

SUPERMASSIVE BLACK HOLE FORMATION AT HIGH REDSHIFTS THROUGH A PRIMORDIAL MAGNETIC FIELD

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ABSTRACT

It has been proposed that primordial gas in early dark matter halos, with virial temperatures $T_{\text{vir}} \gtrsim 10^4$ K, can avoid fragmentation and undergo rapid collapse, possibly resulting in a supermassive black hole. This requires the gas to avoid cooling and to remain at temperatures near $T \sim 10^4$ K. We show that this condition can be satisfied in the presence of a sufficiently strong primordial magnetic field, which heats the collapsing gas via ambipolar diffusion. If the field has a strength above $|B| \gtrsim 3.6$ (comoving) nG, the collapsing gas is kept warm ($T \sim 10^4$ K) until it reaches the critical density $n_{\text{crit}} \approx 10^3 \text{ cm}^{-3}$ at which the roto-vibrational states of H_2 approach local thermodynamic equilibrium. H_2 cooling then remains inefficient and the gas temperature stays near $\sim 10^4$ K, even as it continues to collapse at higher densities. The critical magnetic field strength required to permanently suppress H_2 cooling is somewhat higher than the upper limit of ~ 2 nG from the cosmic microwave background. However, it can be realized in the rare $\gtrsim (2-3)\sigma$ regions of the spatially fluctuating B field; these regions contain a sufficient number of halos to account for $z \approx 6$ quasar black holes.

Key words: black hole physics – cosmology: theory – magnetic fields – molecular processes

Online-only material: color figures

1. INTRODUCTION

The discovery of very bright quasars, with luminosities $\geq 10^{47} \text{ erg s}^{-1}$, at redshift $z \simeq 6$ in the Sloan Digital Sky Survey (SDSS) suggests that some supermassive black holes (SMBHs), as massive as a few $\times 10^9 M_{\odot}$, already existed when the universe was less than 1 Gyr old (see, e.g., Fan 2006 for a review). The presence of these SMBHs presents a puzzle. Metal-free stars, with masses $\sim 100 M_{\odot}$, are expected to form at redshifts as high as $z \gtrsim 25$ (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2008), and leave behind remnant black holes (BHs) with similar masses (Heger et al. 2003). However, the natural timescale, i.e., the Eddington time, for growing these seed BHs by $\gtrsim 7$ orders of magnitude in mass is comparable to the age of the universe (e.g., Haiman & Loeb 2001). This makes it difficult to reach $10^9 M_{\odot}$ without a phase of rapid (super-Eddington) accretion, unless a list of optimistic assumptions are made in hierarchical merger models, in which multiple seed BHs are allowed to grow without interruption, and to combine into a single SMBH (Haiman 2004; Yoo & Miralda-Escudé 2004; Bromley et al. 2004; Shapiro 2005; Volonteri & Rees 2006; Li et al. 2007; Tanaka & Haiman 2009).⁴

An alternative class of explanations involves rapid gas accretion or collapse. In this family of models, primordial gas collapses rapidly into a SMBH as massive as 10^4 – $10^6 M_{\odot}$ (Oh & Haiman 2002; Bromm & Loeb 2003; Koushiappas et al. 2004; Lodato & Natarajan 2006; Spaans & Silk 2006; Begelman et al. 2006; Volonteri et al. 2008; Wise & Abel 2008; Regan & Haehnelt 2009; Shang et al. 2010), possibly by accreting onto a pre-existing smaller seed BH (Volonteri & Rees 2005), or going through the intermediate state of a very massive

star (Bromm & Loeb 2003), a dense stellar cluster (Omukai et al. 2008), or a “quasistar” (Begelman et al. 2008). These so-called direct collapse models involve metal-free gas in relatively massive ($\gtrsim 10^8 M_{\odot}$) dark matter halos at redshift $z \gtrsim 10$, with virial temperatures $T_{\text{vir}} \gtrsim 10^4$ K. The gas that cools and collapses in these halos must avoid fragmentation, shed angular momentum efficiently, and collapse rapidly. These conditions are unlikely to be met, unless the gas remains “warm,” i.e., at temperatures $T_{\text{vir}} \sim 10^4$ K. In particular, in recent numerical simulations, Shang et al. (2010) found that the gas in such halos, when collapsing in isolation, forms H_2 efficiently and cools at temperatures of $T \sim 300$ K. Although no fragmentation was seen, the gas could ultimately fragment on smaller scales that have not yet been resolved (e.g., Turk et al. 2009). More importantly, even if fragmentation was avoided, the cold gas flows inward at low velocities, near the sound speed of ~ 2 – 3 km s^{-1} , with a correspondingly low accretion rate of $\sim 0.01 M_{\odot} \text{ yr}^{-1}$. This results in conditions nearly identical to those in the cores of lower-mass minihalos; extensive ultra-high resolution simulations have concluded that the gas then forms a single $\sim 100 M_{\odot}$ star (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2008) or perhaps a massive binary (Turk et al. 2009), rather than a supermassive star or BH.

H_2 cooling in early galaxies may be avoided when the gas is exposed to an intense UV flux J , either directly photo-dissociating H_2 (in the Lyman–Werner bands near a photon energy of $\sim 12 \text{ eV}$) or photo-dissociating the intermediary H^- (at photon energies $\gtrsim 0.76 \text{ eV}$). Requiring the photo-dissociation timescale, $t_{\text{diss}} \propto J^{-1}$, to be shorter than the H_2 -formation timescale, $t_{\text{form}} \propto \rho^{-1}$, generically yields a critical flux that increases linearly with density, $J^{\text{crit}} \propto \rho$. Since the gas in halos with $T_{\text{vir}} \gtrsim 10^4$ K can cool via atomic Lyman α radiation and loose pressure support, it inevitably collapses further. As a result, in these halos, the critical flux is high, $J^{\text{crit}} \approx 10^2$ – 10^5 (depending on the assumed spectral shape; Shang et al. 2010; see

⁴ On the other hand, we emphasize that the Eddington-limited mass accretion rate needs to be exceeded only by a factor of few. This is certainly plausible theoretically; possibilities include models with a “photon bubble” instability (Begelman 2002) or with photon trapping (e.g., Ohsuga et al. 2005).

also Omukai 2001 and Bromm & Loeb 2003 who found similar, but somewhat higher values), which exceeds the expected level of the cosmic UV background at high redshifts. Only a small subset of all $T_{\text{vir}} \gtrsim 10^4$ K halos, which have unusually close and bright neighbors, may see a sufficiently high flux (Dijkstra et al. 2008). In order to avoid fragmentation, the gas in these halos must also remain essentially free of any metals and dust (Omukai et al. 2008), which may be incompatible with the presence of such nearby luminous galaxies.

In this paper, we consider a different possibility to keep the gas warm, relying on heating by a primordial magnetic field (PMF). Several mechanisms have been proposed to produce a global PMF, with a field strength of order 1 (comoving) nG, during inflation and/or during various phase transitions in the early universe (see, e.g., Widrow 2002, and references therein; but see also Demozzi et al. 2009 for various possible limitations on this scenario). If present, the PMF can be strongly amplified by flux-freezing inside a collapsing primordial gas, affecting H_2 formation and cooling. Sethi et al. (2008; hereafter S08) have shown that 0.2–2 nG fields can significantly enhance the H_2 fraction during the early stages of collapse. Schleicher et al. (2009) found similar results and emphasized that at the high densities ($n \gtrsim 10^8 \text{ cm}^{-3}$) corresponding to later stages of the collapse, magnetic heating from 0.1–1 nG fields results in significantly elevated temperatures.

In this paper, we consider field strengths higher than those in the two previous studies by S08 and Schleicher et al. (2009). Our main result is that, in analogy with the UV-irradiation, there exists a critical magnetic field, which leads to a bifurcation of behaviors. If the PMF has a strength above $B > B_{\text{crit}} \approx 3.5$ nG, then the collapsing gas is kept warm ($T \sim 10^4$ K) until it reaches the critical density $n_{\text{crit}} \approx 10^3 \text{ cm}^{-3}$ at which the rovibrational states of H_2 approach local thermodynamic equilibrium. H_2 cooling then remains inefficient, and the temperature stays near $\sim 10^4$ K, even as the gas collapses further. On the other hand, if $B < B_{\text{crit}}$, H_2 cooling is delayed, but the gas eventually cools down below ~ 1000 K. The critical magnetic field strength we find is a factor of ~ 2 higher than the existing upper limit from the cosmic microwave background (CMB) anisotropies (Yamazaki et al. 2010; see more discussion in Section 5 below). However, it can be realized in the rare $\gtrsim (2-3)\sigma$ regions of the spatially fluctuating B field. As we argue, the abundance of halos located in these high-field regions is sufficient to explain the number of $z \approx 6$ quasars observed in the SDSS.

2. CHEMISTRY AND THERMAL EVOLUTION OF COLLAPSING PRIMORDIAL GAS

The thermal and ionization history of gas collapsing into a high-redshift halo, in the presence of a PMF, is described in detail in S08. The dissipation of the magnetic field owing to ambipolar diffusion and to decaying turbulence in the post recombination era can substantially alter the ionization fraction and temperature of the gas, even beginning before the halo collapse (Sethi & Subramanian 2005, hereafter SS05; Yamazaki et al. 2006; S08; Schleicher et al. 2009).

Here we extend the analysis of S08 up to a higher particle density in the collapsing halo and explore higher magnetic field strengths. In addition, we made the following changes: (1) we track the density evolution of gas in a collapsing halo with the model of Dekel & Birnboim (2006). This change affects the compressional heating rate; the new model allows us to continuously track the density evolution of the shell from the expanding to the collapsing phase, and also enables us to follow

the evolution to higher densities as compared with the top hat collapse model used in S08, (2) we updated the H_2 chemistry network; specifically, we use the recent compilation in Shang et al. (2010; the most significant change is an increase in the collisional H_2 -dissociation rate).

The evolution of the ionization fraction (x_e), magnetic field energy density (E_B), temperature (T), and H_2 molecule fraction (x_{H_2}) are described by the equations

$$\dot{x}_e = [\beta_e(1 - x_e) \exp(-h\nu_\alpha/(k_B T_{\text{cbr}})) - \alpha_e n_b x_e^2] C + \gamma_e n_b (1 - x_e) x_e \quad (1)$$

$$\frac{dE_B}{dt} = \frac{4}{3} \frac{\dot{\rho}}{\rho} - \left(\frac{dE_B}{dt} \right)_{\text{turb}} - \left(\frac{dE_B}{dt} \right)_{\text{ambi}} \quad (2)$$

$$\frac{dT}{dt} = \frac{2}{3} \frac{\dot{n}_b}{n_b} T + k_{iC} x_e (T_{\text{cbr}} - T) + \frac{2}{3 n_b k_B} (L_{\text{heat}} - L_{\text{cool}}), \quad (3)$$

$$\frac{dx_{\text{H}_2}}{dt} = k_m n_b x_e (1 - x_e - 2x_{\text{H}_2}) - k_{\text{des}} n_b x_{\text{H}_2}. \quad (4)$$

The symbols here have their usual meaning; further details and relevant processes are discussed in S08. We list here only the processes that have been added or updated. Most of these processes relate to the formation and destruction of H_2 . The net rate of formation of H_2 through the H^- channel is given by

$$k_m = \frac{k_9 k_{10} x_{\text{HI}} n_b}{k_{10} x_{\text{HI}} n_b + k_\gamma + (k_{13} + k_{21}) x_p n_b + k_{19} x_e n_b + k_{20} x_{\text{HI}} n_b}. \quad (5)$$

The notation of the reaction rates follows the appendix of Shang et al. (2010), except that k_γ is the rate of destruction of H^- by CMB photons, which, in our case, is important before the collapse regime (Equation (8) in S08). The net destruction rate of H_2 , k_{des} , is

$$k_{\text{des}} = k_{15} x_{\text{HI}} + k_{17} x_p + k_{18} x_e. \quad (6)$$

The dominant reaction rates for the range of ionization fractions, densities, and temperatures we obtain in the entire range of our models are: k_9 , k_{10} , k_{20} , k_{18} , and k_{15} .⁵

The cooling processes that dominate L_{cool} in primordial gas in the density and the temperature range we consider are: (1) Compton cooling k_{iC} (Equation (15) in S08), (2) atomic H cooling (Equation (16) in S08), and (3) H_2 molecular cooling (Galli & Palla 1998). The heating rate L_{heat} is given by the magnetic field decay owing to decaying turbulence $(dE_B/dt)_{\text{turb}}$ and ambipolar diffusion $(dE_B/dt)_{\text{ambi}}$. In practice, we find that ambipolar diffusion always dominates in our case; the dissipation rate is given for this process by (Cowling 1956; Shu 1992; SS05)

$$\left(\frac{dE_B}{dt} \right)_{\text{ambi}} = \frac{7 \rho_n f(t)}{48 \pi^2 \gamma \rho_b^2 \rho_i} \int dk_1 \int dk_2 M(k_1) M(k_2) k_1^2 k_2^4. \quad (7)$$

All quantities in Equation (7) are expressed at redshift $z = 0$. The time dependence of the decay rate is given by $f(t) = (1+z)^4$

⁵ We note here that the rate k_{14} , assumed to be zero here, and k_{18} could become more important if we used the rates as given by Schleicher et al. (2009) and Capitelli et al. (2007). If these rates are used, then the critical value of B_0 needed to destroy H_2 in the collapsing halos decreases to ~ 3 nG (cf. Figure 1 below).

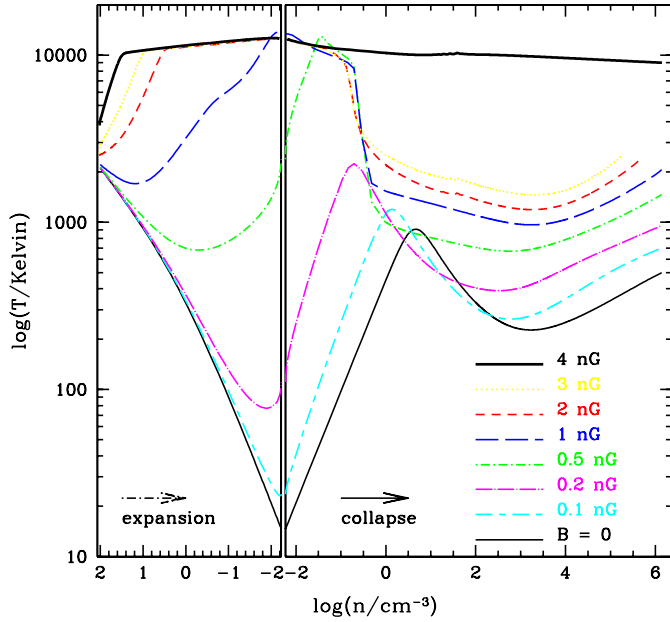


Figure 1. Temperature evolution of a patch of the intergalactic medium is shown as it initially expands and then turns around and collapses to high density. The different curves correspond to different values of the assumed primordial magnetic field, as labeled. The gas evolves from the left to the right on this figure. The left panel shows the expanding phase, starting from an initial density of $\approx 100 \text{ cm}^{-3}$ (corresponding to the mean density at redshift $z \simeq 800$) and ending at the turnaround just below $n = 10^{-2} \text{ cm}^{-3}$. The right panel follows the subsequent temperature evolution in the collapsing phase.

(A color version of this figure is available in the online journal.)

during the pre-collapse stage, and $f(t) \propto \rho^{-4/3}$ during the collapse phase. Here, $M(k) = Ak^n$ is the power spectrum of the tangled magnetic field, with a large- k cutoff at $k = k_{\text{max}} \simeq 235(1 \text{ nG}/B_0) (\text{comoving}) \text{ Mpc}^{-1}$; k_{max} is determined by the effects of damping by radiative viscosity during the pre-recombination era (Jedamzik et al. 1998, Subramanian & Barrow 1998a; see SS05 for further details). B_0 , referred to as the magnetic field strength, is defined as the rms value at $k = 1 \text{ Mpc}^{-1}$. Throughout this paper, we use $n = -2.9$ (for justification and further discussion, see SS05, S08, and references therein). The time evolution of the magnetic field energy is given by Equation (2). We note here that to a very good approximation the magnetic field evolution is given by the flux-frozen condition, because although ambipolar diffusion decreases the field value, in practice, the fractional decrease is negligibly small. This implies a power-law dependence $B \propto \rho^\alpha$ on the gas density with $\alpha = 2/3$ (for more discussion on the magnetic field coupling with the primordial gas, see e.g., Maki & Susa 2004, 2007). In practice, this scaling may be less steep; below we will explore how our results change for different values of α .

Another important scale is the (comoving) magnetic Jeans scale, $k_J \simeq 15(1 \text{ nG}/B_0) \text{ Mpc}^{-1}$ (see, e.g., Equation (6) in SS05, and references therein). This scale, along with the thermal Jeans scale determine the condition that allow a halo to be gravitationally unstable. In our case, the magnetic Jeans scale is larger, and is therefore more restrictive, for $B_0 \geq 1 \text{ nG}$ (S08, Figure 4). PMFs can also induce the formation of first structures in the universe (Wasserman 1978; Kim et al. 1996; Gopal & Sethi 2003; Subramanian & Barrow 1998a; SS05). The total (dark matter + gas) mass of the first structures, determined by

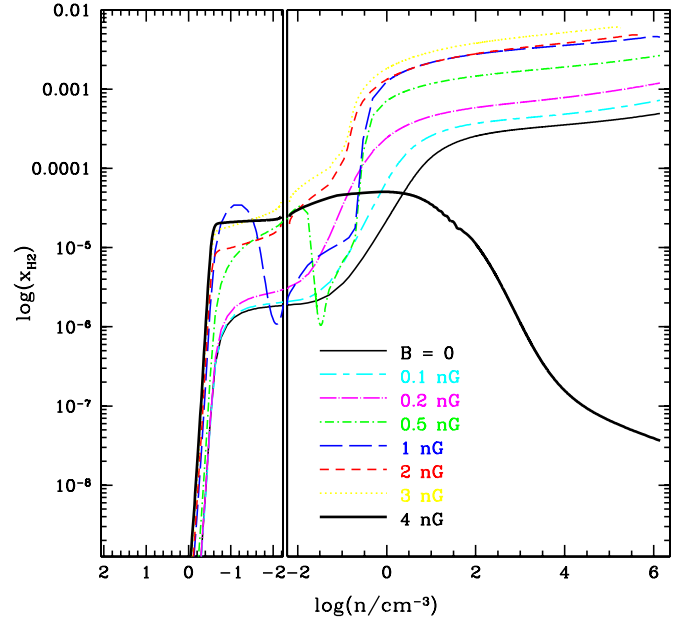


Figure 2. Evolution of the H_2 fraction in the same gas clouds shown in Figure 1. (A color version of this figure is available in the online journal.)

the magnetic Jeans length, is $M \simeq 5 \times 10^8 (B_0/1 \text{ nG})^3 M_\odot$ (e.g., Figure 7 in SS05).

3. RESULTS AND DISCUSSION

We show in Figure 1–3 the evolution of the temperature, the H_2 fraction (defined as the ratio of the H_2 number density to the total hydrogen number density, $n_{\text{H}_2}/n_{\text{H}}$), and the ionized fraction for a single halo from $z \simeq 800$ (corresponding to the initial number density $n \simeq 100 \text{ cm}^{-3}$ on the left of Figures 1–3), down to a maximum density of $n \simeq 10^6 \text{ cm}^{-3}$ in the collapsed halo. Note that the evolution on these figures is monotonically to the right: the x -axis shows the density decreasing to the right (until the turnaround redshift), and then increasing again as the halo collapses.

The figures show the interplay between several physical effects. First, the magnetic field decay directly increases the temperature. This increases the collisional destruction rate of H_2 , but it also increases the electron fraction (owing to more rapid collisional ionization). The larger electron fraction then tends to increase the molecular hydrogen fraction, competing with the effect of the increased collisional H_2 dissociation. The molecular hydrogen cooling rate depends on the temperature directly, and also on the molecular hydrogen fraction. As the temperature reaches $\gtrsim 8000 \text{ K}$, atomic cooling dominates, which again is governed by the ionized fraction.

Figures 1–3 should be viewed together to appreciate the net outcome of these effects on the thermal evolution, for different specific values of the magnetic field. A higher magnetic field strength generally results in more rapid heating, and therefore a higher temperature, at least until halo collapse begins. This, in turn results in higher ionized fractions. However, the thermal evolution is more complicated in the collapsing stage, once molecular hydrogen becomes the dominant coolant.

Prior to turnaround, the gas temperature increases roughly monotonically with the strength of the magnetic field, up to 10^4 K . However, since a higher temperature also means a higher ionized fraction (Figure 2), molecular hydrogen forms at a faster rate. Once the molecular hydrogen becomes the dominant

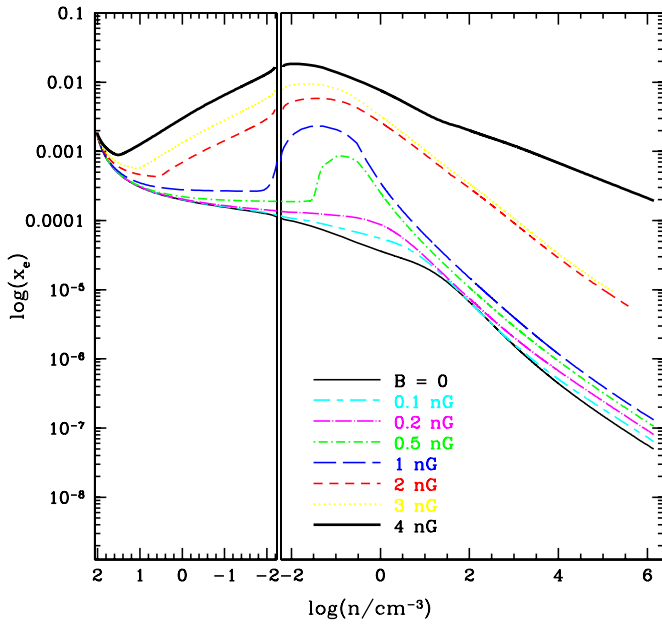


Figure 3. Evolution of the ionized fraction in the same gas clouds shown in Figure 1.

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coolant, at $n \simeq 1 \text{ cm}^{-3}$, the halo with a higher magnetic field can cool below the less magnetized halo.

The most interesting case corresponds to $B_0 = 4 \text{ nG}$ (shown by the thick solid black curves). In this case, the magnetic field dissipation rate is high enough to prevent the formation of molecular hydrogen in the collapsing halo. As seen in Figure 2, the molecular hydrogen starts getting destroyed in the collapsing halo in this case. The direct impact of this predicament on the thermal state of the gas is that the gas fails to cool via H_2 —the cooling remains dominated by the line excitation of the atomic hydrogen.

Our results are in reasonable agreement with the results of Schleicher et al. (2009) for $B_0 \leq 1 \text{ nG}$, the range of magnetic field strengths they considered. We note that the molecular hydrogen fractions, past the turn-around epoch, are lower by more than an order of magnitude compared to the results of S08. This is in line with the observation of Schleicher et al. (2009) that S08 had underestimated the destruction rate of H_2 . The thermal evolution of the gas in the zero magnetic field case ($B_0 \leq 10^{-3} \text{ nG}$ in the figures) also agrees with the results of the one-zone models studied by Omukai (2001).

The most important new result of our analysis is the thermal state of the gas owing to the destruction of the H_2 in the collapsing halo for $B \geq 4 \text{ nG}$. Omukai (2001) analyzed the destruction of H_2 in the collapsing halo in the presence of background UV flux. That analysis suggested that the H_2 formation can be prevented if the halo could be kept at a temperature $\simeq 10^4 \text{ K}$ up to a critical density $n \simeq 2000 \text{ cm}^{-3}$. At higher densities, collisions with hydrogen atoms is more effective in destroying H_2 from higher vibration levels, because the relative occupation probability of vibration states of the H_2 molecular approach thermal equilibrium at these densities (the rate k_{15} in the discussion in Section 2; Martin et al. 1996). In the analysis of Omukai (2001), the reaction rates are also affected by the presence of a background UV field. Our analysis shows that the same result (i.e., lack of any H_2 cooling) can also be obtained by the dissipation of tangled magnetic fields.

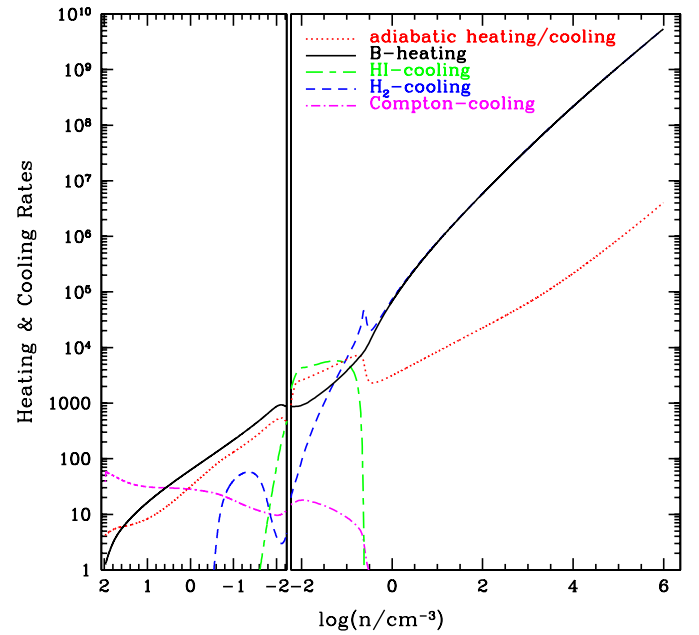


Figure 4. Heating and cooling rates are shown for various processes as labeled, for $B = 1 \text{ nG}$. The rates are in the units $dt/dz = H_0^{-1} \Omega_m^{-1/2} (1+z)^{-5/2}$.

(A color version of this figure is available in the online journal.)

In Figures 4 and 5, we show the heating and cooling rates during the collapse regime, for two values of the magnetic field, 1 and 4 nG, respectively. Apart from a brief initial period, when atomic cooling roughly balances adiabatic heating, the dominant heating and cooling processes in the $B_0 = 1 \text{ nG}$ case, in the collapse stage, are magnetic heating and H_2 cooling, respectively. H_2 cooling quickly becomes more important than magnetic heating, resulting in a rapid temperature drop at densities near $n \approx 0.1\text{--}0.2 \text{ cm}^{-3}$ (see Figure 1). As the halo collapses further, the gas begins to recombine and the ionized fraction decreases (see Figure 3), the magnetic field dissipation rate due to ambipolar diffusion increases as $\propto \rho_b^{4/3}/\rho_i$, while the H_2 cooling rate grows as $x_{\text{H}_2} \rho_b^2$. As a result, the magnetic heating catches up with H_2 cooling, resulting in a nearly constant temperature (see Figure 1)—however, this occurs only after the collapse has proceeded beyond the critical density $n \approx 10^3 \text{ cm}^{-3}$. Atomic cooling or adiabatic heating do not play an important role in the thermal evolution for this strength of the magnetic field.

In contrast, for $B_0 \simeq 4 \text{ nG}$, as shown in Figure 5, the magnetic heating roughly balances atomic H I cooling during the collapse stage, resulting in a nearly constant temperature $T \approx 10^4 \text{ K}$ throughout the entire evolution of the contracting gas. The magnetic heating gives rise to a higher ionization fraction (Figure 3), and therefore aids the formation of H_2 . However, the high temperature of the gas causes the H_2 to get destroyed (Figure 2; this effect is also seen for $B_0 \simeq 1 \text{ nG}$ just before the onset of the halo collapse). The net result for this high value of the magnetic field is that H_2 cannot form fast enough to ever become an important coolant. The halo remains at a temperature $\simeq 10^4 \text{ K}$ up to the critical density; as a result, the H_2 fraction is strongly diminished for the subsequent evolution of the halo. By experimenting with several intermediate values of the magnetic field, we have found that this clear-cut bifurcation in the thermal evolution occurs at a critical magnetic field strength of $B_{\text{crit}} = 3.6 \text{ nG}$.

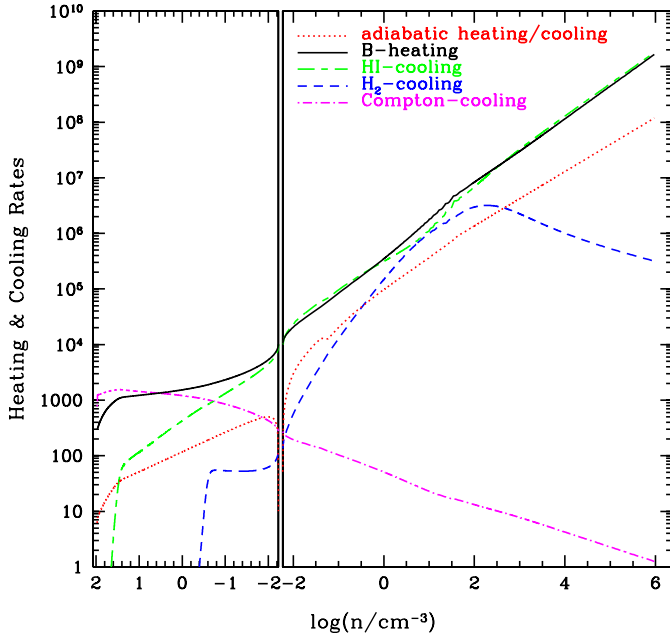


Figure 5. Same as Figure 4, but for $B = 4$ nG.

(A color version of this figure is available in the online journal.)

As noted in Section 2 above, we adopted the model of Dekel & Birnboim (2006) to track the density evolution of the collapsing halo. However, we have checked the robustness of our results against a wide range of collapse histories. Specifically, after the turnaround stage, we artificially multiplied the rate of increase in the density, relative to the Dekel & Birnboim model, by a factor of 0.1 or 1. We have found that the weaker/stronger adiabatic heating delayed/advanced the onset of the catastrophic H_2 cooling (e.g., as seen at $n \approx 10^{-0.8} \text{ cm}^{-3}$ in Figure 1) to higher/lower densities, but the other qualitative features of our results were essentially unchanged. In particular, a bifurcation of behaviors was still found, with a critical density of $B_{\text{crit}} = 3.6$ nG.

Another uncertainty concerns our assumption of flux freezing. Schleicher et al. (2009) note the possibility of the breakdown of this approximation in a collapsing halo. If the field is not sufficiently tangled, collapse can occur with little dissipation in the direction of the field lines; the magnetic field might grow less rapidly than our adopted $\rho^{2/3}$. Our computations in the range $\alpha \simeq 0.55\text{--}0.6$ show that the critical magnetic field required to prevent the halo from cooling increases to $B_0 \simeq 5\text{--}7$ nG. This also leads to the interesting possibility that the average $B_0 \simeq$ a few nG, required to form SMBHs, might be detectable by the future CMB experiments (e.g., Yamazaki et al. 2010) and the $4\sigma\text{--}5\sigma$ fluctuations of the field might leave their trace in the formation of SMBH. We hope to explore this possibility in the future.

At present, the best upper limits on the PMF are in the range 2–3 nG from CMB temperature and polarization anisotropies and from early structure formation (Subramanian & Barrow 1998b, 2002; Durrer et al. 2000; Seshadri & Subramanian 2001; Mack et al. 2002; Lewis 2004; Gopal & Sethi 2005; Kahnishvili & Ratra 2005; Giovannini & Kunze 2008; Yamazaki et al. 2008; Finelli et al. 2008). Recently, Yamazaki et al. (2010) obtained bounds on the strength and spectral index of the magnetic field power spectrum: $B_0 \leq 2$ nG and $n \leq -1.4$. Our results cannot be compared directly to their analysis as we use only a single

value of spectral index ($n = -2.9$) here. The upper limits from CMB on B_0 for this value of n are considerably weaker (Lewis 2004). We note that the effect, we discuss here, might be pronounced for a larger n for a given B_0 . More detailed analysis would be required to directly compare our results with Yamazaki et al. (2010). Our analysis suggests that for $B_0 \geq 4$ nG, the fragmentation of collapsing halos could be prevented, and therefore this could be considered an independent upper bound on the value of B_0 .

4. THE MASS OF THE CENTRAL OBJECT

The mass of the central object that forms in a collapsing protogalaxy can be approximated as follows: there exists a radius at which the mass accretion timescale t_{acc} equals the Kelvin–Helmholtz timescale t_{KH} for a protostar, with the protostellar mass equal to the gas mass enclosed within this radius. For metal-free gas, t_{KH} is approximately 10^5 years, with only a mild dependence on the protostellar mass (Schaerer 2002). The expected mass of the central object then scales approximately as $M \propto t_{\text{acc}}^{-1} \propto c_s^3 \propto T^{3/2}$ (see, e.g., Shang et al. 2010 for the last scalings with the sound speed and gas temperature). This implies that a stellar mass of $\sim 200 M_\odot$, expected for $T = 300$ K, can increase to $\approx 4 \times 10^4 M_\odot$ when H_2 cooling is inefficient and $T \approx 10^4$ K (in their three-dimensional simulations, Shang et al. find a somewhat still steeper scaling). Our proposal here is that a small fraction of halos at $z = 10\text{--}15$, which contain pristine, metal-free gas when they collapse, and which reside in regions of an unusually high initial seed magnetic field, may produce a SMBH with a mass of up to $\sim 10^4\text{--}10^5 M_\odot$. The time available between $z = 6$ and $z = 10\text{--}15$ is $\approx (4\text{--}6) \times 10^8$ yr, allowing for a further growth in mass by a factor of $\approx (2 \times 10^4)\text{--}(3 \times 10^6)$ at the e -folding time of 4×10^7 yr, (corresponding to Eddington-limited growth at the radiative efficiency of 10%). Hence, the $10^{4\text{--}5} M_\odot$ BHs, produced through the PMF, can indeed grow into the $\gtrsim 10^9 M_\odot$ SMBHs by $z = 6$.

The smallest total (dark matter + gas) mass that can collapse for $B_0 \simeq 4$ nG is $M \simeq 3 \times 10^{10} M_\odot$ (as mentioned in Section 3 above). These halos could form either as a result of gravitational instability in the standard Λ CDM model, or via PMF-induced density perturbations (for details on the latter scenario, see e.g., SB08). The abundance of halos in the PMF-induced structure formation case drops very sharply for masses above the Jeans mass (e.g., SS05), and for simplicity, we conservatively drop this contribution in our analysis. In the usual Λ CDM model, using the fitting formula for the halo mass function from Jenkins et al. (2001), and the current best cosmological parameters from Komatsu et al. (2009), we find that the abundance of all $M > 3 \times 10^{10} M_\odot$ halos at $z = 10$ is $\approx 5 \times 10^{-5} (\text{comoving}) \text{ Mpc}^{-3}$. At somewhat higher redshift of $z = 15$, the abundance of halos above the same mass drops sharply to $\approx 3 \times 10^{-8} \text{ Mpc}^{-3}$.

The space density of $\gtrsim 10^9 M_\odot$ SMBHs, inferred from the observed abundance of bright $z \approx 6$ quasars, is $\sim \epsilon_Q^{-1}$ (comoving) Gpc^{-3} . Here, ϵ_Q denotes the duty cycle, defined as the fraction of the Hubble time that $z = 6$ SMBHs are observable as luminous quasars. Assuming a quasar lifetime of ~ 50 Myr (e.g., Martini 2004), we have $\epsilon_Q \sim 0.05$, and the space density of $z = 6$ SMBHs is $\sim 20 \text{ Gpc}^{-3}$. Therefore, at redshift $z = 10$, a fraction as low as $f \sim (20 \text{ Gpc}^{-3}) / (5 \times 10^{-5} \text{ Mpc}^{-3}) = 3 \times 10^{-3}$ of the whole population of $M \gtrsim 3 \times 10^{10} M_\odot$ halos is sufficient to account for the presence of these rare $z \approx 6$ SMBHs. Such a small fraction would correspond to $\sim 2.8\sigma$ upward fluctuations of a Gaussian random PMF. Because of the strong reduction

of the relatively high-mass halos at higher redshift, essentially every $M \gtrsim 3 \times 10^{10} M_{\odot}$ halo would have to host SMBHs at $z \approx 15$, to match the comoving abundance of $z = 6$ quasar BHs. $z \approx 15$ is therefore the earliest epoch for forming the heavy SMBH seeds as envisioned here. As long as the PMF amplitude is $B \gtrsim 1.2$ nG, the critical flux we find, $B \approx 3.6$ nG, would be reached by the $\sim 3\sigma$ upward fluctuations. We note that since our scenario, which is able to explain the rare SDSS quasar black holes, relies on these rare upward field fluctuations, and on the relatively massive, rare halos at high redshift. It would therefore not be able to account for the much more numerous quasar BHs at somewhat lower masses.

As mentioned above, our results are analogous to earlier work, proposing that a UV flux keeps the gas hot and results in SMBH formation. However, it is worth emphasizing two important differences in these two scenarios. First, as Figure 1 shows, even though there is a clear critical B field value, dividing the thermal evolution into two different regimes, even for B field strengths below this value, the minimum temperature reached by the gas is significantly elevated. Hence, sub-critical magnetic fields can still significantly increase the mass of the central object. Second, the gas in the halos must remain essentially free of any metals and dust, in order to avoid fragmentation. This may well be impossible to reconcile with the large required flux, which has to arise from a close neighbor galaxy, in the UV-irradiation scenario. On the other hand, in the magnetic-heating case, there is a priori reason why a region where the PMF has an upward fluctuation would be more likely to be metal enriched. In fact, quite the contrary: the large magnetic Jeans mass will suppress the collapse of gas into lower-mass halos at high redshift, naturally excluding any prior metal pollution farther up in the merger tree of the halo in which the putative SMBH forms.

Finally, we note that in order for the gas to collect at the center of the DM halo, angular momentum needs to be efficiently transported outward. The mechanism of this transport is unclear at present—suggestions have ranged from using unusually low-angular momentum material or transporting angular momentum by global instabilities, such as the “bars within bars” mechanism (see, e.g., the recent review by Volonteri 2010).

5. CONCLUSIONS

We found a plausible novel mechanism to form high-redshift SMBHs by direct gas collapse in early dark matter halos, aided by heating from the dissipation of a PMF. The model avoids many of the assumptions required in earlier models (such as an extremely high UV flux and the absence of H_2 and of other molecules and metals), but it does require a large PMF and relies on metal-free primordial gas. We expect that, in general, *any other* heating mechanism, which can compete with atomic H I cooling in the collapsing halo, down to a density of $n \sim 10^3 \text{ cm}^{-3}$, would produce the same effect as the B field utilized here.

Interestingly, our model requires a magnetic field strength that is close to the existing observational upper limits. We therefore expect that the values $B_0 \simeq \text{a few} \times 10^{-9} \text{ G}$, required to form SMBHs, could be detectable by the future CMB experiments. The upward fluctuations of such a strong PMF might also leave their trace on cosmic structure formation: because of the high-magnetic Jeans mass in these regions, the formation of dwarf–galaxy-sized halos, with masses below $M \simeq \text{a few} \times 10^{10} M_{\odot}$, will be prevented. We expect that this can lead to further constraints on our SMBH-formation scenario,

analogous to constraints on warm dark matter models (which produce a similar suppression of small-scale structures; Barkana et al. 2001).

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