THREE MODES OF METAL-ENRICHED STAR FORMATION IN THE EARLY UNIVERSE

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ABSTRACT

Simulations of the formation of Population III (Pop III) stars suggest that they were much more massive than the Pop II and Pop I stars observed today. This is due to the collapse dynamics of metal-free gas, which is regulated by the radiative cooling of molecular hydrogen. We study how the collapse of gas clouds is altered by the addition of metals to the star-forming environment by performing a series of simulations of pre-enriched star formation at various metallicities. To make a clean comparison with metal-free star formation, we use initial conditions identical to a Pop III star formation simulation, with low ionization and no external radiation other than the cosmic microwave background (CMB). For metallicities below the critical metallicity, Zcr, collapse proceeds similar to the metal-free case, and only massive objects form. For metallicities well above Zcr, efficient cooling rapidly lowers the gas temperature to the temperature of the CMB. The gas is unable to radiatively cool below the CMB temperature, and becomes thermally stable. For high metallicities, Z ≳ 10^{−2.5} Z⊙, this occurs early in the evolution of the gas cloud, when the density is still relatively low. The resulting cloud cores show little or no fragmentation, and would most likely form massive stars. If the metallicity is not vastly above Zcr, the cloud cools efficiently but does not reach the CMB temperature, and fragmentation into multiple objects occurs. We conclude that there were three distinct modes of star formation at high redshift (z ≳ 4): a “primordial” mode, producing massive stars (10s to 100s of M⊙) at very low metallicities (Z ≲ 10^{−4} Z⊙); a CMB-regulated mode, producing moderate mass (10s of M⊙) stars at high metallicities (Z ≳ 10^{−2.5} Z⊙ at redshift z ≳ 15–20); and a low-mass (a few M⊙) mode existing between these two metallicities. As the universe ages and the CMB temperature decreases, the range of the low-mass mode extends to higher metallicities, eventually becoming the only mode of star formation.

Key words: early universe — stars: formation

Online-only material: color figures

1. INTRODUCTION

Understanding the nature of the first stars in the universe is, in principle, a very straightforward problem to solve. The initial conditions are defined by well constrained cosmological parameters (e.g., Spergel et al. 2007; Komatsu et al. 2008) and accepted calculations of big bang nucleosynthesis (e.g., Smith et al. 1993). The relative simplicity of the chemistry of primordial gas (Abel et al. 1997; Galli & Palla 1998), along with powerful numerical methods, has made it possible to accurately characterize the formation process of primordial stars from the assembly of their dark matter halos through the end of the optically thin regime of the collapsing protostar (Abel et al. 2002; Bromm et al. 2002; Bromm & Loeb 2004; Yoshida et al. 2006; O’Shea & Norman 2007; Gao et al. 2007). Results from theory and numerical simulations suggest that the first stars were tens to hundreds of M⊙ (Abel et al. 2002; Omukai & Palla 2003; Tan & McKee 2004; Yoshida et al. 2006; O’Shea & Norman 2007). A direct calculation, however, involves simulating the complex processes of accretion and radiative feedback, a capability currently just beyond the state of the art. In contrast, the challenge of understanding the second generation of stars is significantly more complex. The initial conditions of the first stars essentially depend only on the principles of cold dark matter cosmology and the properties of molecular hydrogen, but the initial conditions of the second stars require a complete solution to the formation and evolution of their predecessors as well as host of additional chemistry and physical processes. The chemical composition and physical conditions of second-generation star-forming environments strongly depend on the exact masses of the first stars (Heger & Woosley 2002; Maeder et al. 2005; Nomoto et al. 2006; Rockefeller et al. 2006) and the mechanics of their supernovae (SNe; Kitayama & Yoshida 2005; Greif et al. 2007).

At the heart of the problem regarding forming the second stars is understanding how the star formation process is altered by the introduction of the first metals in the universe, created in the explosions of the first stars. The chemical composition of a gas determines the efficiency with which it can radiatively cool. Cold, metal-free gas (T < 10^4 K) cools solely through ro-vibrational lines of H2, whose lowest-lying transition has an energy-equivalent temperature of ~ 512 K, resulting in a minimum achievable temperature of ~ 200 K. The energy levels of H2 become thermalized at rather low densities, n ~ 10^4 to 10^5 cm^{−3}, where n is the number density, above which the cooling rate is only proportional to n, instead of n^2. Numerical simulations have shown that this creates a stalling point in the star-formation process, where the free-fall collapse of metal-free gas comes to a halt as the cooling time increases.
to be significantly above the dynamical time (Abel et al. 2002; Bromm et al. 2002). Entry into this “loitering” phase marks the end of hierarchical fragmentation that occurs during the free-fall period, a fragmentation that occurs because the temperature is able to continually decrease with increasing density. The final fragmentation mass scale is then set by the Jeans mass at the temperature and density corresponding to the point where the gas can no longer get colder with increasing density (Larson 1985, 2005). In the metal-free case, this yields a mass scale of \( \sim 1000 M_\odot \), resulting in the high-mass nature of the first stars.

The addition of metals enhances the cooling rate at low temperatures through fine structure and molecular transitions, as well as by continuum emission from dust grains. At low temperatures through fine structure and molecular transitions, the protostellar collapse of metal-enriched gas clouds has been extensively studied with one-zone models coupled to large chemical networks (Omukai 2000; Bromm et al. 2001; Omukai et al. 2005). At higher metallicities, gas-phase metal cooling becomes strong enough for the collapsing cloud to bypass the loitering phase and to undergo continued fragmentation (Bromm et al. 2001; Bromm & Loeb 2003; Santoro & Shull 2006; Smith & Sigurdsson 2007). If dust grains are present, their influence becomes important at very high densities \( n > 10^{12}\text{cm}^{-3} \). This has been shown to induce fragmentation for metallicities as low as \( 10^{-5.3} Z_\odot \) (Omukai et al. 2005; Schneider et al. 2006; Tsuribe & Omukai 2006; Clark et al. 2008). Calculations by Schneider et al. (2004) predicted that up to 30% of the progenitor mass is converted into dust in a pair-instability SN, but observations of Type II SN in the local universe remnants have not returned conclusive evidence of dust (Green et al. 2004; Krause et al. 2004). In the context of star formation in the early universe, the arrival at this critical metallicity, \( Z_{cr} \), at which fragmentation occurs beyond the capabilities of primordial gas, is predicted to be the point where the universal mode of star formation permanently shifts from the high-mass, solitary mode of the first stars to the low-mass, multiply producing mode that is presently observed (Bromm & Loeb 2003; Santoro & Shull 2006; Smith & Sigurdsson 2007).

The protostellar collapse of metal-enriched gas clouds has been extensively studied with one-zone models coupled to large chemical networks (Omukai 2000; Schneider et al. 2003, 2006; Omukai et al. 2005). These studies have given insight into the evolution of the density and temperature of collapsing gas clouds with finite metallicities, but one-zone models cannot speak to the actual process of fragmentation, which requires attention to complex cloud geometries that can only be given by fully three-dimensional hydrodynamic simulations (Larson 2007). The first of such simulations was carried out by Bromm et al. (2001), who included cooling from C, N, O, Fe, S, and Si, but not H\(_2\), finding that clouds with metallicities, \( Z \geq 10^{-3} Z_\odot \), are able to fragment to mass scales lower than in the metal-free case. These simulations had a mass resolution of only 100 \( M_\odot \) and were, therefore, unable to investigate the formation of solar-mass stars. More recently, Smith & Sigurdsson (2007) have performed a series of high-resolution simulations of metal-enriched gas collapse that were able to follow the evolution of gas fragments to subsolar mass scales. They, too, found that gas with metallicities, \( Z \geq 10^{-3} Z_\odot \), will fragment into multiple clumps, while gas with \( Z \leq 10^{-4} Z_\odot \) will produce only one object. However, Smith et al. (2008) reported the existence of regions in density and temperature that are thermally unstable in gas with metallicities as low as \( 10^{-4} Z_\odot \). Fragmentation is traditionally thought to happen when the cooling time is less than the dynamical time, as the gas is able to cool and form perturbations before they can be smoothed out by sound waves.

When this condition, referred to as the fragmentation criterion, is satisfied, fragmentation can also be aided by thermal instabilities (Field 1965), where a slight decrease in temperature or increase in density leads to a higher cooling rate, causing differences in temperature between pockets of gas to grow in a runaway fashion. In the adaptive mesh refinement simulations of Smith & Sigurdsson (2007), grid refinement was performed based on baryon and dark matter overdensities and by ensuring that the Truelove criterion, \( T < \Delta t \), where \( T \) is the local Jeans length and \( \Delta t \) is the grid cell size, was satisfied (Truelove et al. 1997). However, refinement was not performed when the cooling time was less than the hydrodynamic time step. While this was not explicitly wrong, since the radiative cooling solver iterates with time steps that are no larger than 10% of the cooling time, it may have artificially suppressed the growth of thermal instabilities that could have formed extra fragments.

We rerun the simulations of Smith & Sigurdsson (2007) with an additional refinement criterion, which ensures that the hydrodynamic time step is always less than the cooling time on the finest level of resolution. In addition, we extend the series of simulations to include lower metallicities and to more carefully examine the metallicity range between \( 10^{-4} Z_\odot \) and \( 10^{-3} Z_\odot \). We also run similar simulations with two extra sets of initial conditions to confirm the robustness of the results. We describe the setup of our simulations and the improvements over Smith & Sigurdsson (2007) in Section 2. In Section 3, we calculate the gas-phase critical metallicity, evaluate the validity of our assumption of optical thinness, and present the results of the suite of simulations. In Section 4, we discuss our results in the context of star formation at high redshift and make the case for an initial mass function (IMF) that evolves over cosmic time. We also include a discussion of the caveats and limitations of this work. Finally, we conclude with a brief summary of the main conclusions of this work in Section 5.

2. SIMULATION SETUP

We perform a series of 24 primordial star formation simulations using the Eulerian adaptive mesh refinement hydrodynamics + N-body code, Enzo (Bryan & Norman 2000; O’Shea et al. 2004). Excluding our three metal-free control runs, the gas in each simulation is homogeneously pre-enriched to some nonzero metallicity. As in Smith & Sigurdsson (2007), we confine the simulations to constant metallicities with solar abundance patterns, saving the more realistic, and far more complicated, simulations of true second-generation star-forming environments, with heterogeneous metal-mixing and nonsolar abundance patterns, for a future work.

The nature of the initial conditions for our simulations are identical to those used in Smith & Sigurdsson (2007). The simulation box has a comoving size of 300 \( h^{-1}\) kpc, with 128\(^3\) grid cells on the top grid and three nested subgrids, each refining by a factor of 2, for an effective top grid resolution of 1024\(^3\) cells. The cosmological parameters have the following values: \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \Omega_B = 0.04 \), and Hubble constant, \( h = 0.7 \), in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). The power spectrum of initial density
fluctuations is given by Eisenstein & Hu (1999), with $\sigma_8 = 0.9$ and $n = 1$. Refined grids are created during the simulations when the baryon (dark matter) density is 4 (8) times greater than the mean density at that level. The density threshold for refinement decreases at higher levels. The local Jeans length is resolved by a minimum of 16 grid cells at all times, exceeding the Truelove criterion (Truelove et al. 1997) by a factor of 4 along each coordinate axis. In addition, grid refinement occurs whenever the cooling time drops below the integration time step of the hydrodynamic solver. This final refinement criterion was not used in Smith & Sigurdsson (2007). During the simulation, a grid cell is flagged for refinement if one or more of any of these criteria is met.

We perform three sets of simulations. Qualitatively, the three sets are the same. They each have the same cosmological parameters, box size, and resolution. The only difference between them is that their initial conditions were created with three unique randomizations of the initial density and velocity perturbations. Thus, they represent three different realizations of the same problem. The first set of initial conditions is that used by Smith & Sigurdsson (2007). The second and third sets were initially used by O’Shea & Norman (2007) and correspond to the runs named L0_30A and L0_30D in that work, respectively. For each set of initial conditions, we perform a metal-free control run. Excluding the control runs, we run 10 simulations using initial conditions Set 1, with metallicities ranging from $10^{-6}$ $Z_\odot$ to $10^{-2}$ $Z_\odot$. 5 simulations using Set 2, and 6 simulations using Set 3, with metallicities from $10^{-4}$ $Z_\odot$ to $10^{-2}$ $Z_\odot$ for Sets 2 and 3. The final simulation in Set 3 has a metallicity of $10^{-6} Z_\odot$.

### Table 1

| Run | IC | $Z (Z_\odot)$ | $\tilde{z}_{\text{cut}}$ | Grids | $n_{\text{max}}$ (cm$^{-3}$) | $\Delta t_{\text{col}}$ (yr) |
|-----|----|-------------|----------------|-------|-----------------------------|-----------------------------|
| r1_mf | 1 | 0 | 14.761 | 13790 | 6.49 | 5.96 | 10$^{11}$ |
| r1_Z-6 | 1 | 3.6 | 14.762 | 13790 | 6.49 | 5.96 | 10$^{11}$ |
| r1_Z-5 | 1 | 5 | 14.763 | 13790 | 6.49 | 5.96 | 10$^{11}$ |
| r1_Z-4.25 | 1 | 4 | 14.809 | 12955 | 6.40 | 6.75 | 10$^{11}$ |
| r1_Z-4 | 1 | 4 | 14.830 | 12954 | 6.40 | 6.75 | 10$^{11}$ |
| r1_Z-3.75 | 1 | 3.75 | 14.848 | 13003 | 6.38 | 6.97 | 10$^{11}$ |
| r1_Z-3.5 | 1 | 3.5 | 14.874 | 12883 | 6.40 | 6.89 | 10$^{11}$ |
| r1_Z-3.25 | 1 | 3.25 | 14.936 | 12888 | 6.36 | 6.97 | 10$^{11}$ |
| r1_Z-3 | 1 | 3 | 15.073 | 12581 | 6.25 | 6.42 | 10$^{11}$ |
| r1_Z-2.5 | 1 | 2.5 | 16.180 | 11187 | 5.69 | 7.40 | 10$^{11}$ |
| r1_Z-2 | 1 | 2 | 19.481 | 8693 | 4.57 | 1.56 | 10$^{11}$ |
| r2_mf | 2 | 0 | 17.409 | 8684 | 4.76 | 7.97 | 10$^{11}$ |
| r2_Z-4 | 2 | 4 | 17.555 | 8509 | 4.74 | 8.39 | 10$^{11}$ |
| r2_Z-3.5 | 2 | 3.5 | 17.654 | 8476 | 4.71 | 8.20 | 10$^{11}$ |
| r2_Z-3 | 2 | 3 | 17.955 | 8408 | 4.67 | 7.30 | 10$^{11}$ |
| r2_Z-2.5 | 2 | 2.5 | 18.537 | 8022 | 4.51 | 4.41 | 10$^{11}$ |
| r2_Z-2 | 2 | 2 | 20.441 | 7194 | 4.09 | 1.92 | 10$^{11}$ |
| r3_mf | 3 | 0 | 23.885 | 7771 | 4.25 | 1.63 | 10$^{11}$ |
| r3_Z-4 | 3 | 4 | 23.966 | 7722 | 4.23 | 1.65 | 10$^{11}$ |
| r3_Z-3.5 | 3 | 3.5 | 24.122 | 7640 | 4.21 | 1.42 | 10$^{11}$ |
| r3_Z-3 | 3 | 3 | 24.390 | 7366 | 4.17 | 1.29 | 10$^{11}$ |
| r3_Z-2.5 | 3 | 2.5 | 24.732 | 7145 | 4.13 | 1.20 | 10$^{11}$ |
| r3_Z-2 | 3 | 2 | 25.028 | 7083 | 4.09 | 6.53 | 10$^{11}$ |
| r3_Z-2noCMB | 3 | 2 | 25.255 | 7424 | 4.29 | 6.02 | 10$^{11}$ |

**Notes:** $\tilde{z}_{\text{cut}}$ is the redshift at the onset of the runaway collapse. The total number of grid cells include those that are covered by child grids at higher levels of refinement. $n_{\text{max}}$ is the proper maximum baryon number density within the box. $\Delta t_{\text{col}}$ is the time difference to runaway collapse from the metal-free case.

3. RESULTS

3.1. Critical Metallicities

The gas-phase critical metallicity, $Z_{\text{cr}}$, has been analytically estimated by calculating the chemical abundance required for the cooling time to equal the dynamical time at the stalling point for metal-free gas, $n \sim 10^4$ cm$^{-3}$ and $T \sim 200$ K. Bromm & Loeb (2003) performed this exercise with C and O, but excluding cooling from H$_2$, and Santoro & Shull (2006) did...
where \( G \), \( r_{3, mf} \), \( r_{2, mf} \), and \( r_{1, mf} \) are the proper number density, \( H_2 \) number density, and temperature at the temperature minimum where \( H_2 \) becomes thermalized in each of the metal-free simulations. The final column is the log of the metallicity required to equate the cooling time to the dynamical time for the conditions listed.

so with C, O, Fe, Si, and including \( H_2 \). Santoro & Shull (2006) considered densities above and below the stalling point as well. The general consensus from these studies is that \( Z_{cr} \approx 10^{-3.5} Z_\odot \) at \( n = 10^4 \text{ cm}^{-3} \).

We observe a small amount of variance in the values of the density and temperature at which the temperature minimum occurs in our three metal-free runs. Since the exact value of the critical metallicity depends on the precise conditions at the temperature minimum, that is, temperature, total density, and \( H_2 \) density, we calculate the critical metallicity for each of the three runs separately. To do this, we define the cooling time in the following way:

\[
\tau_{\text{cool}} = \frac{nkT}{\gamma - 1}[\Lambda'_{H_2} + \Lambda'_{\text{metal}}],
\]

where \( k \) is Boltzmann’s constant, \( \gamma = 5/3 \), and \( \Lambda'_{H_2} \) and \( \Lambda'_{\text{metal}} \) are the cooling rates of \( H_2 \) and the metals in units of erg s\(^{-1}\) cm\(^{-3}\). We use \( \Lambda' \) to avoid confusion with the term, \( \Lambda \), which is often expressed in units of erg s\(^{-1}\) cm\(^{-3}\). We then set Equation (1) equal to the dynamical time,

\[
\tau_{\text{dyn}} = \sqrt{\frac{3\pi}{16G\rho}}.
\]

where \( G \) is the gravitational constant and \( \rho \) is the mass density. We calculate \( Z_{cr} \) for the conditions at the temperature minimum in each metal-free simulation using the \( H_2 \) cooling rates of Galli & Palla (1998) and the metal cooling rates of Smith et al. (2008). The results are shown in Table 2. The systematic shift toward lower values of \( Z_{cr} \) compared to previous calculations is most likely due to the fact that the minimum temperatures are slightly higher than 200 K, where both the \( H_2 \) and metal cooling rates are higher. In addition, cooling from \( H_2 \) was not included in the calculation of Bromm & Loeb (2003), meaning that more cooling from the metals would have been required.

There is a correlation between \( Z_{cr} \) and the collapse redshift of the simulation, with the highest value of \( Z_{cr} \) coming from the highest collapse redshift, despite the lack of such a correlation for \( n, n_{H_2}, \) or \( T \). However, there is a correlation between the \( H_2 \) fraction and collapse redshift, which has been observed in the Pop III simulations of O’Shea & Norman (2007). They found that the higher \( H_2 \) fractions result from the generally warmer gas in halos that collapse at higher redshifts, which is simply a function of the linear dependence upon redshift of the virial temperature. This may be the dominant factor, but with only three data points, it is unclear whether the observed trend is even significant. In addition, the artificial nature of our initial conditions may make this finding inapplicable to the real world.

We see a trend with metallicity and collapse redshift that is similar to what was reported by Smith & Sigurdsson (2007), where simulations with higher metallicities reach the runaway collapse phase earlier. We define \( \Delta t_{\text{col}} \) as the difference in time to runaway collapse between a simulation with nonzero metallicity and the metal-free run with the same initial conditions. An increase in metallicity by 0.5 dex results in an increase in \( \Delta t_{\text{col}} \) by a factor of approximately 1.3–4. Similarly, when compared within a set, the simulations collapsing later have a higher number of total grids and grid cells in their final output, since the lower-density envelope gas has had more time to evolve and reach higher densities.

### 3.2. Radial Profiles

In Figure 1, we show projections of mass-weighted mean number density for the final output of all runs in Set 1. Each projection is centered on the location of maximum baryon density in the simulation box and has a width of 0.5 pc proper. The labels in each panel indicate the log of the metallicity with respect to solar for that run. The images were made with the YT analysis toolkit (Turk 2008; yt.enzotools.org).

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

### Table 2

| Run  | \( n \) (cm\(^{-3}\)) | \( n_{H_2} \) (cm\(^{-3}\)) | \( T \) | \( \log(Z_{cr}/Z_\odot) \) |
|------|----------------|-----------------|-------|-----------------|
| r1_mf | 6.89 \times 10^4 | 3.42 | 283 | -4.08 |
| r2_mf | 3.64 \times 10^4 | 1.86 | 214 | -3.90 |
| r3_mf | 1.19 \times 10^4 | 6.53 | 260 | -3.85 |

**Notes.** Critical metallicities calculated for each metal-free simulation, \( n, n_{H_2}, \) and \( T \) are the proper number density, \( H_2 \) number density, and temperature at the temperature minimum where \( H_2 \) becomes thermalized in each of the metal-free simulations. The final column is the log of the metallicity required to equate the cooling time to the dynamical time for the conditions listed.
profiles follow an \(r^{-2.2}\) power law. To highlight the difference in density between each run, in panel (a) of Figure 2, we plot the value of \((n \times r^2)\), instead of simply \(n\). We choose to scale the density by \(r^2\) instead of \(r^{-2.2}\) because it is easier to glean the true density from the figure. Over most of the plotted range, the run with the lowest metallicity has the highest density. In the isothermal collapse model of Shu (1977), the accretion rate is proportional to the cube of the sound speed, or \(T^{3/2}\). Figure 2(b) shows that while isothermality does not really apply, there is a clear correlation between the temperature and density. The runs with the highest metallicity, and subsequently the coldest gas, are the least dense. In addition, within individual runs, an increase in the gas temperature is matched by an increase in the density.

The instantaneous accretion rate at a given radius is a function of the infall velocity at that position. Although there are some exceptions, the correlation between temperature/sound speed and infall velocity, with higher temperatures/sound speeds corresponding to higher velocities, generally holds. This was also found to be true by O’Shea & Norman (2007) in their simulations of Pop III star formation. We find that the inflow is roughly transonic throughout the entire density range, showing that even though the collapsing clouds are not isothermal spheres, their accretion rates are still largely regulated by the sound speed.

### 3.3. Optical Depth

The fragmentation of collapsing gas sensitively depends on its thermal evolution, which is effectively a measure of the radiative cooling properties of the gas as a function of density and temperature. Since our radiative cooling method, described above, assumes optical thinness, the results of our simulations are only valid where \(\tau \ll 1\). The optically-thin assumption begins to break down at densities \(n \gtrsim 10^{10} \text{ cm}^{-3}\) (Omukai et al. 2005). The optical depth at a frequency \(\nu\) is expressed as

\[
\tau_{\nu} = \int \kappa_{\nu} \rho \, d\ell,
\]

where \(\kappa_{\nu}\) is the opacity, \(\rho\) is the mass density, and \(d\ell\) is the distance traveled by a photon. At a given density, the cloud has a characteristic size \(r(\rho)\), shown in Figure 2(a). If a photon emitted from a region with density \(\rho\) is able to travel a distance \(\sim r(\rho)\) without being reabsorbed, then it will not alter the thermal evolution of the cloud, and the assumption of optical thinness holds. Using the Cloudy software, we calculate values of the absorption coefficient, \(\alpha_{\nu} \equiv \kappa_{\nu} \rho\), as a function of density, metallicity, temperature, and frequency. Equation (3) then takes the form

\[
\tau_{\nu} = \alpha_{\nu}(\rho, Z, T) \, r(\rho).
\]

For metallicities \(Z \lesssim 10^{-2} Z_{\odot}\) and in the absence of dust, metal cooling is dominated by fine-structure transitions of O i and Fe II (Santoro & Shull 2006; Smith et al. 2008). In Figure 3, we plot the optical depth from Equation (4) for the Fe II line at 25.99 \(\mu\)m and the O i line at 63.18 \(\mu\)m as a function of density using the spherically averaged densities and temperatures shown in Figure 2. At low energies and in the absence of dust grains, the largest contributor to the opacity is free–free absorption, which is dominated by H for low metallicities. As a result, the opacity in the energy range of interest is essentially independent of metallicity for metallicities less than solar. When the metals become a considerable fraction of the total gas content, above \(Z \sim 10 Z_{\odot}\) or so, the opacity at low energy for dust-free gas begins to grow with metallicity. In Figure 3, the apparent decrease in the optical depth at the highest metallicities is due to the flattening of the density profile at small radii. As such, the final point for each curve in Figure 3 should be ignored. For values inside the point where the density profile flattens, it would be more reasonable to use the radius at which the density turns over for the calculation of \(\tau\). Fortunately, \(\tau\) remains significantly less than 1 throughout all of our simulations, peaking at roughly 0.25 at the highest densities for the runs with the lowest metallicities. The lower optical depth in the higher metallicity runs is due to the smaller characteristic size of the core, as seen in Figure 2(a). It should also be noted that some molecules are missing from the Cloudy dust-free
et al. (1998), we define a clump, there referred to as a fragment, as "the mass contained between a local density maximum and the lowest isodensity surface surrounding only that maximum," to quote that work (page 842). We begin by identifying all grid cells within a sphere of radius 5 pc, centered on the point of maximum density. We then create density contours using all the cells within the sphere. In density space, the first contour spans the entire range of density within the sphere, effectively creating one large contour. The contour becomes the parent clump of all other clumps that will be found as the process continues. On the second iteration, we create contours with the same maximum as before, but with the minimum increased by 1/4 dex. If more than one contour exists, these groups of cells become child clumps of the group made by the previous iteration. The process continues in a recursive fashion, creating groups of cells based on contours of increasing density, identified only within the cells of the parent clump, ending when the minimum contour density has reached the constant maximum. Effectively, we create a family tree of clumps, with the very first group as the trunk of the tree. During the clump finding process, a child clump is only kept if it is gravitationally self-bound or has children of its own that are bound. When determining whether a clump is bound, we consider the thermal energy of the gas and its kinetic energy with respect to the bulk center of motion.

In Figure 4, we plot a histogram of all the number of clumps found in each run within the 5 pc sphere, as a function of the metallicity of the run. For this plot, we only include bound child clumps with no children of their own. When enlarging the radius of the sphere from 5 pc to 10 pc, no additional clumps were found in any of the runs. Figure 4 confirms what is seen in Figure 1. In all runs with metallicities below Z_{cr}, only a single bound clump is found. As the metallicity increases, the number of clumps increases and then decreases back to only a single clump for the highest metallicities, with the exception of r3_Z-2, which has two bound clumps. The range of metallicities where fragmentation occurs is consistent between Sets 1 and 3, but offset by 0.5 dex toward higher metallicities for Set 2. It is not clear what causes this offset, but the qualitative trend of an increasing and then a decreasing number of clumps exists in all three sets. It is also worthwhile to note that runs r1_Z-4, r1_Z-3.75, and r2_Z-3.5, while slightly above Z_{cr}, do not show fragmentation.

During the simulations, the Enzo code creates a snapshot of the entire box each time the maximum level of refinement increases. This provides us with multiple data outputs as the central density increases during runaway collapse. We ran the clump finder on all data outputs created during this period, searching for the first data output in which multiple clumps are found. Within this output, we take the minimum density within the clump to be the density at which fragmentation occurred. In Table 3, we list the fragmentation densities for all simulations in which multiple clumps were found. In runs with two clumps, the fragmentation density is the same for both clumps, since it represents the lowest density contour for which the two objects are separate. In run r1_Z-3.25, which has three clumps, the core initially fragmented into two clumps at n = 1.55 \times 10^5 \mathrm{cm}^{-3}. One data output later, one of these clumps again fragmented at n = 8.73 \times 10^4 \mathrm{cm}^{-3}. A similar thing occurred in run r3_Z-2noCMB with four clumps forming initially and one of these again fragmenting later.

At densities of roughly 10^6 \mathrm{cm}^{-3}, H_2 formation via three-body reactions begins to rapidly increase the H_2 fraction (Abel chemistry network that could contribute to the opacity, such as TiO. As such, the optical depths calculated could be slightly higher for the high metallicity simulations. However, we show in Section 3.4 that fragmentation in our simulations occurs well before this becomes a concern.

### 3.4. Fragmentation

In order to quantify the degree of fragmentation within each run, we employ a clump finding algorithm to search for bound clumps within 5 pc of the density maximum. As in Truelove et al. (1998), we define a clump, there referred to as a fragment, as "the mass contained between a local density maximum and the lowest isodensity surface surrounding only that maximum," to quote that work (page 842). We begin by identifying all grid cells within a sphere of radius 5 pc, centered on the point of maximum density. We then create density contours using all the cells within the sphere. In density space, the first contour spans the entire range of density within the sphere, effectively creating one large contour. The contour becomes the parent clump of all other clumps that will be found as the process continues. On the second iteration, we create contours with the same maximum as before, but with the minimum increased by 1/4 dex. If more than one contour exists, these groups of cells become child clumps of the group made by the previous iteration. The process continues in a recursive fashion, creating groups of cells based on contours of increasing density, identified only within the cells of the parent clump, ending when the minimum contour density has reached the constant maximum. Effectively, we create a family tree of clumps, with the very first group as the trunk of the tree. During the clump finding process, a child clump is only kept if it is gravitationally self-bound or has children of its own that are bound. When determining whether a clump is bound, we consider the thermal energy of the gas and its kinetic energy with respect to the bulk center of motion.

In Figure 4, we plot a histogram of all the number of clumps found in each run within the 5 pc sphere, as a function of the metallicity of the run. For this plot, we only include bound child clumps with no children of their own. When enlarging the radius of the sphere from 5 pc to 10 pc, no additional clumps were found in any of the runs. Figure 4 confirms what is seen in Figure 1. In all runs with metallicities below Z_{cr}, only a single bound clump is found. As the metallicity increases, the number of clumps increases and then decreases back to only a single clump for the highest metallicities, with the exception of r3_Z-2, which has two bound clumps. The range of metallicities where fragmentation occurs is consistent between Sets 1 and 3, but offset by 0.5 dex toward higher metallicities for Set 2. It is not clear what causes this offset, but the qualitative trend of an increasing and then a decreasing number of clumps exists in all three sets. It is also worthwhile to note that runs r1_Z-4, r1_Z-3.75, and r2_Z-3.5, while slightly above Z_{cr}, do not show fragmentation.

During the simulations, the Enzo code creates a snapshot of the entire box each time the maximum level of refinement increases. This provides us with multiple data outputs as the central density increases during runaway collapse. We ran the clump finder on all data outputs created during this period, searching for the first data output in which multiple clumps are found. Within this output, we take the minimum density within the clump to be the density at which fragmentation occurred. In Table 3, we list the fragmentation densities for all simulations in which multiple clumps were found. In runs with two clumps, the fragmentation density is the same for both clumps, since it represents the lowest density contour for which the two objects are separate. In run r1_Z-3.25, which has three clumps, the core initially fragmented into two clumps at n = 1.55 \times 10^5 \mathrm{cm}^{-3}. One data output later, one of these clumps again fragmented at n = 8.73 \times 10^4 \mathrm{cm}^{-3}. A similar thing occurred in run r3_Z-2noCMB with four clumps forming initially and one of these again fragmenting later.

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At densities of roughly 10^6 \mathrm{cm}^{-3}, H_2 formation via three-body reactions begins to rapidly increase the H_2 fraction (Abel
Figure 5. Mass-weighted, average temperature as a function of number density for all runs in Set 1. The colors are the same as in Figure 2, including the runs with metallicities $Z = 10^{-4.25} Z_\odot$ (dashed-yellow), $10^{-3.75} Z_\odot$ (dashed-green), and $10^{-3.25} Z_\odot$ (dashed-blue). The thin, black, dashed lines indicate lines of constant Jeans mass in $M_\odot$. The horizontal, blue, dashed line denotes the temperature of the CMB at $z = 19$, the approximate redshift of collapse for runs r1_Z-2.5 and r1_Z-2. The central cores in these two runs were both able to cool to the temperature of the CMB.

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

| Run            | Clump Mass ($M_\odot$) | $n_{\text{tag}}$ (cm$^{-3}$) |
|----------------|-------------------------|--------------------------------|
| r1_Z-3.5       | 54.4, 4.98              | $1.55 \times 10^5$            |
| r1_Z-3.25      | 22.1                    | $1.55 \times 10^5$            |
| r2_Z-3         | 5.46, 1.40              | $8.73 \times 10^6$            |
| r2_Z-2.5       | 6.26, 1.89              | $2.75 \times 10^9$            |
| r3_Z-3.5       | 54.4, 4.98              | $1.55 \times 10^5$            |
| r3_Z-2         | 289, 105                | $1.55 \times 10^4$            |
| r3_Z-2noCMB    | 11.7                    | $2.76 \times 10^4$            |
|                | 4.38, 4.06              | $4.91 \times 10^5$            |
|                | 32.6, 0.49              | $8.73 \times 10^5$            |

Notes. Number density at which fragmentation occurs within simulations where multiple bound clumps are identified and the masses of the clumps associated with that episode of fragmentation. The fragmentation density is taken to be the minimum density within a clump, taken from the earliest data output where that clump is identified.

In Figures 5 and 6, we plot the number density versus gas temperature for the final output of each simulation. Due to the self-similar nature of the collapse, Figures 5 and 6 can also be used to understand the evolution of the central core throughout the collapse. In all the runs with $Z < Z_{cr}$, the cooling is too low to prevent the temperature from rising at the H$_2$ thermalization density, $n \sim 10^4$ cm$^{-3}$. Therefore, the minimum fragmentation mass for these runs, set by the Jeans mass as the temperature minimum, is well over 1000 $M_\odot$, which is nearly equivalent to the total enclosed mass. Even though runs r1_Z-4 and r1_Z-3.75 are above $Z_{cr}$, the additional cooling provided by the metals is not sufficient to significantly lower the minimum fragmentation mass. For runs r1_Z-3.5 and r1_Z-3.25, the more efficient cooling lowers the minimum fragmentation mass to just over 100 $M_\odot$, which is approximately a factor of a few lower than the total mass within 1 pc.

For the runs with the highest metallicities, as in runs r1_Z-2.5 and r1_Z-2, the gas cools all the way to the temperature of the CMB. The cooling proceeds so efficiently that the gas has
not had sufficient time to reach high densities before hitting the temperature floor of the CMB. Fragmentation can only continue as long as the temperature decreases with increasing density (Larson 1985, 2005). Although the temperature decreases slightly in runs r1_Z-2.5 and r1_Z-2 for densities greater than $10^3$ cm$^{-3}$, the temperature minimum is effectively at $n = 10^4$ cm$^{-3}$, where the gas reaches the CMB temperature. Near the CMB temperature, the value of the cooling rate, $\Lambda$, effectively becomes $(\Lambda(T) - \Lambda(T_{\mathrm{CMB}}))$. Therefore, when the gas reaches the CMB temperature, the cooling rate drops to zero and the cooling time becomes infinite. The gas cloud becomes extremely thermally stable, preventing further fragmentation.

To verify that the CMB indeed suppresses fragmentation, we run one simulation, r3_Z-2_noCMB, with the CMB temperature floor removed. We choose initial condition Set 3 for this exercise since it has the highest CMB temperature at the redshift of collapse and should, therefore, show the greatest contrast with the CMB removed. In Figure 7, we show mass-weighted mean number density projections of the central 5 pc for runs, r3_mf, r3_Z-2, and r3_Z-2_noCMB. Run r3_Z-2 has a much clumpier structure than its metal-free counterpart, even with the CMB temperature floor present. However, when the temperature floor is removed, the gas is able to collapse into a long, thin filament with far more small-scale structure. As shown in Figure 4, we find the most bound clumps in this run (4 within 1 pc of the density peak and 1 more within 5 pc). In Figure 8, we show mass-weighted mean temperature projections for the same runs as Figure 7. We overlay contours of projected mean number density of $10^4$ cm$^{-3}$. Figure 6 shows that this is the approximate density at which the cloud in run r3_Z-2 first reaches the CMB temperature. In run r3_Z-2_noCMB, it took $\approx 400,000$ years for the central density to increase from $10^4$ cm$^{-3}$ to $10^5$ cm$^{-3}$, which is similar to the timescale in a dynamical collapse. In run r3_Z-2, the equivalent change in density took $\sim 1.9$ million years, indicating that cooling to the CMB temperature has indeed ended free-fall collapse.

In the projections of run r3_Z-2 in Figure 8, the two largest contours roughly represent the two bound clumps found within the 5 pc radius sphere. The gas within the clumps has a very uniform temperature, as its cooling has been abruptly halted at the CMB temperature ($\sim 71$ K). The two clumps have masses of roughly 100 and 300 $M_\odot$, respectively. It is unlikely that they will fragment further, since the Jeans mass of each clump is nearly equivalent to its total mass. At a temperature of 71 K, sound waves will travel $\sim 1.7$ pc in the 1.9 Myr required for any additional fragments to increase in density by an order of magnitude once they have cooled to the CMB temperature. Any additional fragments that might possibly condense out of lower density gas must be approximately this large in order to collapse, suggesting that they will also be very massive. It is interesting to note that the two bound clumps in the simulation are also about this size.

In contrast, the gas inside the contours of run r3_Z-2_noCMB shows significantly more structure in temperature. The cold knots in run r3_Z-2_noCMB seen in Figure 8 correspond to the high-density regions seen in Figure 7. Four of the five bound

![Figure 6](image6.png)

**Figure 6.** Mass-weighted, average temperature as a function of number density for all the runs in Set 2 (left) and Set 3 (right). For both panels, the metallicities are $Z = 0$ (solid-black), $10^{-2} Z_\odot$ (green), $10^{-3} Z_\odot$ (blue), $10^{-4} Z_\odot$ (purple), $10^{-5} Z_\odot$ (dashed-black), and $10^{-6} Z_\odot$ (dashed-red). In the bottom panel, the dashed-orange line corresponds to run r3_Z-2_noCMB, with $Z = 10^{-2} Z_\odot$, but with the CMB temperature floor removed. All curves in Figures 5 and 6 with the same colors refer to simulations with the same metallicities. The thin, black, dashed lines indicate lines of constant Jeans mass in $M_\odot$. The horizontal, blue, dashed lines denote the temperature of the CMB at $z = 19$ (left) and 25 (right).

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

![Figure 7](image7.png)

**Figure 7.** Projections of mass-weighted mean number density along the $x$ (left), $y$ (center), and $z$ (right) axes for the final output of runs r3_mf with zero-metallicity (top), r3_Z-2 with $Z = 10^{-2} Z_\odot$ (middle), and r3_Z-2_noCMB with $Z = 10^{-2} Z_\odot$ and the CMB temperature floor removed (bottom). Each projection is centered on the location of maximum density in the simulation box and has a width of 5 pc proper. The images were made with the YT analysis tool kit (Turk 2008, yt.enzotools.org).

(A color version of this figure is available in the online journal.)
clumps were Jeans unstable, with masses of 4, 4, 12, and 33 $M_{\odot}$, respectively. The fifth, with $M \sim 0.5 M_{\odot}$, is approximately 1/6 of its Jeans mass. The most massive clump is about 5 times more massive than its Jeans mass.

4. DISCUSSION

We have shown that fragmentation occurs within a collapsing cloud when the metallicity is above the critical metallicity. The exact value of the critical metallicity required to prevent an increase in temperature at the stalling point of H$_2$ slightly varies from halo to halo. Within our three sets of initial conditions, the values of $Z_{cr}$ are correlated to the collapse redshift of the metal-free runs, with the highest $Z_{cr}$ corresponding to the highest redshift. However, it is unclear whether this is significant. If the metallicity is only marginally higher than $Z_{cr}$, fragmentation is unlikely to occur, as the increase in temperature at the H$_2$ stalling point is only delayed momentarily. Thus, it is unlikely that a sharp transition in the star formation mode occurs at just the moment when the critical metallicity is reached.

Fragmentation is suppressed when the metallicity is high enough such that the gas is able to cool to the temperature of the CMB when the central density is still relatively low. We confirm that the CMB is responsible for the observed suppression of fragmentation by running an identical simulation without the CMB. In this simulation where the CMB is absent, we find more bound clumps than in any other of the runs in this study. Two bound clumps were found in run r3_Z-2, where the gas was able to cool to the CMB temperature. However, both of these clumps were quite massive ($M \gtrsim 100 M_{\odot}$), and we showed in Section 3.4 that it is unlikely that they will fragment into smaller objects. We observe a small amount of variance in the metallicity range in which fragmentation occurs that does not appear to be related to the CMB. Just as the exact value of $Z_{cr}$ seems to vary from halo to halo, we suspect that the range of metallicities where fragmentation occurs will also be influenced by the individual properties of a halo and its particular evolution.

The mass scale of collapsing clumps can be estimated from the Jeans mass at the end of the cooling phase. This implies the existence of three distinct metallicity regimes for star formation. In the first regime, $Z \lesssim Z_{cr}$, which we refer to as the “primordial” mode, metals do not provide enough additional cooling to allow the gas temperature to continue to decrease monotonically with increasing density when the core reaches the H$_2$ thermalization density. In this case, the collapse proceeds in a similar way to the metal-free scenario, resulting in the formation of a single, massive object. There is also the potential for stars forming in this mode to be somewhat less massive than the very first stars. The fragmentation mass scale for extremely low metallicity gas ($Z \ll Z_{cr}$) may be lowered though compression by shocks from Pop III SNe and enhanced cooling from HD in relic H ii regions (Mackey et al. 2003; Johnson & Bromm 2006).

At the other extreme, we define $Z_{CMB}$ as the metallicity at which the gas can cool to the CMB temperature. When $Z \gg Z_{CMB}$, the cloud core will efficiently cool to the temperature of the CMB when the central density is still relatively low. In this scenario, fragmentation is limited by cooling rapidly to the CMB temperature, as the mass scale is determined by the Jeans mass at the density when the core first reaches the CMB temperature. We refer to this as the CMB-regulated star formation mode, similar to Tumlinson (2007b). As fragmentation is severely limited in this mode, these stars will most likely be more massive on average than the characteristic mass of stars forming today.

Finally, our simulations have shown that a special range exists in metallicity, $Z_{cr} \lesssim Z < Z_{CMB}$, where the core does not reheat at the metal-free stalling point, but also cannot cool all the way to the CMB temperature. The minimum temperature is set only by the balance of radiative cooling and adiabatic heating. The mass scale is not regulated externally by the CMB, but rather internally by the metallicity-dependent gas cooling. Hence, we term this the metallicity-regulated star formation mode. This mode produces the lowest mass stars of the three modes mentioned.

The CMB-regulated star formation mode creates a means by which a higher number of massive stars are formed in very early universe, when the CMB temperature was much higher. As the universe evolves, the CMB temperature will slowly decrease, which will increase the metallicity required to reach the CMB temperature, referred to here as $Z_{CMB}$. The decrease in the CMB temperature also means that the fragmentation mass scale will be lower at the point where the gas reaches the temperature floor. Thus, the characteristic mass of stars produced by the CMB-regulated mode will slowly decrease with time. This behavior is in agreement with the model of an IMF that evolves with redshift formulated by Larson (1998). As the metallicity threshold for the CMB-regulated mode advances to higher metallicity, the range of operation of the metallicity-regulated mode extends to take its place. We lack sufficient data in this study to predict the evolution of $Z_{CMB}$ with redshift. However, in a forthcoming paper, we will map out the evolution of $Z_{CMB}$ versus $z$ with additional simulations collapsing as much lower
redshifts. Observations of nearby star-forming clouds show that the minimum achievable temperature in the local universe is roughly 10 K (e.g., Evans 1999). This implied that the CMB-regulated star formation mode is in operation up to \( z \sim 2.7 \), at the absolute latest. A growing amount of evidence has been presented that the stellar IMF evolves with redshift (e.g., Fardal et al. 2007; Tumlinson 2007b; van Dokkum 2008; Davé 2008; Wilkins et al. 2008). Interestingly, van Dokkum (2008), Davé (2008), and Wilkins et al. (2008) reported evidence from high redshift that the IMF may deviate from the standard Salpeter IMF, favoring higher-mass stars for \( z \geq 2.4 \).

If dust is present in the very early universe, this would extend the range of the metallicity-regulated star formation mode to metallicities as low as \( Z \sim 10^{-5.5} Z_{\odot} \) (Omukai et al. 2005; Schneider et al. 2006; Tsuribe & Omukai 2006; Clark et al. 2008). The existence of low-mass, hyper-metal-poor stars, HE0107-5240 (Christlieb et al. 2002), and HE1327-2326 (Fremel et al. 2005), both with \([\text{Fe}/H] < -5\), may provide evidence of this. Both of these stars show extremely enhanced C and O abundances, which would make their effective metallicities (in terms of the radiative cooling ability of gas with that abundance) much higher. However, it is pointed out by Tumlinson (2007a, 2007b) that the abundance patterns of these stars are best recreated by a scenario in which the C and O enhancement comes via binary mass transfer from an intermediate-mass asymptotic giant branch (AGB) star, meaning the stars are truly metal poor. In that case, these two low-mass stars would likely require dust in order to form at such low metallicity. Tumlinson (2007b) also showed that such a high fraction of carbon-enhanced metal-poor stars (CEMPs) requires a higher than normal fraction of more massive stars that go through the AGB phase. Tumlinson (2007b) claimed that the evolution of CEMP fraction with metallicity (with a higher CEMP fraction at lower metallicity) already shows the influence of the CMB on the initial mass function. If a CEMP star and its binary companion were formed from gas at the same metallicity, there would have to be process at work that would prevent the dust cooling fragmentation from forming only low-mass stars. The star formation models of Omukai et al. (2005) do not indicate that the dust cooling phase that induces low-mass fragmentation is able to reach the CMB temperature for \( Z < 10^{-4} Z_{\odot} \). This may simply imply that metal mixing from the first SNe is highly heterogeneous, allowing stars to form simultaneously with largely different abundances.

In this work, we study only gas clouds with solar abundance patterns. Most likely, the first metals in the universe will not have solar abundance patterns. However, from the perspective of simulating metal-enriched star formation, it is not the specific elemental abundances of a gas cloud that are important, but rather the total cooling rate produced by the gas. Therefore, given that it is the sum of the metals that is important, and not the abundance pattern, the results of this work are robust in spite of the fact that the abundance patterns used are likely to be incorrect.

There appears to be some discrepancy between our results and those of Japans et al. (2007), who saw no evidence of fragmentation induced by gas-phase metal cooling. This is potentially resolved by the fact that in that work, the gas collapse is only strictly followed up to densities of \( 5 \times 10^2 \text{ cm}^{-3} \) before sink particles are created. Figures 5 and 6 show very little difference in the thermal structure of the gas for densities below \( 5 \times 10^3 \text{ cm}^{-3} \). Additionally, our clump-finding algorithm found only a single bound clump within every simulation when the analysis was performed on data outputs that were made when the maximum density was only \( \sim 10^3 \text{ cm}^{-3} \). Multiple clumps were only found when the clouds had reached somewhat higher densities. Finally, the simulations in this work began with cold, neutral gas, whereas their simulations began with hot, ionized gas. Had their simulations been run to higher densities, any dissimilarities might also be due to using different initial conditions.

5. CONCLUSION

We have performed a series of high-resolution simulations of metal-enriched star formation using cosmological, Pop III style initial conditions, and assuming fully-homogeneous metal enrichment. We have shown that our results apply to more than a single star-forming region by using three different sets of initial conditions with identical cosmological parameters and resolution, but with three unique random seeds with which to create the initial perturbations in the density and velocity fields. From the results of these simulations, the main conclusions of this work are as follows.

1. Fragmentation does not occur when the metallicity is only slightly above \( Z_{\text{cr}} \), since this only leads to a small delay in the onset of the loitering phase that is brought on by a decrease in the efficiency of \( H_2 \) cooling. The density at which the temperature begins to increase with increasing density is only marginally higher than in the metal-free case, and, therefore, does not lead to a significant lowering of the minimum Jeans mass. Within our simulations, \( Z_{\text{cr}} \) is roughly \( 10^{-3.9} Z_{\odot} \). We find that fragmentation does not occur until the metallicity is roughly 0.5 dex above \( Z_{\text{cr}} \).

2. Fragmentation is suppressed when the metallicity is high enough such that the gas is able to cool to the temperature of the CMB when the density of the collapsing cloud is still relatively low (\( n \sim 10^4 \text{ cm}^{-3} \)). The Jeans mass at the density and temperature at which the cloud first reaches the CMB temperature sets the minimum fragmentation mass within the cloud, and as such only massive clumps are able to form.

3. Metal-enriched star formation occurs in three modes that are separated by two metallicity thresholds, \( Z_{\text{cr}} \) and \( Z_{\text{CMB}} \). \( Z_{\text{cr}} \) is the conventional critical metallicity and \( Z_{\text{CMB}} \) is the metallicity at which the gas is able to cool to the temperature of the CMB at a given redshift. At the approximate collapse redshifts of our simulations, \( z \sim 20 \), \( Z_{\text{CMB}} \) is between \( 10^{-3} \) and \( 10^{-2.5} Z_{\odot} \). The three modes of star formation are:

- **The primordial mode** (\( Z < Z_{\text{cr}} \)). The additional cooling provided by the metals is not enough to significantly alter the thermal structure of the cloud relative to the metal-free case. No fragmentation occurs and the star will have a mass similar to a Pop III star.

- **The metallicity-regulated mode** (\( Z_{\text{cr}} < Z < Z_{\text{CMB}} \)). Metal cooling is high enough to allow the cloud to continue to cool past the metal-free loitering phase, but not high enough to cool it to the temperature of the CMB. The minimum fragmentation mass is set at lower temperatures and higher densities than in the primordial case, and fragmentation into multiple objects occurs. Based on the masses of clumps formed within our simulations, stars forming in this mode could have masses of the order of a few \( M_{\odot} \) or less.

- **The CMB-regulated mode** (\( Z > Z_{\text{CMB}} \)). Fragmentation is suppressed when the cloud is able to cool to the CMB
temperature, as is described in point 2 of the conclusions. At minimum, stars forming in the CMB-regulated mode will be more massive than stars forming in the metallicity-regulated mode. \( Z_{\text{CMB}} \) will increase as the CMB temperature lowers with time. As such, the masses of stars forming in the CMB-regulated mode will slowly decrease. This mode will vanish altogether when the CMB temperature reaches the observed minimum temperature of nearby molecular clouds (\( T \sim 10 \text{ K} \) at \( z \sim 2.7 \)).

4. By demonstrating that the CMB can suppress fragmentation, we have provided a key conceptual piece CMB-IMF hypothesis (Tumlinson 2007b). As pointed out by Tumlinson (2007b), an IMF that evolves with redshift, producing more massive stars in the past, has consequences that may already be testable by observations.

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