Session II

First Stars

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André Maeder answering a question.

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From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Formation of the First Stars

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Abstract. How and when did the first generation of stars form at the end of the cosmic dark ages? Quite generically, within variants of the cold dark matter model of cosmological structure formation, the first sources of light are expected to form in $\sim 10^6 M_\odot$ dark matter potential wells at redshifts $z \geqslant 20$. I discuss the physical processes that govern the formation of the first stars. These so-called Population III stars are predicted to be predominantly very massive, and to have contributed significantly to the early reionization of the intergalactic medium. Such an early reionization epoch is inferred from the recent measurement of the Thomson optical depth by the *WMAP* satellite. I address the importance 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, at later times, and present possible observational probes. This transition could have been gradual, giving rise to an intermediate-mass population of still virtually metal-free stars ("Population II.5"). These stars could have given rise to the peculiar class of black-hole forming supernovae inferred from the abundance pattern of extremely iron-poor stars.

Keywords. Cosmology: theory, stars: formation, supernovae: general

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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 $M_* \geqslant 100 M_\odot$ (Bromm, Coppi, & Larson (1999); Bromm, Coppi, & Larson (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

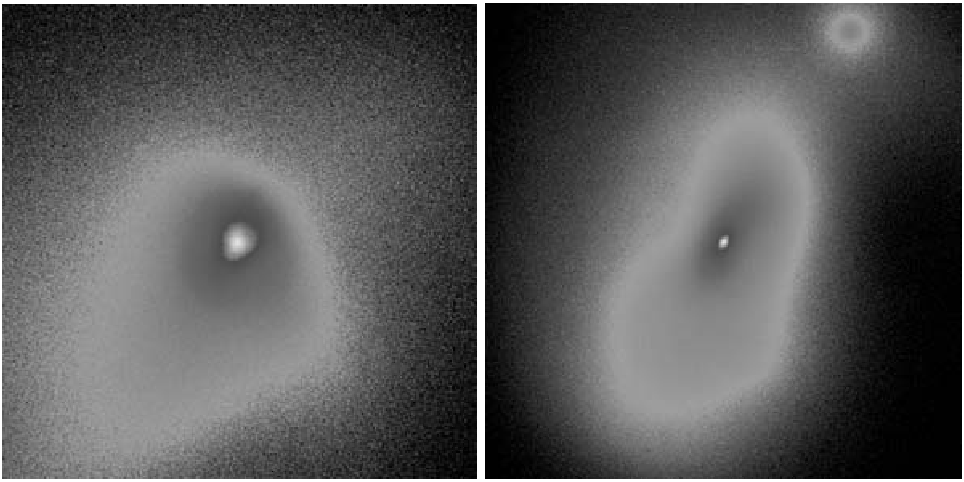

Figure 1. Collapse and fragmentation of a primordial cloud. Shown is the projected gas density at a redshift $z \simeq 21.5$, briefly after gravitational runaway collapse has commenced in the center of the cloud. *Left:* The coarse-grained morphology in a box with linear physical size of 23.5 pc. *Right:* 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).)

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 of upcoming instruments, such as the *James Webb Space Telescope* (JWST) †, 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 mass scale of the first stars. This mass scale is observed to be $\sim 1 M_{\odot}$ in the present-day universe. To investigate

† See http:// ngst.gsfc.nasa.gov.

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, Coppi, & Larson (2002) for details). Improving on earlier work (Bromm, Coppi, & Larson (1999), Bromm, Coppi, & Larson (2002)) by initializing our simulation according to the ΛCDM model, we focus here on an isolated overdense region that corresponds to a $3\sigma-$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), Omukai & Palla (2003); Ripamonti *et al.* (2002); Tan & McKee (2003)). 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,

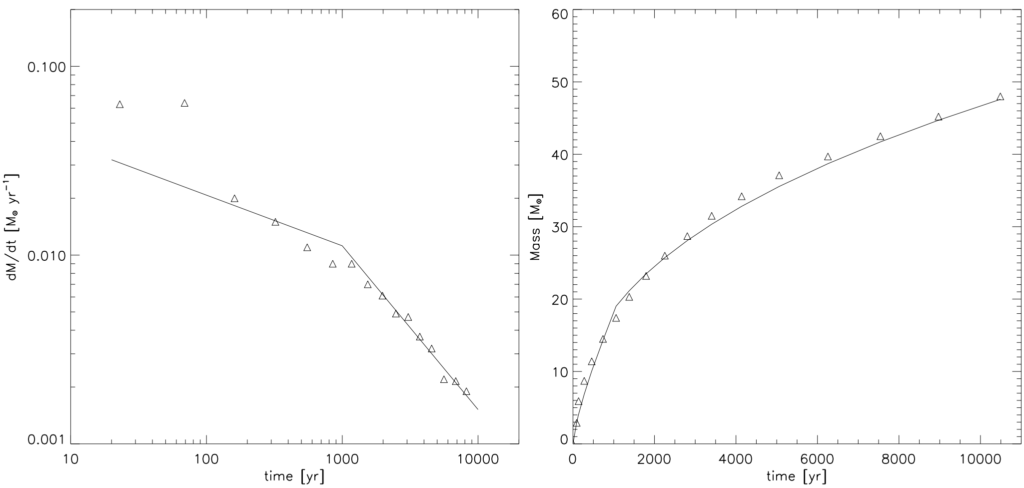

Figure 2. Accretion onto a primordial protostar. The morphology of this accretion flow is shown in Fig. 1. *Left:* Accretion rate (in $M_\odot$ yr^{-1}) vs. time (in yr) since molecular core formation. *Right:* Mass of the central core (in $M_\odot$) vs. time. *Solid line:* Accretion history approximated 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).)

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$\dot{M}_{\rm acc} \sim 0.1 M_{\odot}$ 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); Omukai & Palla (2003); Omukai & Inutsuka (2002); Ripamonti *et al.* (2002); Tan & McKee (2003)). 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 (2003)). 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), Umeda & Nomoto (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 by introducing separate critical abundances for carbon and oxygen, $[{\rm C/H}]_{\rm crit}$ and $[{\rm O/H}]_{\rm crit}$, respectively, where $[{\rm A/H}]= \log_{10}(N_{\rm A}/N_{\rm H}) - \log_{10}(N_{\rm A}/N_{\rm H})_{\odot}$. 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)).

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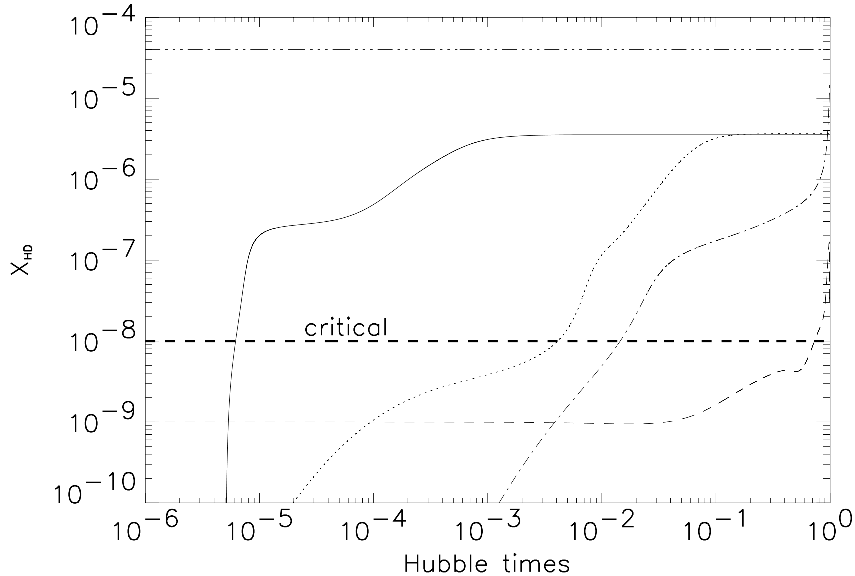

Figure 3. Evolution of HD abundance in four distinct cases. *Solid line:* Gas compressed and heated by a SN explosion with $u_{\rm sh}$= 100 km s^{-1}. *Dotted line:* Gas shocked in the build-up of a 3σ fluctuation dark matter halo collapsing at $z \simeq 15$. *Dash-dotted line:* Gas collapsing inside 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 floor 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 (2005).)

Numerically, the critical C and O abundances are estimated to be: $[{\rm C/H}]_{\rm crit} \simeq -3.5 \pm 0.1$ and $[{\rm O/H}]_{\rm crit} \simeq -3.1 \pm 0.2$.

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: $T_{\rm CMB} = 2.7\,{\rm K}(1+z)$ (e.g., Larson (1998), Clarke & Bromm (2003)). At $z \simeq 15$, this results in a characteristic stellar mass of $M_{*} \sim 20 M_{\odot}(n_f/10^4\,{\rm cm}^{-3})^{-1/2}$, where $n_f > 10^4\,{\rm cm}^{-3}$ 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, Bromm, & Hernquist (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)).

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Recently, the additional boost to the cooling of still metal-free gas provided by HD has been investigated (e.g., Johnson & Bromm (2005), 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 $Z \leqslant Z_{\rm crit} \sim 10^{-3.5} Z_{\odot}$, 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

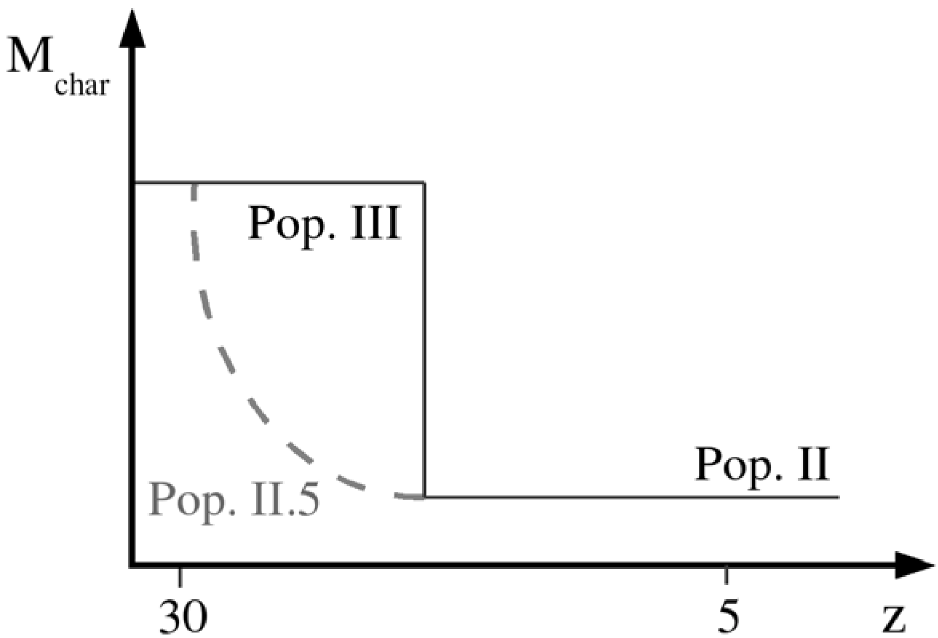

Figure 4. Characteristic mass of stars as a function of redshift. Pop III stars, formed out of metal-free gas, and not going through a fully ionized phase prior to the onset of collapse, have typical masses of $M_* \sim 100 M_{\odot}$. Pop II stars, formed out of already metal-enriched gas, are formed 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 (2005).)

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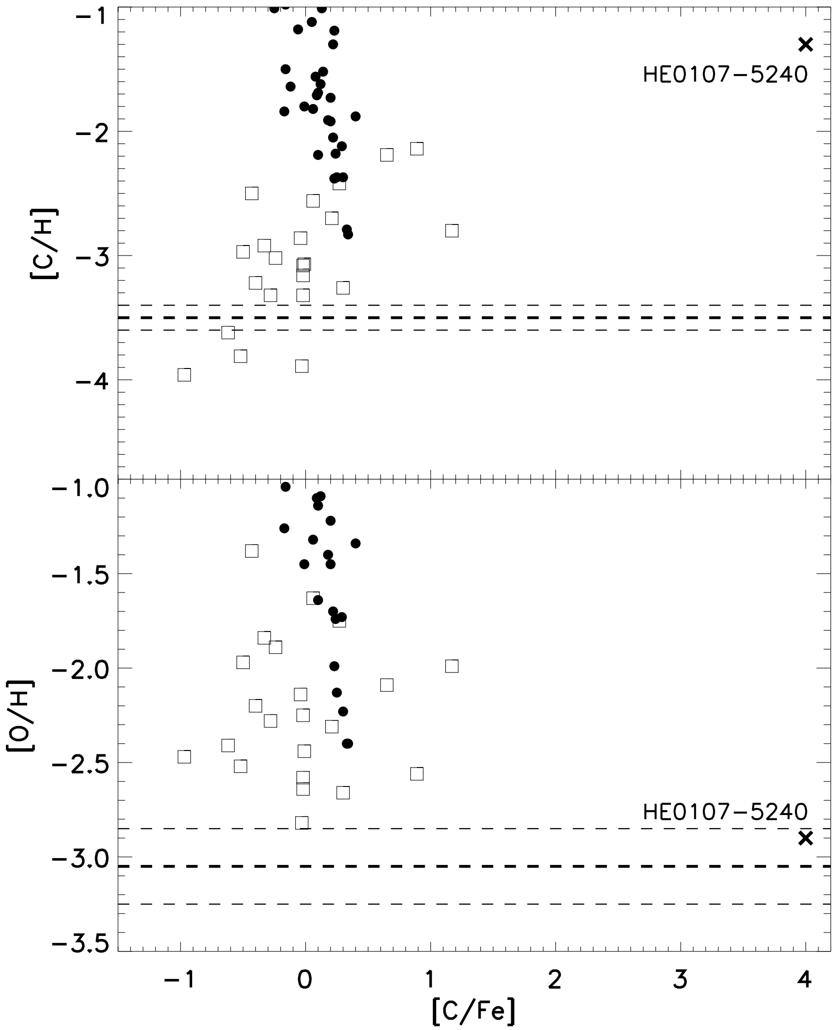

Figure 5. Observed abundances in low-metallicity Galactic halo stars. For both carbon (*upper panel*) and oxygen (*lower panel*), filled circles correspond to samples of dwarf and subgiant stars, and open squares to a sample of giant stars (see Bromm & Loeb (2003) for references). The dashed lines indicate 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)).

et al. (2002); Frebel *et al.* (2005)). This finding indicatesthat 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 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.

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