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FORMATION OF MASSIVE PRIMORDIAL STARS IN A REIONIZED GAS

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ABSTRACT

We use cosmological hydrodynamic simulations with unprecedented resolution to study the formation of primordial stars in an ionized gas at high redshifts. Our approach includes all the relevant atomic and molecular physics to follow the thermal evolution of a prestellar gas cloud to very high densities of $\sim 10^{18}\text{cm}^{-3}$. We locate a star-forming gas cloud within a reionized region in our cosmological simulation. The gas cloud cools by HD line cooling down to a few tens Kelvin, which is lower than possible by H₂ cooling only. Owing to the low temperature, the first run-away collapse is triggered when the gas cloud's mass is $\sim 40M_{\odot}$. We show that the cloud core remains stable against chemo-thermal instability and also against gravitational deformation throughout its evolution. Consequently, a single proto-stellar seed is formed, which accretes the surrounding hot gas at the rate $\dot{M} \gtrsim 10^{-3}M_{\odot}/\text{yr}$. We carry out proto-stellar evolution calculations using the inferred accretion rate. The resulting mass of the star when it reaches the zero-age main sequence is $M_{\text{ZAMS}} \sim 40M_{\odot}$. We argue that, since the obtained M_{ZAMS} is as large as the mass of the collapsing parent cloud, the final stellar mass should be close to this value. Such massive, rather than exceptionally massive, primordial stars are expected to cause early chemical enrichment of the Universe by exploding as black hole-forming super/hypernovae, and may also be progenitors of high redshift γ -ray bursts. The elemental abundance patterns of recently discovered hyper metal-poor stars suggest that they might have been born from the interstellar medium that was metal-enriched by supernovae of these massive primordial stars.

Subject headings: stars:formation

1. INTRODUCTION

Recent observations of high redshift galaxies (Kashikawa et al. 2006), quasars (Fan et al. 2006), and gamma-ray bursts (Totani et al. 2006) provide rich information on the ionization structure of the intergalactic medium (IGM) at $z \sim 6 - 7$. The observations indicate that a large fraction of the IGM was already ionized when the Universe was less than one billion years old, but suggest also that a substantial fraction was still neutral. Combined with polarization measurements of the cosmic microwave background (CMB) radiation by the WMAP satellite (Spergel et al. 2007; Page et al. 2007), it is inferred that cosmic reionization was extended and lasted for several hundred million years (see, e.g. McQuinn et al. 2006).

The standard cosmological model based on cold dark matter and dark energy predicts that the first stars form in low-mass halos at high redshifts (Couchman & Rees 1986; Yoshida et al. 2003). Reionization subsequently proceeds in a patchy manner, whereby HII regions develop around individual sources and eventually percolate (Gnedin & Ostriker 1997; Miralda-Escude et al. 2000; Sokasian et al. 2003, 2004; Furlanetto et al. 2004, 2006; Zahn et al. 2007). Since the sources, massive stars, are expected to emit ionizing photons for only a few to ten million years, the reionized IGM will start recombining and cooling when the stars die. We study the formation

of primordial stars in such reionized regions.

While there have been a number of numerical studies of the formation of primordial stars in a neutral gas (Omukai & Nishi 1998; Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006, hereafter Y06), the evolution of a primordial gas cloud during/after reionization has not been examined in detail. It is well-known that the thermal evolution of a recombining gas differs significantly from initially neutral primordial gas (e.g., Nagakura & Omukai 2005; Johnson & Bromm 2006). Moreover, it has been suggested that cooling by HD molecules leads to the formation of low-mass, possibly near solar-mass, primordial stars (Uehara & Inutsuka 2000; Nakamura & Umemura 2002). It is important to determine whether or not such small mass gas clumps are formed in a reionized IGM at high redshifts.

Earlier (Yoshida et al. 2007; hereafter Y07), we used a large cosmological simulation to study the evolution of early relic HII regions until second-generation gas clouds are form. In this *Letter*, we further explore the evolution of these prestellar gas clouds. We investigate in detail the structure of such gas clouds and examine whether they become chemo-thermally unstable to fragmentation into smaller clumps. We then compute the gas mass accretion rate and use it as an input to a proto-stellar calculation.

2. PHYSICAL CONDITIONS AROUND THE PROTOSTAR

We use the simulation outputs of Y07. Briefly, they carried out radiation-hydrodynamics calculations of the formation and evolution of early HII /HeIII regions around the first stars. They showed that the ionized gas cools and re-collapses in a growing dark matter halo within a hundred million years, to form so-called second generation star(s). They also examined the impact of an

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external far-UV background radiation field.

FIG. 1.— Top: Radial temperature profile as a function of enclosed gas mass. We explain the characteristic features as follows: (A) Efficient molecular hydrogen production in the recombining gas enables rapid cooling to a few hundred Kelvin; (B) HD molecules are formed and the gas cools further below 100 K; (C) heating by the CMB floors the gas temperature, and the cloud starts to contract gravitationally; (D) three-body reactions kick in and the core becomes fully molecular; (E) the core is already optically thick to H_2 lines but cools by collision-induced emission; (F) the core becomes optically thick to continuum. Bottom: Instantaneous gas mass accretion rate as a function of enclosed gas mass. The solid circle indicates where the enclosed gas mass exceeds the locally estimated Bonnor-Ebert mass. The dot-dashed line is the accretion rate around the first generation star in the simulation of Y06.

We use the output of the fiducial run of Y07, in which a second generation star forms at $z = 16$ in a halo with mass $\sim 10^7 M_\odot$, whose virial temperature is $\sim 10^4$ K. In addition to the atomic and molecular physics described in Y07, we have also implemented computation of local optical depth to continuum radiation using the Planck opacity table of Lenzuni et al. (1991). The continuum opacity is used to evaluate the net cooling rate by collision-induced emission.

Figure 1 shows the radial profiles of gas temperature and gas mass accretion rate in the star-forming gas cloud. We use the final output of the simulation when the central density is 10^{18} cm^{-3} . The density profile at this time is close to a single power-law of $\rho \propto r^{-2.3}$ over nearly 20 decades in density. The characteristic features of the temperature profile can be understood by appealing to various atomic and molecular processes, as denoted in the figure and explained in the caption. Radiative cooling of a molecular gas is halted by effective heating from CMB photons that have a temperature of $T_{\text{CMB}} = 2.728(1+z)$

at redshift z . The minimum temperature of the molecular gas cloud is limited to this value. We calculate the Bonnor-Ebert mass using the density, temperature and molecular fraction profiles; the cloud is dynamically unstable at a mass scale of $\sim 40 M_\odot$. This is the mass for the first run-away collapse of the star-forming cloud. Note that it is essentially the Jeans mass at the temperature minimum.

The gas mass accretion rate shown in the bottom panel of Figure 1 reflects the temperature structure. Note that, overall, the accretion rate is much smaller than that for the first star simulated by Y06 (dot-dashed line). This can be understood by the fact that the mass accretion rate is roughly $\dot{M} \propto c_s^3/G$, where c_s is the sound speed. HD cooling enables the gas cloud to cool to lower temperatures than is possible by H_2 cooling, and hence the accretion rate within the cloud is smaller.

We do not consider cooling by heavy elements in our simulation, assuming that the gas is not chemically enriched. However, the overall thermal evolution will not differ much from that shown in Figure 1, unless a significant amount of dust is present, because cooling by metal lines is efficient only at low densities. HD cooling alone can bring the gas to T_{CMB} , and the gas temperature cannot fall below this even with atomic metal cooling.

FIG. 2.— Growth parameter $Q = t_{\text{dyn}}/t_g$ versus gas density. We use an output when the central density is 10^{12} cm^{-3} and show the distribution of the gas elements in this plane as grey-contours. All of the gas elements are in the stable region $Q < 1$, where the dynamical time is shorter than the growth time of the perturbations.

3. THERMAL INSTABILITY AND FRAGMENTATION

An important question is whether or not the gas cloud becomes thermally unstable owing to efficient molecule production and cooling which operates at densities $n > 10^8 \text{ cm}^{-3}$. We calculate the growth rate of isobaric perturbations following Omukai & Yoshii (2003). We solve the dispersion relation for perturbations in temperature, density, and molecular fraction, $(\delta T, \delta \rho, \delta f) \propto \exp(\omega t)$, under isobaric conditions. We define the growth param-

eter as the ratio of the characteristic growth time scale t_g of the perturbations to the dynamical time t_{dyn} :

$$Q = \omega t_{\text{dyn}} = \frac{t_{\text{dyn}}}{t_g}. \quad (1)$$

Figure 2 shows Q as a function of local gas density. Clearly, all the gas elements are in the stable region $Q < 1$, where the dynamical time is shorter than the growth time scale. We thus conclude that the chemothermal instability does not operate in this regime. Note that, because of the harder effective equation of state than the initially neutral primordial gas in the relevant density and temperature range, gravitational deformation is less effective for the gas cloud. We followed Omukai et al. (2005) and checked that the cloud is also stable against gravitational deformation. Our simulation indeed shows that the cloud core remains stable against fragmentation, as expected.

4. PROTO-STELLAR EVOLUTION

We carry out proto-stellar evolution calculations to study the growth of the protostar in detail. We employ the scheme described by Stahler, Shu, & Taam (1980) as modified by Stahler et al. (1986) and Omukai & Palla (2003). We use the mass accretion rate shown in Figure 1 as input to the protostellar evolution code, assuming that the gas is accreted in an approximately spherical manner. As is shown in Figure 1, the central part is accreting the surrounding gas at a rate $\sim 10^{-3} M_\odot/\text{yr}$ and thus a star with mass $\sim 10 M_\odot$ will form within 10^4 years. However, the final stellar mass is determined by processes such as radiative feedback from the protostar. We treat the evolution of a protostar as a sequence of a growing hydrostatic core with an accreting envelope. The ordinary stellar structure equations are applied to the hydrostatic core. The structure of the accreting envelope is calculated under the assumption that the flow is steady for a given mass accretion rate.

Figure 3 shows the resulting evolution of the protostar. After a transient phase and an adiabatic growth phase at $M_* < 10 M_\odot$, the protostar enters the Kelvin-Helmholtz phase and contracts by radiating its thermal energy. When the central temperature reaches 10^8K , hydrogen burning by the CNO cycle begins with a slight amount of carbon synthesized by helium burning. This phase is marked by a solid circle in the figure. The energy generation by hydrogen burning halts contraction when the mass is $35 M_\odot$ and its radius is ~ 2.8 solar radii. Soon after, the star reaches the zero-age main sequence (ZAMS). The protostar relaxes to a ZAMS star within about 10^5 years from the birth of the protostellar seed. Accretion is not halted by radiation from the protostar to the end of our calculation.

It is important to point out that the mass of the parent cloud from which the star formed is $M_{\text{cloud}} \sim 40 M_\odot$. The final stellar mass is likely limited by the mass of the gravitationally unstable parent cloud. We thus argue that primordial stars formed from an ionized gas are massive, with a characteristic mass of several tens of solar masses, allowing overall uncertainties in the accretion physics and also the dependence of the minimum gas temperature on redshift (see next section). They are smaller than the first stars formed from a neutral gas, but

are not low-mass objects as suggested by earlier studies.

FIG. 3.— Evolution of the proto-stellar radius and the mass (solid line). The solid circle marks the time when efficient hydrogen burning begins. The dotted line shows the mass (and radius) growth which is calculated under the assumption that a larger amount of gas than the parent cloud can be accreted. For reference we also show the result from Y06 for a first generation star that forms in a neutral gas cloud.

5. DISCUSSION

Recent theoretical studies of the formation of the first stars indicate that they were likely rather massive, with a characteristic mass greater than a hundred solar masses (Abel et al. 2002; Omukai & Palla 2003; Y06; Gao et al. 2007). We have explicitly shown, for the first time, that primordial stars formed from a reionized gas have a smaller mass ($\sim 40 M_\odot$) than these first stars. The low temperature of the gas cloud owes to HD cooling, and the correspondingly small collapse mass and low accretion rate lead to the smaller final stellar mass. We note that various proto-stellar feedback effects such as mass outflow, which we do not take into account, could briefly shut off accretion (Machida et al. 2006), and then the final mass would be even *lower*.

Intriguingly, the elemental abundance patterns of hyper metal-poor stars discovered by Christlieb et al. (2002) and Frebel et al. (2005) indicate that early metal-enrichment was caused by supernova explosions with a progenitor mass of $\sim 25 M_\odot$ (Umeda & Nomoto 2003; Iwamoto et al. 2005). Massive primordial stars formed in reionized regions, such as those studied here, may be responsible for supernova explosions in the early Universe (Tumlinson et al. 2004; Greif & Bromm 2006).

We have shown that the minimum temperature of the gas cloud is limited by the CMB, and thus the thermal evolution is slightly different if the gas cloud collapses late at a lower redshift. We ran simulations varying the collapse redshift (in practice, the CMB temperature) to examine this effect. The simulations show that the mass scale for the first runaway collapse becomes smaller, down to $M_{\text{cloud}} \sim 10 M_\odot$, owing to the decrease in the minimum gas temperature. While this might seem to

suggest a lower characteristic mass for primordial stars formed at lower redshifts, the effect of photo-dissociating radiation in the far-ultra violet (FUV) needs to be considered carefully in this context, because a very weak FUV radiation field is enough to destroy the H_2 and HD molecules in a primordial gas cloud.

We carried out one-zone calculations of a collapsing primordial gas as in Nagakura & Omukai (2005), but with photodissociation of H_2 , HD, and H^- . The temperature evolution for primordial clouds with different FUV strength is shown in Figure 4. We identify a critical flux of $G_0 = 10^{-2}$ in terms of the Habing parameter (Habing 1968), or equivalently $3 \times 10^{-22} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{str}^{-1}$, above which the formation of (and hence cooling by) H_2 molecules is limited by photo-dissociation, and the gas cloud starts contracting gravitationally before its temperature is lowered to < 100 K by HD cooling. The critical intensity is likely to be reached before the completion of global reionization (e.g., Haiman et al. 1997; Yoshida et al. 2003). It is also expected that FUV radiation from a nearby source exceeds this limit. For example, a massive star with a few tens solar-masses emits photons in the Lyman-Werner bands at a rate of $L_{\text{LW}} \sim 10^{24} \text{erg s}^{-1} \text{Hz}^{-1}$. For a typical physical condition in an early relic HII region (see Y07), HD formation will be suppressed if another massive star is located within a radius of $r_{\text{diss.}} = 80 (n_{H_2}/10^{-3} \text{cm}^{-3})^{-3/11} \text{pc}$ even if we account for gas self-shielding. The number of stars formed by HD cooling is likely limited within a relic HII region, and thus the formation efficiency of these stars appears to be low.

It is also worth discussing the effect of metallicity. Atomic metal line cooling at low densities will not significantly affect the evolution of the collapsing gas clouds, because T_{CMB} determines the minimum gas temperature even in the presence of metal cooling. On the other hand, the existence of dust may play an important role in significantly changing the characteristic mass of collapsing gas clouds. Schneider et al. (2006) show that thermal dust emission in such clouds can result in low temperatures at high gas densities, lowering the collapse mass scale to below one solar mass. Therefore our conclusion remains robust unless a significant amount of dust is present in the gas clouds.

Finally, there is an interesting possibility of observing the death of massive primordial stars as gamma-ray bursts. Tominaga et al. (2007) recently suggested that primordial stars with mass $\sim 40 M_\odot$ trigger long-duration gamma-ray bursts and faint supernovae, such as those observed in the nearby Universe (e.g., Fynbo et al. 2006). Future observations of bright gamma-ray bursts and the absorption lines in their radiation spectra will provide invaluable information on the interstellar medium at high redshifts (Inoue, Omukai, & Ciardi 2005).

FIG. 4.— Temperature evolution of an initially ionized primordial gas with FUV radiation. The FUV radiation flux is parametrized by the Habing parameter G_0 , which corresponds to the mean intensity of $\sim 3 \times 10^{-20} G_0 \text{erg s}^{-1} \text{cm}^{-2} \text{str}^{-1} \text{Hz}^{-1}$ in the LW wavelength range. The initial number density, temperature and ionization degree are 1cm^{-3} , 7000K, and 0.1, respectively.

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