however, describes the population of SMBHs at redshift $z < 5$, and nothing is known about the radiative efficiency of pregalactic quasars in the early universe. The numbers quoted above, in fact, may suggest that the picture that we have of the low-redshift universe may not apply at earlier times.

In this paper we follow earlier papers in considering a scenario for the hierarchical assembly of SMBHs that traces its seeds back to the very first generation of stars, in minihalos above the cosmological Jeans mass collapsing at $z \approx 20$ from the high-$\sigma$ peaks of the primordial density field. However, we introduce two new features: (1) we consider more explicitly the configuration of the gas from which the accretion occurs: a dense, cold disk of gas, likely to form in halos with $T_{\text{vir}} > 10^5$ K and zero metallicity (Oh & Haiman 2002); and (2) we explore the assumption that at early stages, accretion occurs at a “Bondi” rate that is higher than the standard rate for $\epsilon \approx 0.1$.

The evolution of the first MBHs into the first pregalactic quasars and their impact on the reionization of the universe in this scenario has been explored recently by Madau et al. (2004). We here expand and deepen the previous study, focusing in particular on the interplay of gas cooling and BH feeding.

In § 2 we review the model for assembly of MBHs in cold dark matter (CDM) cosmogonies. We then address the conditions of the gas around the MBHs in the cores of high-redshift minihalos (§ 3) before and after the onset of pregalactic quasar activity. We compute the global evolution of the MBH population and discuss its implications in § 4, and finally, we summarize our results in § 5. Unless otherwise stated, all results shown below refer to the currently favored ΛCDM world model with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\Omega_b = 0.045$, $\sigma_8 = 0.93$, and $n = 1$.

2. ASSEMBLY OF PREGALACTIC MBHs

The main features of a plausible scenario for the hierarchical assembly, growth, and dynamics of MBHs in a ΛCDM cosmology have been discussed by Volonteri et al. (2003, 2005) and

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3.2. Accretion onto a Central MBH

As described in §2, we assume that one seed MBH forms in each of the rare density peaks above 4 σ at z = 24. The MBH is supposed to be at rest in the center of the halo after the formation and collapse of a Population III star in the central region of the minihalos.

Let us now consider a MBH seed in a metal-free halo with $T_{\text{vir}} \simeq 10^4$ K. As delineated in §3.1, a fat disk of cold ($5000$ K < $T_{\text{gas}} < 10^4$ K) gas likely condenses at the center of the halo. This gas can supply fuel for accretion onto a MBH within it. We now discuss how stable supercritical accretion (i.e., much larger than the Eddington rate) of the gas can proceed.

In a spherical geometry, matter can infall onto the hole at a rate that can be estimated using the Bondi-Hoyle formula (Bondi & Hoyle 1944)

$$\dot{M}_{\text{Bondi}} = \frac{\alpha 4\pi G^2 M_{\text{BH}}^2 n_{\text{HI}} n_{\text{H}}}{c_s^3},$$

where $\alpha$ is a dimensionless parameter of order unity, and $c_s \sim 10(T/10^4 \text{ K})^{1/2}$ km s$^{-1}$ is the sound speed of the gas.

It is useful to compare the above accretion rate to the Eddington rate:

$$\frac{\dot{M}_{\text{Bondi}}}{\dot{M}_{\text{Edd}}} = 40 \frac{M_{\text{BH,3}} n_{0,4} T_{\text{gas,8000}}^{-3/2}}{\dot{M}_{\text{Edd}}},$$

where the central density $n_{0,4}$ is in units of $10^4$ cm$^{-3}$, and the MBH mass, $M_{\text{BH,3}}$, is normalized to $10^3 M_\odot$. Clearly, for the typical black hole masses and gas densities we are considering here, $\dot{M}_{\text{Bondi}} \gg \dot{M}_{\text{Edd}}$.

The Bondi radius for the MBH is $r_{\text{acc}} = GM_{\text{BH}}/c_s^2 \simeq 0.05$ pc ($M_{\text{BH,3}}/10^3 M_\odot$)($T_{\text{gas,8000}}$ K$^{-3/2}$). Let us now compare the Bondi accretion radius to the fat disk thickness:

$$r_{\text{acc}} \simeq 0.05 \frac{GM_{\text{BH}}}{c_s^2} \left(4\pi G\mu n_{\text{H}} n_{\text{HI}}\right)^{1/2}$$

$$= 6 \times 10^{-2} M_{\text{BH,3}} T_{\text{gas,8000}}^{-1.5} n_{0,4}^{-1/2} \times 0.05.$$
latter is, by definition, equal to the sound speed, while the former is a factor \(r_{\text{acc}}/R_d\) smaller than \(v_d\), the rotation velocity of the gas disk at \(R_d\), \(v_d \gtrsim c_s\). The angular momentum is nonetheless too large for the gas to fall radially into the hole, and a tiny accretion disk forms. The outer edge of the accretion disk, \(r_{\text{in}}\), can be expressed as

\[
\frac{r_{\text{in}}}{r_S} = 3 \times 10^2 \frac{v_d^2}{c_s^2} M_{\text{BH},3}^{2/3} \frac{r_{\text{acc},2}}{r_{\text{vir}}} \frac{R_{\text{d}}^{-2}}{t_{\text{vir}} \frac{1}{6}},
\]

where \(r_S\) is the Schwarzschild radius of the hole, \(v_d\) is in units of \(10 \text{ km s}^{-1}\), and we have assumed specific angular momentum conservation inside \(r_{\text{acc}}\). The accretion disk therefore has a size of order of the trapping radius:

\[
\frac{r_{\text{tr}}}{r_S} = \frac{M}{M_{\text{Edd}}} = 12 \frac{r_{\text{in}} v_d^2}{c_s^2} M_{\text{BH},3}^{-1} t_{\text{vir}}^{2/3} r_{\text{d}}^{-2} n_{0.4},
\]

i.e., the radius at which radiation is trapped as the infall speed of the gas is larger than the diffusion speed of the radiation. The trapping radius is equivalent to the radius of spherization defined by Shakura & Sunyaev (1973), where the thickness of the disk becomes of the same order as \(r_{\text{tr}}\); at smaller radii the inflow is quasi-spherical.

Begelman (1979) and Begelman & Meier (1982) studied supercritical accretion onto a BH in spherical geometry and quiescent thick disks, respectively. In the spherical case, radiation pressure cannot prevent the accretion rate from being supercritical, while the emergent luminosity is limited to \(L_{\text{Edd}}\). The case with angular momentum is more complicated (especially with regard to the role of winds). Although this issue remains unclear, it still seems possible that when the inflow rate is supercritical, the radiative efficiency drops so that the hole can accept the material without greatly exceeding the Eddington luminosity. The efficiency could be low either because most radiation is trapped and advected inward or because the flow adjusts so that the material can plunge in from an orbit with small binding energy (Abramowicz & Lasota 1980).

Despite the uncertainties, it seems worthwhile to explore the consequences for black hole growth at an early phase when the MBH can accept most of the mass infalling at a rate that can be estimated using the Bondi-Hoyle formula and can therefore grow much more rapidly than the Eddington rate would allow.

The conditions for quasi-spherical geometry hold when the accretion radius is much smaller than the disk thickness, i.e., when the MBH and the halo are small and the gas temperature is \(\approx 8000 \text{ K}\). The gas temperature cannot be much larger than \(\approx 10^4 \text{ K}\), as the dense gas can radiate away all the energy injected by the quasar in photoionizing photons.

On the other hand, if the gas is able to cool down to \(10^4 < T_{\text{gas}} < 200 \text{ K}\) due to the formation of molecular hydrogen or metal pollution, collapse and fragmentation in the disk would suddenly halt the Bondi-style accretion. We therefore argue that this supercritical accretion phase would end when the universe is enriched by metals at \(6 < z < 10\).

In the absence of metals, \(H_2\) would be the main coolant, but the strong internal feedback provided by the pregalactic quasar emission within a galaxy easily suppresses \(H_2\) formation. In fact, assuming a nonthermal power-law component (\(\alpha = 1\) in the 11.15–13.6 eV range), the total rate of dissociations produced by the pregalactic quasars in the gas disk is \(N_{\text{gas}} \approx 10^{53} \chi L_{\text{MBH}} (M_{\text{BH}}/10^8 M_\odot) (n_0/10^6 \text{ cm}^3) (2\pi/\text{pc})^2 s^{-3} \approx 3\). The total number of molecules in the disk is \(N_{\text{H}_2} \approx 10^{53} \chi L_{\text{MBH}} (M_{\text{disc}}/10^6 M_\odot)\). The time-scale for dissociating all the \(H_2\) molecules present in the disk is thus very short. While the pregalactic quasar is shining, \(H_2\) formation is therefore completely halted in the disk, and cooling below \(\approx 4000 \text{ K}\) is impossible.

4. RESULTS

To assess the relative importance of these processes, we trace the evolution of a MBH along with its host halo. We generate Monte Carlo realizations (based on the extended Press-Schechter formalism) of the merger hierarchy of a \(M_h = 10^{13} M_\odot\) halo at \(z = 6\). The halo mass is chosen by requiring that the number density in halos more massive than \(M_h\) matches the space density of quasars at \(z = 6\) (Fan et al. 2003, 2004). We then extract from the trees the mass-growth history of the main halo and of smaller satellites (selecting only density peaks above 4 \(\sigma\) and grant these halos a MBH seed.

When the halo virial temperature becomes larger than \(10^4 \text{ K}\), the MBH is surrounded by a coldish (\(T_{\text{gas}} = 8000 \text{ K}\)) disk. The accretion rate is set at the Bondi rate, as determined by the gas density at the accretion radius. The luminosity, however, does not exceed the Eddington luminosity. During the accretion process, the radius of the inner disk increases steeply with the hole mass, thus making super-Eddington accretion less likely to be sustained. We assume here that when the radius of the accretion disk becomes a factor of 5 larger (although the choice of the exact value is somehow arbitrary), an outflow develops, blowing away the disk. A subsequent major merger then has to occur before a fresh supply of fuel is available to the MBH. Typically, the conditions for supercritical accretion are satisfied only once per MBH. If they are not, the MBH accretes at the Eddington value during the subsequent accretion episode(s). The radiative efficiency then evolves with the MBH spin, adopting the standard definition for circular equatorial orbits around a Kerr hole. The MBH’s spin is modified during the accretion phase, as described in Volonteri et al. (2005). Figure 1 shows the evolution of the MBH (mass and accretion rate) and disk in the main halo of one of the merger trees. This halo represents a 5 \(\sigma\) density fluctuation at \(z = 24\). The virial temperature of the main halo is larger than \(10^4 \text{ K}\) at \(z \approx 24\), and the MBH starts growing very early. The accretion rate is initially supercritical by a factor of 10 and grows up to a factor of about \(10^4\), thus making the flow more and more spherical (see eq. [8]). On the other hand, the whole “plump” accretion disk grows in size until it crosses the trapping surface and reaches the assumed threshold for the end of the activity. The figure also shows the effect of a larger or smaller fraction of the baryons ending up in the fat disk. A large supply of fuel (\(f_d = 0.5\)) triggers rapid accretion early on, but the accretion is quenched sooner. In both cases the spin parameter is set as \(\lambda = 0.05\). MBHs in halos with a small spin parameter have an early and short supercritical accretion episode (cf. eqs. [3] and [7]), while in the case of a high spin parameter, the supercritical phase typically happens with a more dramatic growth of the BH mass at lower redshift.

Our assumed threshold for MBH formation (density peaks above 4 \(\sigma\)) selects only the most massive and rare halos at a given redshift. This ensures that superaccreting systems are not widespread. Let us consider comparatively smaller halos (e.g., massive satellites of the main halo; Fig. 2) with virial temperature below \(10^4 \text{ K}\) at \(z \approx 24\). They accrete mass along the merger hierarchy, until their mass implies a virial temperature larger than \(10^4 \text{ K}\). Atomic cooling, therefore, becomes effective at lower redshift, so there is only a short time (if any) for the rapid growth to take place. The effect of supercriticality on black holes hosted in smaller halos
Fig. 1.—Evolution of the accretion rate and MBH mass growth in the main halo of the merger trees; $M_h = 10^{13} M_\odot$ at $z = 6$. Top panels: $f_d = 0.5$. Bottom panels: $f_d = 0.1$. Left panels: MBH mass as a function of redshift for the model discussed in this paper (solid lines) and assuming Eddington accretion rate at all times, with $\epsilon = 0.15$ (dashed lines). Right panels: MBH accretion rate, in units of the Eddington rate.
Fig. 2.—Same as Fig. 1, but for a massive satellite halo. This halo is a 4 $\sigma$ peak in the density fluctuations field and therefore represents the minimum mass of a halo that is granted a seed MBH in our model.
is thus mild. Note that we have created a whole set of merger trees, and they give qualitatively very similar results.

5. DISCUSSION

In this paper we have envisaged an early stage of supercritical accretion during the global evolution of a SMBH (see also Kauffmann & Haehnelt 2000). Fuel is supplied by a dense gaseous disk forming in halos with \( T_{\text{vir}} > 10^4 \) K, at which hydrogen atomic cooling is effective.

If the disk rotates as a rigid body, the gas infalling on the central MBH has a small transverse velocity. A tiny accretion disk can form within the radius at which radiation is trapped and the MBH can accept most of the infalling mass. Even if this phase lasts only until the universe is enriched by metals, the quick start allows the holes in the most massive halos to reach the high SMBH masses suggested by the SDSS quasars. It is worth noting that supercritical accretion in the fashion described here occurs at very high redshift and stops well before \( z \approx 6 \). We do not expect, therefore, that SDSS quasars are accreting above the Eddington value, consistent with observations (Barth et al. 2003; Wilott et al. 2003). A signature of supercritical accretion is the occurrence of outflows, which we envisage would quench activity. Outflows from these sources could leave their imprint by spreading metals into the IGM early on.

One might be concerned that this model overproduces large SMBHs at low redshift. This is not the case, since only a tiny fraction of halos have \( T_{\text{vir}} \gtrsim 10^4 \) K, when the universe is still metal-free. Assuming that metal pollution starts affecting the disk cooling and fragmentation at \( z \lesssim 10 \), only a fraction (\( \approx 2 \times 10^{-3} \)) of halos at this time are likely to be the outcome of a merger hierarchy that involves a seed MBH at \( z \gtrsim 20 \). So, even if all these halos with mass \( M_h \sim 10^{10} M_\odot \) hosted a MBH with mass \( \sim 10^6 M_\odot \), the density \( \Omega_{\text{MBH}} = (0.002 \Omega_{\text{m}} (M_{\text{MBH}})) / M_h = 10^{-8} \) would still be much lower than the local one. We will discuss this issue in detail along with the possibility that black holes can be displaced from galaxy centers and ejected into the intergalactic medium (IGM) by the "gravitational rock" effect in a subsequent paper.

This model allows a very "economic" reionization in terms of BH seed density. Madau et al. (2004) found that pregalactic quasars powered by SMBHs forming in 3.5 \( \sigma \) peaks reionize the IGM if they accrete at the Eddington rate a mass of order \( 10^9 M_\odot \), and they give qualitatively very similar results. This latter assumption implies that all galaxies in the local universe with total mass \( M_\text{tot} > 5 \times 10^9 M_\odot \) are expected to host a central MBH. If a phase of supercritical accretion is taken into consideration, then the number of ionizing photons per hydrogen atom produced by pregalactic quasars approaches unity at \( z \gtrsim 15 \), even assuming a very low initial density in seeds (e.g., 4 \( \sigma \) peaks), thus relieving the need for a very large number of seeds, which are difficult to reconcile with low-redshift constraints.

The growth of SMBHs that can power SDSS quasars can be explained within a \( \Lambda \)CDM universe assuming a more optimistic view in terms of accretion and merging. Yoo & Miralda-Escudé (2004) showed that \( z \approx 6 \) quasars can be explained assuming continued Eddington-limited accretion onto MBHs forming in halos with \( T_{\text{vir}} > 2000 \) K at \( z \lesssim 40 \). Their model also assumes a much higher influence of BH mergers in increasing the MBH mass: a contribution by itself of the order of \( 10^9 M_\odot \). Their investigation takes into account the negative feedback that dynamical processes at BH mergers ("gravitational rocket"; see also Haiman 2004) impose on the growth of SMBHs. A heavy influence of MBH mergers in building up SMBHs can be probed by their gravitational wave emission by using the planned Laser Interferometer Space Antenna.

As pointed out by Shapiro (2005), explaining the presence of SMBHs at \( z \approx 6 \) is extremely difficult if accretion occurs at the Eddington rate and via a standard thin disk. If alignment between the accretion disk and the MBH spin is efficient on very short timescales, MBHs quickly end up maximally spinning, with a radiative efficiency \( \epsilon \approx 0.4 \) (cf. eq. [1]). Shapiro therefore suggests that accretion occurs via disks in which viscosity is due to magnetohydrodynamic (MHD) turbulence. Gammie et al. (2004) simulations suggest in fact that the maximum spin MBHs can achieve by coupling with MHD disks is smaller than 1, and the corresponding maximum radiative efficiency is \( \epsilon \approx 0.19 \). However, the gain in time available for SMBH growth is less than a factor of 3, thus probably requiring that dynamical negative feedback is not important.

The issues we have discussed in this paper will be clarified by better evidence on miniquasars and on the reionization history at \( z \approx 10 \). Future missions such as the Low Frequency Array (LOFAR) and the Square Kilometre Array (SKA) will directly probe the IGM up to high redshift. Our discussion also provides added motivation for ongoing studies of the flow patterns that occur when gas falls toward a hole at a supercritical rate.

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