Stellar Evolution at low Metallicity: Mass Loss, Eplosions, Cosmology
ASP Conference Series, Vol. 353, 2006
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The Early Generations of Low-metallicity Stars

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Abstract. The first generations of low-metallicity stars formed at the end of the cosmic dark ages. I discuss the physics of their formation, and how they transformed the early universe from an initially very simple state into one of ever increasing complexity. Specifically, I address the role of heavy elements in bringing about the transition from an early star formation mode dominated by massive stars to the familiar mode dominated by low mass stars, and suggest possible observational probes, such as extremely low-metallicity Galactic halo stars and high-redshift gamma-ray bursts.

1. Introduction

One of the grand challenges in modern cosmology is posed by the question: How did the first stars in the universe form, what were their physical properties, and what was their impact on cosmic history (e.g., Bromm & Larson 2004)? The first stars, formed at the end of the cosmic dark ages, ionized (e.g., Wyithe & Loeb 2003; Cen 2003) and metal-enriched (e.g., Furlanetto & Loeb 2003) the intergalactic medium (IGM) and consequently had important effects on subsequent galaxy formation (e.g., Barkana & Loeb 2001) and on the large-scale polarization anisotropies of the cosmic microwave background (Kaplinghat et al. 2002). *When did the cosmic dark ages end?* In the context of popular cold dark matter (CDM) models of hierarchical structure formation, the first stars are predicted to have formed in dark matter halos of mass $\sim 10^6 M_\odot$ that collapsed at redshifts $z \simeq 20 - 30$ (e.g., Barkana & Loeb 2001; Yoshida et al. 2003).

Results from recent numerical simulations of the collapse and fragmentation of primordial clouds suggest that the first stars were predominantly very massive, with typical masses $M_* \geq 100 M_\odot$ (Bromm, Coppi, & Larson 1999, 2002; Nakamura & Umemura 2001; Abel, Bryan, & Norman 2002). Despite the progress already made, many important questions remain unanswered. An example for an open question is: *How does the primordial initial mass function (IMF) look like?* Having constrained the characteristic mass scale, still leaves undetermined the overall range of stellar masses and the power-law slope which is likely to be a function of mass. In addition, it is presently unknown whether binaries or, more generally, clusters of zero-metallicity stars, can form. *What is the nature of the feedback that the first stars exert on their surroundings?* The first stars are expected to produce copious amounts of UV photons and to possibly explode as energetic hypernovae. These negative feedback effects could suppress star formation in neighboring high-density clumps.

Predicting the properties of the first sources of light, in particular their expected luminosities and spectral energy distributions, is important for the design

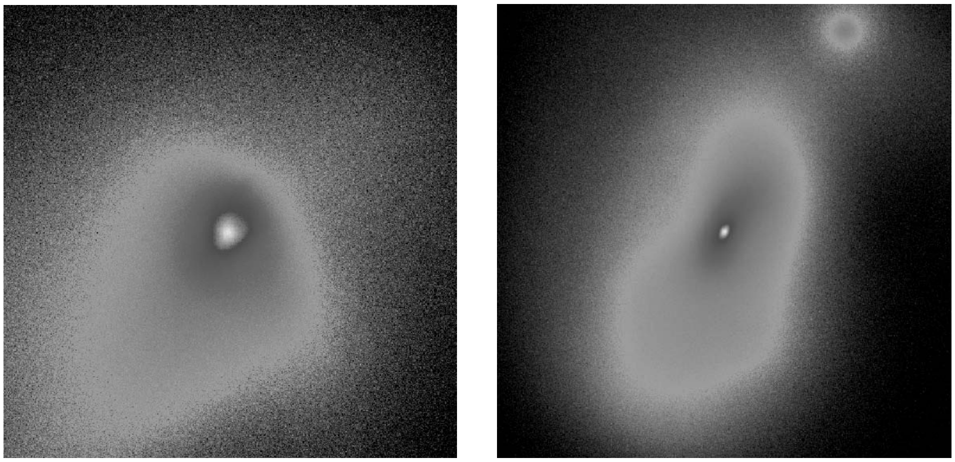

Figure 1. Collapse and fragmentation of a primordial cloud. Shown is the projected gas density at a redshift $z \simeq 21.5$, briefly after gravitational runaway collapse has commenced in the center of the cloud. *Left:* The coarse-grained morphology in a box with linear physical size of 23.5 pc. *Right:* The fine-grain morphology in a box with linear physical size of 0.5 pc. The central density peak, vigorously gaining mass by accretion, is accompanied by a secondary clump. (Adapted from Bromm & Loeb 2004.)

of upcoming instruments, such as the *James Webb Space Telescope* (JWST) [1], or the next generation of large (> 10m) ground-based telescopes. The hope is that over the upcoming decade, it will become possible to confront current theoretical predictions about the properties of the first stars with direct observational data.

2. Population III star formation

The metal-rich chemistry, magnetohydrodynamics, and radiative transfer involved in present-day star formation is complex, and we still lack a comprehensive theoretical framework that predicts the IMF from first principles (see Larson 2003 for a recent review). Star formation in the high redshift universe, on the other hand, poses a theoretically more tractable problem due to a number of simplifying features, such as: (i) the initial absence of heavy metals and therefore of dust; and (ii) the absence of dynamically-significant magnetic fields, in the pristine gas left over from the big bang. The cooling of the primordial gas does then only depend on hydrogen in its atomic and molecular form. Whereas the initial state of the star forming cloud is poorly constrained in the present-day interstellar medium, the corresponding initial conditions for primordial star formation are simple, given by the popular ΛCDM model of cosmological structure formation.

How did the first stars form? A complete answer to this question would entail a theoretical prediction for the Population III IMF, which is rather challenging. Let us start by addressing the simpler problem of estimating the characteristic

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[1] See http:// ngst.gsfc.nasa.gov.

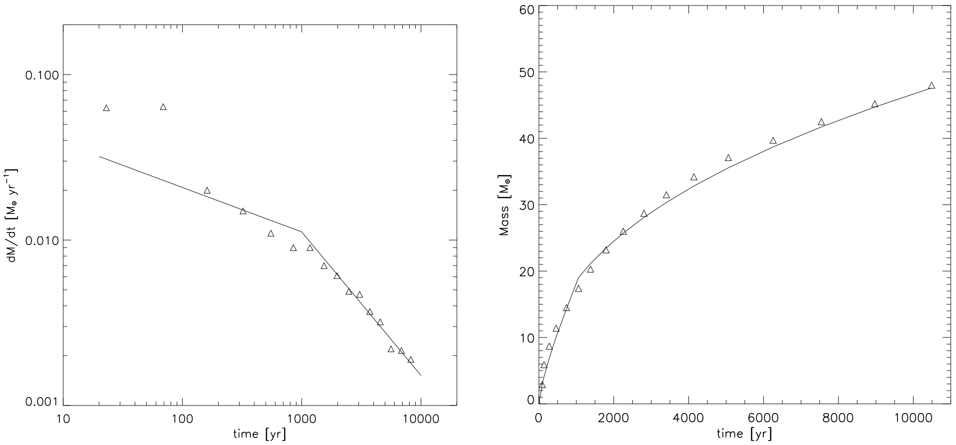

Figure 2. Accretion onto a primordial protostar. The morphology of this accretion flow is shown in Fig. 1. *Left:* Accretion rate (in $M_{\odot}$ yr^{-1}) vs. time (in yr) since molecular core formation. *Right:* Mass of the central core (in $M_{\odot}$) vs. time. *Solid line:* Accretion history approximated as: $M_* \propto t^{0.75}$ at $t < 10^3$ yr, and $M_* \propto t^{0.4}$ afterwards. Using this analytical approximation, we extrapolate that the protostellar mass has grown to $\sim 120 M_{\odot}$ after $\sim 10^5$ yr, and to $\sim 500 M_{\odot}$ after $\sim 3 \times 10^6$ yr, the total lifetime of a very massive star. (Adapted from Bromm & Loeb 2004.)

mass scale of the first stars. This mass scale is observed to be $\sim 1 M_{\odot}$ in the present-day universe. To investigate the collapse and fragmentation of primordial gas, we have carried out numerical simulations, using the smoothed particle hydrodynamics (SPH) method. We have included the chemistry and cooling physics relevant for the evolution of metal-free gas (see Bromm et al. 2002 for details). Improving on earlier work (Bromm et al. 1999, 2002) by initializing our simulation according to the ΛCDM model, we focus here on an isolated overdense region that corresponds to a 3σ−peak: a halo containing a total mass of $10^6 M_{\odot}$, and collapsing at a redshift $z_{\rm vir} \simeq 20$ (Bromm & Loeb 2004). In Figure 1 (*left panel*), we show the gas density within the central ~ 25 pc, briefly after the first high-density clump has formed as a result of gravitational runaway collapse.

How massive were the first stars? Star formation typically proceeds from the 'inside-out', through the accretion of gas onto a central hydrostatic core. Whereas the initial mass of the hydrostatic core is very similar for primordial and present-day star formation (Omukai & Nishi 1998), the accretion process – ultimately responsible for setting the final stellar mass, is expected to be rather different. On dimensional grounds, the accretion rate is simply related to the sound speed cubed over Newton's constant (or equivalently given by the ratio of the Jeans mass and the free-fall time): $\dot{M}_{\rm acc} \sim c_s^3/G \propto T^{3/2}$. A simple comparison of the temperatures in present-day star forming regions ($T \sim 10$ K) with those in primordial ones ($T \sim 200 - 300$ K) already indicates a difference in the accretion rate of more than two orders of magnitude.

Our high-resolution simulation enables us to study the three-dimensional accretion flow around the protostar (see also Omukai & Palla 2001, 2003; Ripamonti et al. 2002; Tan & McKee 2004). We allow the gas to reach densities of 10^{12} cm^{-3} before being incorporated into a central sink particle. At these high densities, three-body reactions (Palla, Salpeter, & Stahler 1983) have converted the gas into a fully molecular form. In Figure 2, we show how the molecular core grows in mass over the first $\sim 10^4$ yr after its formation. The accretion rate (*left panel*) is initially very high, $\dot{M}_{\rm acc} \sim 0.1 M_{\odot}$ yr^{-1}, and subsequently declines with time. The mass of the molecular core (*right panel*), taken as an estimator of the proto-stellar mass, grows approximately as: $M_{*} \sim \int \dot{M}_{\rm acc} {\rm d}t \propto t^{0.75}$ at $t < 10^3$ yr, and $M_{*} \propto t^{0.4}$ afterwards. A rough upper limit for the final mass of the star is then: $M_{*}(t = 3 \times 10^6 {\rm yr}) \sim 500 M_{\odot}$. In deriving this upper bound, we have conservatively assumed that accretion cannot go on for longer than the total lifetime of a very massive star (VMS).

Can a Population III star ever reach this asymptotic mass limit? The answer to this question is not yet known with any certainty, and it depends on whether the accretion from a dust-free envelope is eventually terminated by feedback from the star (e.g., Omukai & Palla 2001, 2003; Omukai & Inutsuka 2002; Ripamonti et al. 2002; Tan & McKee 2004). The standard mechanism by which accretion may be terminated in metal-rich gas, namely radiation pressure on dust grains (e.g., Wolfire & Cassinelli 1987), is evidently not effective for gas with a primordial composition. Recently, it has been speculated that accretion could instead be turned off through the formation of an H II region (Omukai & Inutsuka 2002), or through the radiation pressure exerted by trapped Lyα photons (Tan & McKee 2004). The termination of the accretion process defines the current unsolved frontier in studies of Population III star formation.

3. Second generation stars

How and when did the transition take place from the early formation of massive stars to that of low-mass stars at later times? In contrast to the formation mode of massive stars (Population III) at high redshifts, fragmentation is observed to favor stars below a solar mass (Population I and II) in the present-day universe. The transition between these fundamental modes is expected to be mainly driven by the progressive enrichment of the cosmic gas with heavy elements, which enables the gas to cool to lower temperatures. The concept of a 'critical metallicity', $Z_{\rm crit}$, has been used to characterize the transition between Population III and Population II formation modes, where Z denotes the mass fraction contributed by all heavy elements (Omukai 2000; Bromm et al. 2001; Schneider et al. 2002; Schneider et al. 2003; Mackey, Bromm, & Hernquist 2003; Yoshida, Bromm, & Hernquist 2004). These studies have constrained this important parameter to only within a few orders of magnitude, $Z_{\rm crit} \sim 10^{-6} - 10^{-3} Z_{\odot}$, under the implicit assumption of solar relative abundances of metals. This assumption is likely to be violated by the metal yields of the first SNe at high-redshifts, for which strong deviations from solar abundance ratios are predicted (e.g., Heger & Woosley 2002; Qian & Wasserburg 2002; Umeda & Nomoto 2002, 2003).

Recently, we have shown that the transition between the above star formation modes is driven primarily by fine-structure line cooling of singly-ionized carbon or neutral atomic oxygen (Bromm & Loeb 2003). Earlier estimates of $Z_{\rm crit}$ which did not explicitly distinguish between different coolants are refined

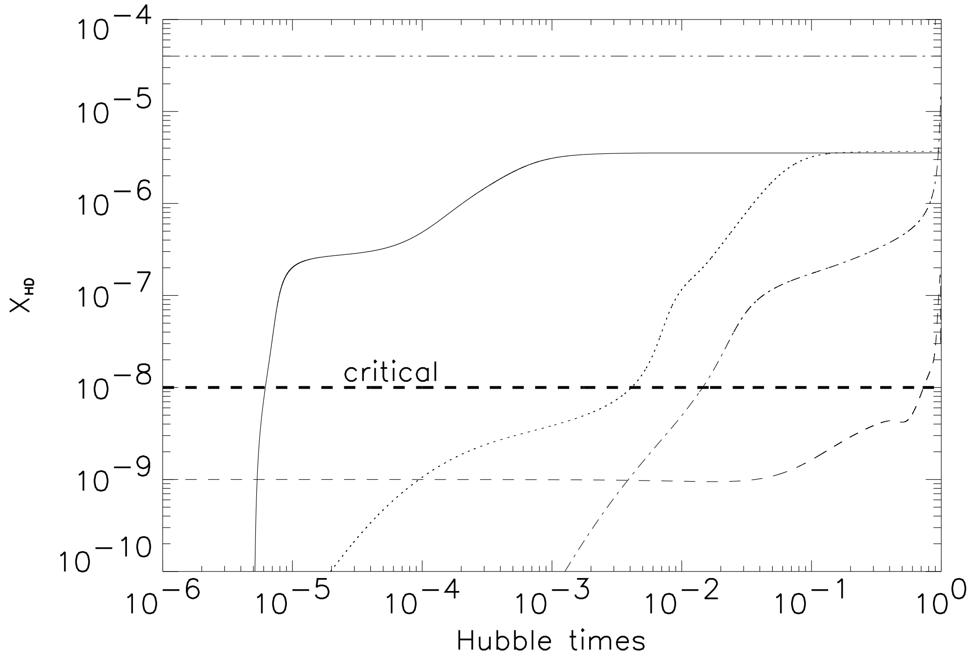

Figure 3. Evolution of HD abundance in four distinct cases. *Solid line:* Gas compressed and heated by a SN explosion with $u_{\rm sh}$= 100 km $\rm s^{-1}$. *Dotted line:* Gas shocked in the build-up of a 3σ fluctuation dark matter halo collapsing at $z \simeq 15$. *Dash-dotted line:* Gas collapsing inside a relic HII region, which is left behind after the death of a very massive Pop III star. *Dashed line:* Gas collapsing inside a minihalo at $z \simeq 20$. In this case, the gas does not experience a strong shock, and is never ionized. Contrary to the other three cases, where the gas went through a fully ionized phase, HD cooling is not important here. The critical HD abundance, shown by the bold dashed line, is defined such that primordial gas is able to cool to the CMB temperature within the fraction of a Hubble time. The CMB sets a minimum floor to the gas temperature, because radiative cooling below this fllor is thermodynamically not possible. The HD abundance exceeds the critical value in a time which is short compared to the Hubble time for all fully-ionized, strongly shocked cases. (Adapted from Johnson & Bromm 2006.)

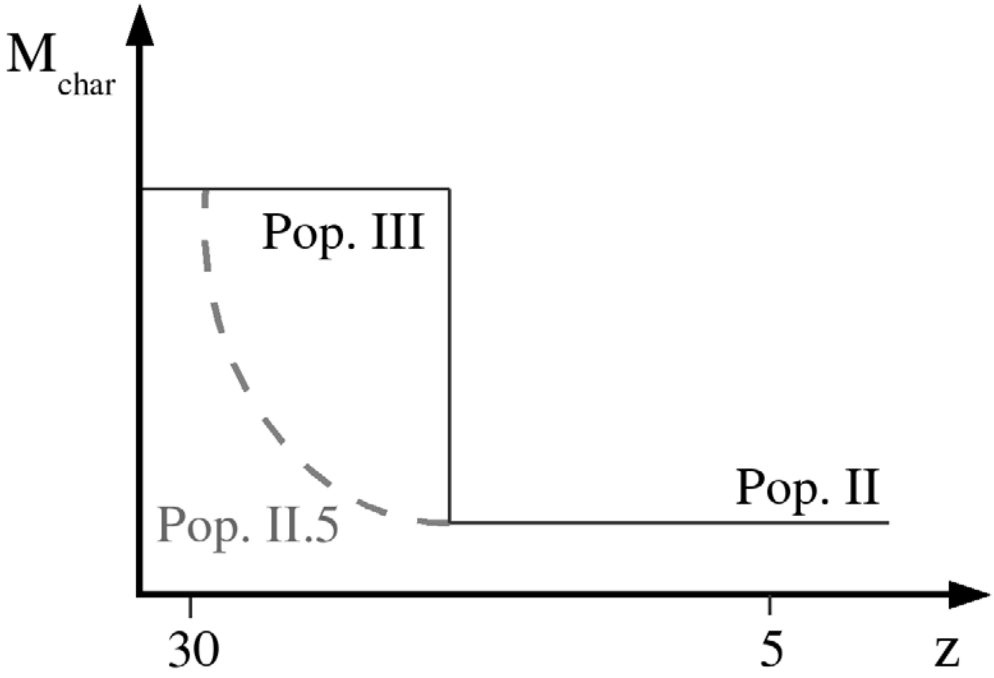

Figure 4. Characteristic mass of stars as a function of redshift. Pop III stars, formed out of metal-free gas, and not going through a fully ionized phase prior to the onset of collapse, have typical masses of $M_* \sim 100 M_\odot$. Pop II stars, formed out of already metal-enriched gas, are formed at lower redshifts, and have typical masses of $M_* \sim 1 M_\odot$. Pop II.5 stars, formed out of strongly shocked, but still virtually metal-free gas, are hypothesized to have typical masses that are intermediate between Pop III and Pop II with $M_* \sim 10 M_\odot$. (Adapted from Johnson & Bromm 2006.)

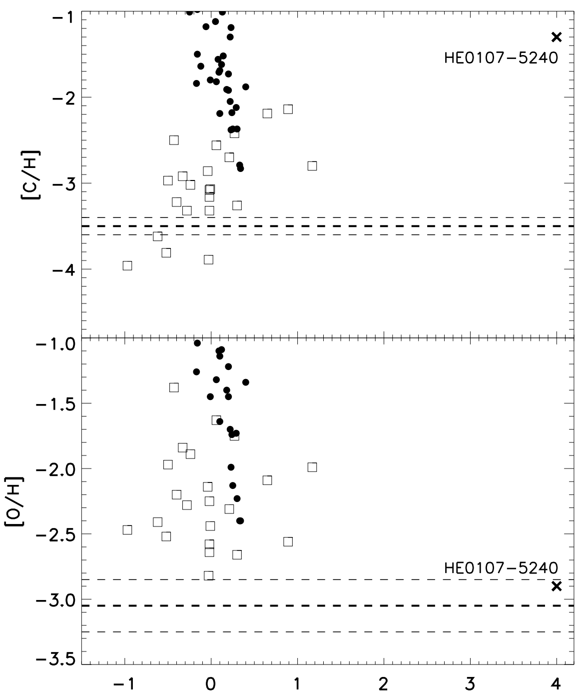

Figure 5. Observed abundances in low-metallicity Galactic halo stars. For both carbon (*upper panel*) and oxygen (*lower panel*), filled circles correspond to samples of dwarf and subgiant stars, and open squares to a sample of giant stars (references in Bromm & Loeb 2003). The dashed lines indicate the predicted critical carbon and oxygen abundances. Highlighted (*cross*) is the location of the extremely iron-poor giant star HE0107-5240. (Adapted from Bromm & Loeb 2003.)

by introducing separate critical abundances for carbon and oxygen, $[\mathrm{C/H}]_{\mathrm{crit}}$ and $[\mathrm{O/H}]_{\mathrm{crit}}$, respectively, where $[\mathrm{A/H}] = \log_{10}(N_{\mathrm{A}}/N_{\mathrm{H}}) - \log_{10}(N_{\mathrm{A}}/N_{\mathrm{H}})_{\odot}$. Since C and O are also the most important coolants throughout most of the cool atomic ISM in present-day galaxies, it is not implausible that these species might be responsible for the global shift in the star formation mode. Under the temperature and density conditions that characterize Population III star formation, the fine-structure lines of O I and C II dominate over all other metal transitions. Cooling due to molecules becomes important only at lower temperatures, and cooling due to dust grains only at higher densities (e.g., Omukai 2000,Schneider et al. 2003). Numerically, the critical C and O abundances are estimated to be: $[\mathrm{C/H}]_{\mathrm{crit}} \simeq -3.5 \pm 0.1$ and $[\mathrm{O/H}]_{\mathrm{crit}} \simeq -3.1 \pm 0.2$.

Even if sufficient C or O atoms are present to further cool the gas, there will be a minimum attainable temperature that is set by the interaction of the atoms with the thermal CMB: $T_{\mathrm{CMB}} = 2.7\,\mathrm{K}(1+z)$ (e.g., Larson 1998; Clarke & Bromm 2003). At $z \simeq 15$, this results in a characteristic stellar mass of $M_* \sim 20 M_{\odot} (n_f/10^4\,\mathrm{cm}^{-3})^{-1/2}$, where $n_f > 10^4\,\mathrm{cm}^{-3}$ is the density at which opacity prevents further fragmentation. It is possible that the transition from the high-mass to the low-mass star formation mode was modulated by the CMB temperature and was therefore gradual, involving intermediate-mass ('Population II.5') stars at intermediate redshifts (Mackey et al. 2003). This transitional population could give rise to the faint SNe that have been proposed to explain the observed abundance patterns in metal-poor stars (Umeda & Nomoto 2002, 2003). When and how uniformly the transition in the cosmic star formation mode did take place was governed by the detailed enrichment history of the IGM. This in turn was determined by the hydrodynamical transport and mixing of metals from the first SN explosions (e.g., Mori, Ferrara, & Madau 2002; Bromm, Yoshida, & Hernquist 2003; Scannapieco, Schneider, & Ferrara 2003; Wada & Venkatesan 2003).

Recently, the additional boost to the cooling of still metal-free gas provided by HD has been investigated (e.g., Johnson & Bromm 2006, and references therein). If the primordial gas goes through a strongly shocked, fully ionized phase prior to the onset of protostellar collapse, cooling is possible down to the temperature of the CMB which sets the minimum floor accessible via radiative cooling (see Figure 3). The lower temperatures in turn could allow the fragmentation into intermediate-mass stars, with masses of order a few tens of $M_\odot$, giving rise to a possible "Population II.5" (see Figure 4).

4. Stellar Fossils

It has long been realized that the most metal-poor stars found in our cosmic neighborhood would encode the signature from the first stars within their elemental abundance pattern. For many decades, however, the observational search has failed to discover a truly first-generation star with zero metallicity. Indeed, there seemed to have been an observational lower limit of [Fe/H] ~ -4 (e.g., Carr 1987). In view of the recent theoretical prediction that most Population III stars were very massive, with associated lifetimes of $\sim 10^6$ yr, the failure to find any 'living' Population III star in the Galaxy is not surprising, as they would all have died a long time ago. Furthermore, theory has predicted that star formation out of extremely low-metallicity gas, with $Z \leq Z_{\rm crit} \sim 10^{-3.5} Z_\odot$, would be essentially equivalent to that out of truly primordial gas. Again, this theoretical prediction was in accordance with the apparent observed lower-metallicity cutoff.

Recently, however, this simple picture has been challenged by the discovery of the star HE0107-5240 with a mass of $0.8 M_\odot$ and an *iron* abundance of [Fe/H] $= -5.3$ (Christlieb et al. 2002; Frebel et al. 2005). This finding indicates that at least some low mass stars could have formed out of extremely low-metallicity gas. Does the existence of this star invalidate the theory of a metallicity threshold for enabling low-mass star formation? A possible explanation (Umeda & Nomoto 2003) could lie in the unusually high abundances of carbon and oxygen in HE0107-5240.

In Figure 5, the theoretical C and O thresholds (Bromm & Loeb 2003) are compared to the observed abundances in metal-poor dwarf and giant stars in the halo of our Galaxy (see Bromm & Loeb 2003 for references). As can be seen, all data points lie above the critical O abundance but a few cases lie below the critical C threshold. All of these low mass stars are consistent with the model since the corresponding O abundances lie above the predicted threshold. The sub-critical [C/H] abundances could have either originated in the progenitor

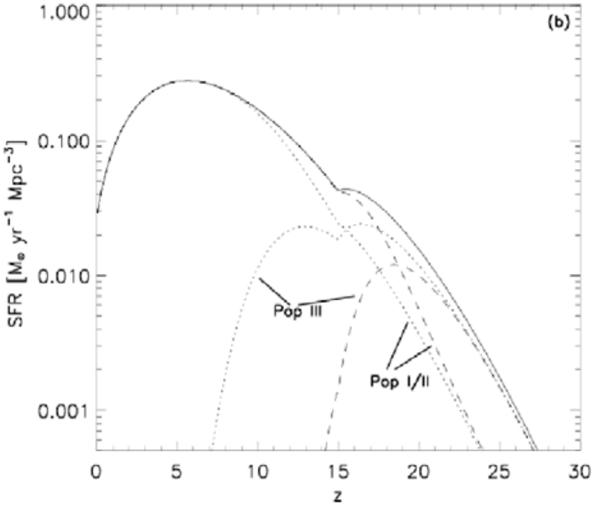

Figure 6. Cosmic comoving star formation rate (SFR) in units of $M_{\odot}$ yr^{-1} Mpc^{-3}, as a function of redshift (from Bromm & Loeb 2006). We assume that cooling in primordial gas is due to atomic hydrogen only, a star formation efficiency of $\eta_* = 10\%$, and reionization beginning at $z_{\rm reion} \approx 17$. *Solid line:* Total comoving SFR. *Dotted lines:* Contribution to the total SFR from Pop I/II and Pop III for the case of weak chemical feedback. *Dashed lines:* Contribution to the total SFR from Pop I/II and Pop III for the case of strong chemical feedback. Pop III star formation is restricted to high redshifts, but extends over a significant range, $\Delta z \sim 10 - 15$.

cloud or from the mixing of CNO-processed material (with carbon converted into nitrogen) into the stellar atmosphere during the red giant phase. Note that the extremely iron-poor star HE0107-5240 has C and O abundances that both lie above the respective critical levels. The formation of this low mass star ($\sim 0.8 M_{\odot}$) is therefore consistent with the theoretical framework considered by Bromm & Loeb (2003).

The lessons from stellar archaeology on the nature of the first stars are likely to increase in importance, since greatly improved, large surveys of metal-poor Galactic halo stars are under way, or are currently being planned.

5. Gamma-ray Bursts from the First Stars

Gamma-ray bursts (GRBs) offer a unique window into star formation in the high-redshift universe. It is of great importance to constrain the Pop III star formation mode, and in particular to determine down to which redshift it continues to be prominent. The extent of the Pop III star formation will affect models of the initial stages of reionization (e.g., Wyithe & Loeb 2003; Ciardi, Ferrara, & White 2003; Sokasian et al. 2004; Yoshida, Bromm, & Hernquist 2004; Alvarez, Bromm, & Shapiro 2006) and metal enrichment (e.g., Mackey et al. 2003;

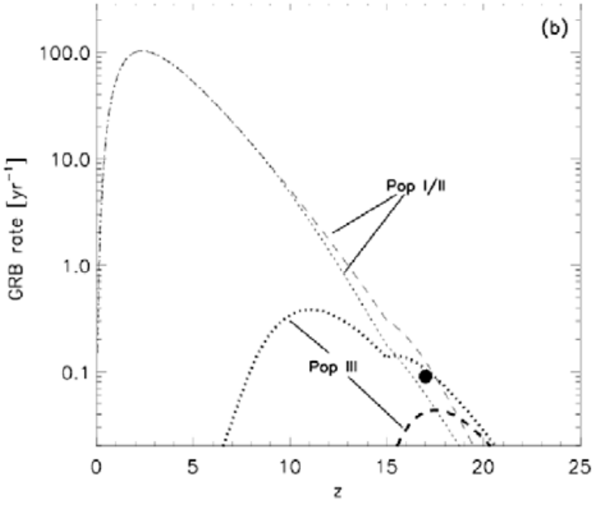

Figure 7. Predicted GRB rate to be observed by *Swift* (from Bromm & Loeb 2006). Shown is the observed number of bursts per year, $dN_{\rm GRB}^{\rm obs}/d\ln(1+z)$, as a function of redshift. All rates are calculated with a constant GRB efficiency, $\eta_{\rm GRB} \simeq 2 \times 10^{-9}$ bursts $M_{\odot}^{-1}$, using the cosmic SFRs from Fig. 6. *Dotted lines:* Contribution to the observed GRB rate from Pop I/II and Pop III for the case of weak chemical feedback. *Dashed lines:* Contribution to the GRB rate from Pop I/II and Pop III for the case of strong chemical feedback. *Filled circle:* GRB rate from Pop III stars if these were responsible for reionizing the universe at $z \sim 17$.

Furlanetto & Loeb 2003, 2005; Schneider et al. 2003; Simcoe, Sargent, & Rauch 2004), and will determine whether planned surveys will be able to effectively probe Pop III stars (e.g., Scannapieco et al. 2005). The constraints on Pop III star formation will also determine whether the first stars could have contributed a significant fraction to the cosmic near-IR background (e.g., Santos, Bromm, & Kamionkowski 2002; Salvaterra & Ferrara 2003; Kashlinsky et al. 2005; Madau & Silk 2005).

To constrain high-redshift star formation, one has to carry out a two-step approach:
(1) What is the signature of GRBs that originate in metal-free, Pop III progenitors? Simply knowing that a given GRB came from a high redshift is not sufficient to reach a definite conclusion as to the nature of the progenitor. Pregalactic metal enrichment was likely quite inhomogeneous, and we expect normal Pop I and II stars to exist in galaxies that were already metal-enriched at these high redshifts (Bromm & Loeb 2006). Pop III and Pop I/II star formation is thus predicted to have occurred concurrently at $z > 5$. How is the predicted high mass-scale for Pop III stars reflected in the observational signature of the resulting GRBs? Our preliminary results indicate that circumburst densities are systematically higher in Pop III environments. GRB afterglows will then be

much brighter than for conventional GRBs. In addition, due to the systematically increased progenitor masses, the Pop III distribution may be biased toward long-duration events.
(2) The modelling of Pop III cosmic star formation histories has a number of free parameters, such as the star formation efficiency and the strength of the chemical feedback. The latter refers to the timescale for, and spatial extent of, the distribution of the first heavy elements that were produced inside of Pop III stars, and subsequently dispersed into the IGM by supernova blast waves. Comparing with theoretical GRB redshift distributions one can use the GRB redshift distribution observed by *Swift* to calibrate the free model parameters. In particular, one can use this strategy to measure the redshift where Pop III star formation terminates.

In Figure 6 and 7, we illustrate this approach (based on Bromm & Loeb 2006). Figure 7 leads to the robust expectation that $\sim 10\%$ of all *Swift* bursts should originate at $z > 5$. This prediction is based on the contribution from Population I/II stars which are known to exist even at these high redshifts. Additional GRBs could be triggered by Pop III stars, with a highly uncertain efficiency. Assuming that long-duration GRBs are produced by the collapsar mechanism, a Pop III star with a close binary companion provides a plausible GRB progenitor. We have estimated the Pop III GRB efficiency, reflecting the probability of forming sufficiently close and massive binary systems, to lie between zero (if tight Pop III binaries do not exist) and ~ 10 times the empirically inferred value for Population I/II (due to the increased fraction of black hole forming progenitors among the massive Population III stars).

A key ingredient in determining the underlying star formation history from the observed GRB redshift distribution is the GRB luminosity function, which is only poorly constrained at present. The improved statistics provided by *Swift* will enable the construction of an empirical luminosity function. With an improved luminosity function, we will be able to re-calibrate the theoretical prediction in Figure 7 more reliably.

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Discussion

Meynet: 1) From what you presented, can we conclude that all very metal-poor stars observed with, let's say an [Fe/H] below - 5, would be C-rich?
2) What can you say about the angular momentum of the first stars? At which fraction of the critical velocity would they be formed?

Bromm: 1) Yes, to first order, they would have to be C- or O-rich.
2) At present, we don't have a good understanding of the Pop III angular momentum properties. This is tied up with the question of whether Pop III stars always form in isolation, or as a member of a multiple or cluster.

van Loon: H_2 is critical for the cooling of a collapsing cloud at zero metallicity. H_2 is difficult to form, and usually grain surface processes are involved as a channel for the formation of H_2. In the absence of dust grains, at zero metallicity, how is H_2 formed?

Bromm: H_2 is formed in the gas phase, involving free electrons as catalysts: 1) $\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \mathrm{h}\upsilon$, 2) $\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^-$. This yields a molecule fraction of order 1/1 000.

Omukai: 1) In your talk, you assumed that onset of nuclear fusion stops the accretion and thus sets the upper mass limit of the first stars. But according to my calculation, the accretion continues even after the star reaches the main sequence. How do you think about this?
2) You derived the critical metallicity for the transition to low mass star formation made by considering only metal line cooling. I speculate that even with smaller amount of metallicity dust cooling induces rapid cooling at high density regime and causes fragmentation. Therefore, the critical metallicity can be lower than your analysis.

Bromm: 1) In Omukai & Palla (2001, 2003) you showed that accretion can continue even after the star has reached the main sequence. Our estimate of $\mathrm{M}_* \sim 120\mathrm{M}_\odot$ after having accreted for one Kelvin-Helmholtz time is only meant as a back-of-the-envelope estimate.
2) I agree that with dust, $\mathrm{Z}_{\mathrm{crit}}$ would be even lower.

Zinnecker: Volker, what is the number density of Pop III stars (number per co-moving volume) in the early universe?

Bromm: Hans, of order a few hundred per co-moving Mpc^3. You need that number to have a significant feedback, radiative or chemical, from Pop III on the IGM.

de Koter: You mentioned that the dimension of the accretion disk that formed in your simulation of the collapse of one of the mini halo's that first formed in the Universe is of order several tens of AU. This is about an order of a magnitude smaller than the characteristic dimension of accretion disks of Herbig and T Tauri stars in the present day universe. Is there a special reason for this?