::

The formation of the first low-mass stars from gas with low carbon and oxygen abundances

Volker Bromm & Abraham Loeb

Astronomy Department, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA

....

The first stars in the Universe are predicted to have been much more massive than the Sun[1–3]. Gravitational condensation, accompanied by cooling of the primordial gas via molecular hydrogen, yields a minimum fragmentation scale of a few hundred solar masses. Numerical simulations indicate that once a gas clump acquires this mass it undergoes a slow, quasi-hydrostatic contraction without further fragmentation[1,2]; lower-mass stars cannot form. Here we show that as soon as the primordial gas—left over from the Big Bang—is enriched by elements ejected from supernovae to a carbon or oxygen abundance as small as ~ 0.01–0.1 per cent of that found in the Sun, cooling by singly ionized carbon or neutral oxygen can lead to the formation of low-mass stars by allowing cloud fragmentation to smaller clumps. This mechanism naturally accommodates the recent discovery[4] of solar-mass stars with unusually low iron abundances ($10^{-5.3}$ solar) but with relatively high ($10^{-1.3}$ solar) carbon abundance. The critical abundances that we derive can be used to identify those metal-poor stars in our Galaxy with elemental patterns imprinted by the first supernovae. We also find that the minimum stellar mass at early epochs is partially regulated by the temperature of the cosmic microwave background.

The microphysics of cooling due to the presence of molecular hydrogen (H_2) within the first gas clouds to condense in the Universe introduces a characteristic temperature ($T_c \approx 100$–200 K) and hydrogen density ($n_c \approx 10^4$ cm^{-3}) to the formation process of the first stars[1,2]. The temperature floor is set by the energy separation of the lowest-lying rotational levels of H_2, and the characteristic density leads to the thermalization of these levels, at which point cooling becomes less efficient. The minimum mass scale for fragmentation is approximately given by the Jeans mass, $M_J \simeq 400 M_\odot (T/200\,\mathrm{K})^{3/2}(n/10^4\,\mathrm{cm}^{-3})^{-1/2}$ where subscript $\odot$ refers to the Sun. The final mass of a star is determined by the accretion process onto the nascent protostellar core, resulting in $M_\star \simeq \alpha M_J$ with $\alpha \lesssim 0.5$ (refs 5, 6). In contrast to the formation mode of massive stars (population III) at high redshifts, fragmentation is observed to favour 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 (or 'metals'), which enable the gas to cool to lower temperatures.

The concept of a 'critical metallicity', Z_{crit}, has been used[7–11] to characterize the transition between population III and population II formation modes (where Z denotes the mass fraction contributed by all heavy elements). Previous studies[7,8,11] have only constrained this important parameter to within a few orders of magnitude, $Z_{crit} \approx 10^{-6}$–$10^{-3} Z_\odot$, under the implicit assumption of solar relative abundances of metals. This assumption is likely to be violated by the metal yields of the first supernovae at high redshifts, for which strong deviations from solar abundance ratios are predicted[12–17]. The cooling rate of the metals depends on their ionization state, which in turn is controlled by the ionizing backgrounds (ultraviolet and X-ray photons or cosmic rays) that were not fully considered in earlier studies.

Here we show that the transition between the above star for-mation modes is driven primarily by fine-structure line cooling of singly ionized carbon or neutral atomic oxygen. We refine earlier estimates of Z_{crit} which did not explicitly distinguish between different coolants, by introducing separate critical abundances for carbon and oxygen, $[C/H]_{crit}$ and $[O/H]_{crit}$, respectively, where $[A/H] = \log_{10}(N_A/N_H) - \log_{10}(N_A/N_H)_\odot$. Why are C and O identified as the key species responsible for the global shift in the star formation mode? We find that under the temperature and density conditions that characterize population III star formation, the most important coolants are O I and C II, whose fine-structure lines dominate all other metal transitions[18]. Cooling due to molecules becomes important only at lower temperatures, and cooling due to dust grains only at higher densities[7,11,18].
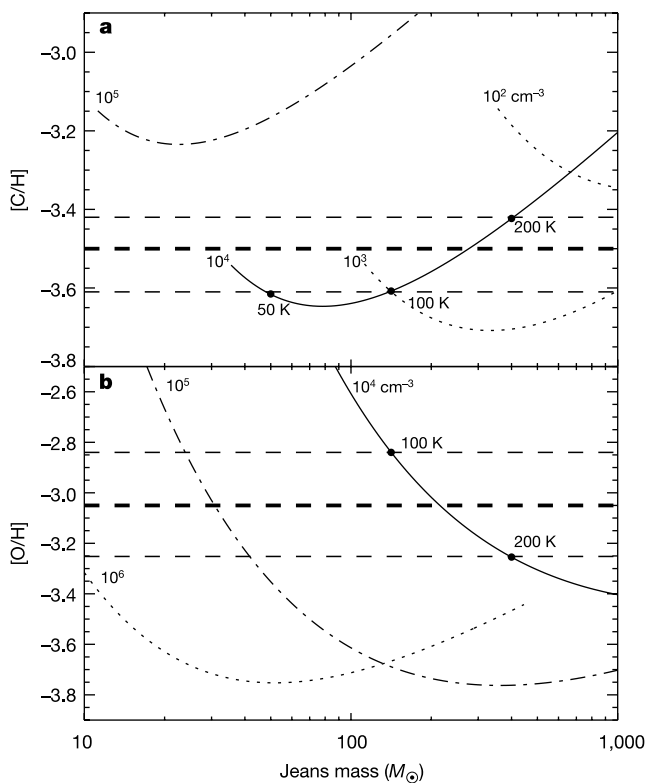
The conditions that terminate the predominance of massive, population III stars have dramatic implications for the reionization history of the Universe. Massive stars are much more efficient at producing ionizing radiation than low mass stars, owing to their high surface temperature ($\sim 10^5$ K). In particular, metal-free stars with a mass $\gtrsim 100 M_\odot$ produce $\sim 5 \times 10^4$ hydrogen ionizing photons per baryon incorporated into them, a yield higher by an order of magnitude than obtained for a present-day mass function of stars[19,20]. Massive stars can therefore reionize the Universe early[21–23] at $z \approx 17$, as required by the recent detection[24] of large-scale polarization anisotropies in the cosmic microwave background. A strong ultraviolet flux just below the Lyman limit ($h\nu < 13.6$ eV) is predicted[25] to be emitted by the same stars that are responsible for the reionization of the intergalactic medium. This soft ultraviolet radiation can penetrate the neutral intergalactic medium and ionize any trace amount of neutral carbon due to its low first-ionization potential of 11.26 eV. Because carbon is highly underabundant, the ultraviolet background can ionize carbon throughout the Universe well before hydrogen reionization. Oxygen, on the other hand, will be predominantly neutral prior to reionization because its ionization potential is 13.62 eV. Cooling is mediated by excitations due to collisions of the respective metal with free electrons or hydrogen atoms. At the low fractional abundances of electrons, $x_e \lesssim 10^{-4}$, expected in the neutral (rapidly recombining) gas at $z \approx 15$, collisions with hydrogen atoms dominate. Even if the gas had initially been ionized to a much higher degree owing to the impact of the supernova ejecta, it would have recombined to the level stated above within its free-fall time: $t_{ff} \approx 5 \times 10^5 (n/10^4\,\mathrm{cm}^{-3})^{-1/2}$ yr. This renders our analysis independent of the very uncertain hydrogen-ionizing backgrounds at high redshifts (cosmic rays or soft X-rays).

We now derive the critical C and O abundances. Our starting point is the characteristic state reached in primordial gas that cools only through molecular hydrogen. For the gas to fragment further (instead of following a slow contraction to a single massive star[1,2]), additional cooling due to C II or O I is required. Fragmentation requires that the radiative cooling rate be higher than the free-fall compressional heating rate. We find the critical metal abundances by equating the two rates: $\Lambda_{CII,OI}(n, T) \simeq 1.5 n k_B T / t_{ff}$, where k_B is Boltzmann's constant. In evaluating this threshold condition, we solve the respective rate equations for C II (a two-level system) and O I (a three-level system), including all possible radiative and collisional transitions[18]. We assume that the emission of the fine-structure lines proceeds under optically thin conditions, as appropriate for the low atomic abundances considered here[18]. We find the critical C and O abundances by setting $n \approx n_c$ and $T \approx T_c$, and estimate the uncertainties by considering a plausible range near these values (100 K $\lesssim T \lesssim$ 200 K).

In Fig. 1, we show the threshold C and O abundances that enable continued fragmentation for various temperature and density values. It is convenient to plot these quantities as functions of the Jeans mass ($\propto T^{3/2} n^{-1/2}$). We find critical abundance values of $[C/H]_{crit} \simeq -3.5 \pm 0.1$ and $[O/H]_{crit} \simeq -3.05 \pm 0.2$. Strictly speaking, these threshold levels are the required abundances in
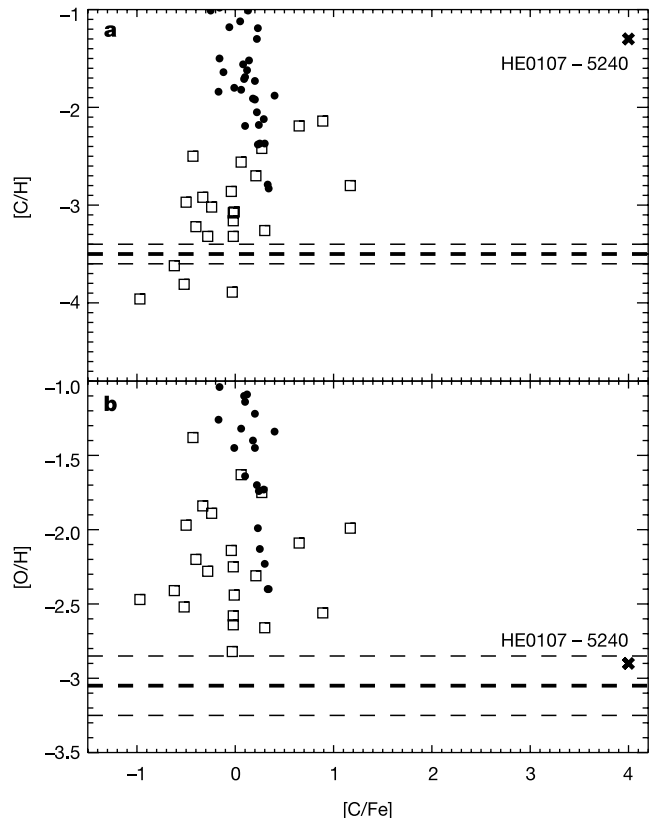
the gas phase. If a fraction of these elements were depleted onto dust grains, then the total C and O elemental abundances would have to be correspondingly higher. Considering the large current uncertainties in modelling the properties and formation channels of dust at low metal abundances[11], we assume the limiting case of zero C and O depletion onto dust when comparing our theoretical predictions with observed stellar abundances.

We stress that even if sufficient C or O atoms are present to cool the gas further, there will be a minimum attainable temperature[6,26] that is set by the interaction of the atoms with the thermal cosmic microwave background $T_{CMB} = 2.7 \, K(1 + z)$. At $z \simeq 15$, this results in a minimum fragment mass of $M_\star \approx 20 M_\odot (n_f/10^4 \, cm^{-3})^{-1/2}$, where $n_f > 10^4 \, cm^{-3}$ is the density at which opacity prevents further fragmentation[27]. It is possible that the transition from the high-mass to the low-mass star formation mode was modulated by the cosmic microwave background temperature and was therefore gradual[6], involving intermediate-mass ('population II.5') stars[10] at intermediate redshifts. This transitional population can give rise to the faint supernovae that have been proposed to explain the observed abundance patterns in metal-poor stars[15,17]. These solar-mass stars themselves should have formed out of metal-poor gas at relatively late times when the cosmic microwave background temperature was sufficiently low.

In relating our results to theoretical nucleosynthetic yields, one has to address the degree of mixing, or dilution, that the supernovae ejecta experience. Supernovae at high redshifts occur in dark matter halos with shallow potential wells, so that the resulting blast wave is predicted[28] to escape into the expanding intergalactic medium. The dilution mass can then be estimated as $M_{dil} \simeq 2E_{SN}/v^2$, where E_{SN} is the explosion kinetic energy, and $v = H(z)r$ is the Hubble velocity at a distance r. Using standard cosmological parameters and ignoring radiative losses[28], we get $M_{dil} \simeq 10^7 M_\odot (E_{SN}/10^{53} \, erg)^{3/5}[(1 + z)/16]^{-3/5}$. In the expected mass range of the pair-instability supernovae[12] and the corresponding explosion energies $E_{SN} \simeq 10^{51} - 10^{53}$ erg, one finds dilution masses that are more than two orders of magnitude larger than typical values for type II supernovae in nearby galaxies[14]. However, depending on the exact values of the ejected mass of C and O and the respective explosion energies, a single supernova event could already lead to [C/H] and [O/H] ratios that 'overshoot' the critical abundances. For example, the abundances resulting from the explosion and subsequent mixing of a pair-instability supernova at the low-mass end[12] are [C/H] $\simeq -2.9$ and [O/H] $\simeq -2.4$, respectively, roughly 0.5 dex above the critical levels. Nevertheless, a single pair-instability supernova at the high-mass end would produce final, mixed abundances still below critical. Because the dilution mass scales as the number of simultaneous supernovae to the 3/5 power while the ejecta mass scales linearly with this number, multiple simultaneous supernovae

Figure 1 Required carbon and oxygen abundances (relative to solar values) for cooling a clump of metal-poor gas faster than its free-fall (compressional heating) time. The minimum abundances are shown as functions of the initial Jeans mass of the clump (with higher abundances allowing the clump to cool and further fragment). **a**, Singly ionized carbon; **b**, neutral oxygen. The curves are labelled by the hydrogen number density in units of cm^{-3}, with the solid curve marking the characteristic density in pre-stellar clumps of metal-poor gas, $n_c \approx 10^4 \, cm^{-3}$. Heavy filled dots indicate particular temperature values. The critical abundance is delineated by the horizontal dashed lines, with a heavy line indicating the central value and the adjacent light lines bracketing the uncertainty within the characteristic temperature range, $T_c \approx 100-200 \, K$, and density, $\sim 10^4 \, cm^{-3}$, of pre-stellar clumps. The figure indicates the minimum metal abundance at which fragmentation into low-mass stars starts, but it does not provide information about the minimum mass of the fragments at the end of the cooling process.

Figure 2 Observed abundances in low-metallicity Galactic halo stars. For both carbon (**a**) and oxygen (**b**), filled circles correspond to samples of dwarf and subgiant stars[29], and open squares to a sample of giant stars[30]. Both data sets were obtained at a high signal-to-noise ratio using the ultraviolet–visual echelle spectrograph (UVES) on the Very Large Telescope (VLT). The dashed lines indicate the predicted level of critical carbon and oxygen abundances from Fig. 1. According to our theoretical model, all low-mass dwarf stars ought to lie above the critical threshold level of at least one of the two elements. Indeed all stars in the existing data sets satisfy this condition. We highlight the location of the extremely iron-poor giant star HE0107−5240 (marked by a cross), whose carbon and oxygen abundances are both above the critical levels[4].

within the same galaxy would be less effective at diluting their metal abundances into the expanding intergalactic medium. But further dilution may occur during the hierarchical assembly of galaxies, as infall may add metal-free gas from the intergalactic medium to the enriched interstellar medium.

In Fig. 2 we compare our theoretical thresholds to the observed C and O abundances in metal-poor dwarf[29] and giant[30] stars in the halo of our Galaxy. 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 our model because the corresponding O abundances lie above the predicted threshold. The sub-critical [C/H] abundances could have originated either 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. To guard against this a posteriori processing of C, dwarf stars should be preferred, as they provide a more reliable record of the primordial abundance pattern that was present at birth. However, because dwarfs are fainter, another strategy would be to focus on giants which show evidence for weak mixing (for example, in terms of high ^{12}C/^{13}C isotope ratio or low ^{14}N abundance). The current data on dwarf stars (filled symbols in Fig. 2) does not yet reach C and O abundances that are sufficiently low to probe the theoretical cooling thresholds. Note also that the extremely iron-poor star HE0107−5240 has C and O abundances that both lie above the respective critical levels (Bessell, M. et al., manuscript in preparation). The formation of this low-mass star ($\sim 0.8 M_\odot$) is therefore consistent with the theoretical framework considered here[11,17].

Our model suggests a powerful new probe of the first supernovae to have exploded in the Universe. By selecting an unbiased new sample of Galactic halo stars with C or O abundances close to the theoretical critical values, it should be possible to sample individual supernova events originating in the earliest epochs of cosmic star formation. The value of [C/Fe] would be indicative of the particular supernova type. For example, the very high value of [C/Fe] $\simeq +4$ observed[4] in HE0107−5240 can be explained by a core-collapse supernova which leaves behind a black hole after fallback of most of the outer stellar envelope[17]. Modern surveys select metal-poor stars based on their weak or absent Ca ɪɪ K-lines. Our model suggests that a better strategy to select truly 'second generation' stars is to look for stars with the lowest abundances of carbon and oxygen. □

1. Abel, T., Bryan, G. & Norman, M. The formation of the first star in the universe. Science 295, 93–98 (2002).
2. Bromm, V., Coppi, P. S. & Larson, R. B. The formation of the first stars. I. The primordial star-forming cloud. Astrophys. J. 564, 23–51 (2002).
3. Nakamura, F. & Umemura, M. The stellar initial mass function in primordial galaxies. Astrophys. J. 569, 549–557 (2002).
4. Christlieb, N. et al. A stellar relic from the early Milky Way. Nature 419, 904–906 (2002).
5. McKee, C. F. & Tan, J. C. Massive star formation in 100,000 years from turbulent and pressurized molecular clouds. Nature 416, 59–61 (2002).
6. Clarke, C. J. & Bromm, V. The characteristic stellar mass as a function of redshift. Mon. Not. R. Astron. Soc. 343, 1224–1230 (2003).
7. Omukai, K. Protostellar collapse with various metallicities. Astrophys. J. 534, 809–824 (2000).
8. Bromm, V., Ferrara, A., Coppi, P. S. & Larson, R. B. The fragmentation of pre-enriched primordial objects. Mon. Not. R. Astron Soc. 328, 969–976 (2001).
9. Schneider, R., Ferrara, A., Natarajan, P. & Omukai, K. First stars, very massive black holes, and metals. Astrophys. J. 571, 30–39 (2002).
10. Mackey, J., Bromm, V. & Hernquist, L. Three epochs of star formation in the high-redshift universe. Astrophys. J. 586, 1–11 (2003).
11. Schneider, R., Ferrara, A., Salvaterra, R., Omukai, K. & Bromm, V. Low-mass relics of early star formation. Nature 422, 869–871 (2003).
12. Heger, A. & Woosley, S. E. The nucleosynthetic signature of population III. Astrophys. J. 567, 532–543 (2002).
13. Qian, Y.-Z., Sargent, W. L. W. & Wasserburg, G. J. The prompt inventory from very massive stars and elemental abundances in Lyα systems. Astrophys. J. 569, L61–L64 (2002).
14. Qian, Y.-Z. & Wasserburg, G. J. Determination of nucleosynthetic yields of supernovae and very massive stars from abundances in metal-poor stars. Astrophys. J. 567, 515–531 (2002).
15. Umeda, H. & Nomoto, K. Nucleosynthesis of zinc and iron peak elements in population III type II supernovae. Astrophys. J. 565, 385–404 (2002).
16. Sneden, C. & Cowan, J. J. Genesis of the heaviest elements in the Milky Way Galaxy. Science 299, 70–75 (2003).
17. Umeda, H. & Nomoto, K. First-generation black-hole-forming supernovae and the metal abundance pattern of a very iron-poor star. Nature 422, 871–873 (2003).
18. Hollenbach, D. & McKee, C. F. Molecule formation and infrared emission in fast interstellar shocks. Astrophys. J. 342, 306–336 (1989).
19. Tumlinson, J. & Shull, J. M. Zero-metallicity stars and the effects of the first stars on reionization. Astrophys. J. 528, L65–L68 (2000).
20. Bromm, V., Kudritzki, R. P. & Loeb, A. Generic spectrum and ionization efficiency of a heavy initial mass function for the first stars. Astrophys. J. 552, 464–472 (2001).
21. Cen, R. The implications of Wilkinson Microwave Anisotropy Probe observations for population III star formation processes. Astrophys. J. 591, L5–L8 (2003).
22. Sokasian, A., Yoshida, N., Abel, T., Hernquist, L. & Springel, V. Cosmic reionisation by stellar sources: Population III stars. Mon. Not. R. Astron. Soc. (submitted); preprint at ⟨http://xxx.lanl.gov/astro-ph/0302213⟩ (2003).
23. Wyithe, J. S. B. & Loeb, A. Was the universe reionized by massive metal-free stars? Astrophys. J. 588, L69–L72 (2003).
24. Kogut, A. et al. Wilkinson Microwave Anisotropy Probe WMAP first year observations: TE polarization. Astrophys. J. Suppl. 148, 161–173 (2003).
25. Bromm, V. & Loeb, A. Formation of the first supermassive black holes. Astrophys. J. 596, 34–46 (2003).
26. Larson, R. B. Early star formation and the evolution of the stellar initial mass function in galaxies. Mon. Not. R. Astron. Soc. 301, 569–581 (1998).
27. Rees, M. J. Opacity-limited hierarchical fragmentation and the masses of protostars. Mon. Not. R. Astron. Soc. 176, 483–486 (1976).
28. Bromm, V., Yoshida, N. & Hernquist, L. The first supernova explosions in the universe. Astrophys. J. (in the press); preprint at ⟨http://xxx.lanl.gov/astro-ph/0305333⟩ (2003).
29. Akerman, C. J., Carigi, L., Nissen, P. E., Pettini, M. & Asplund, M. The evolution of the C/O ratio in metal-poor halo stars. Astron. Astrophys. (submitted).
30. Cayrel, R. et al. Abundance patterns and supernova yields in the early Galaxy from C to Zn. Astron. Astrophys. (submitted).

....

A coherent three-dimensional Fermi surface in a high-transition-temperature superconductor

N. E. Hussey[1]**, M. Abdel-Jawad**[1]**, A. Carrington**[1]**, A. P. Mackenzie**[2] **& L. Balicas**[3]

[1]*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK*
[2]*School of Physics and Astronomy, University of St Andrews, St Andrews, Fife KY16 9SS, UK*
[3]*National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32306, USA*

....

All conventional metals are known to possess a three-dimensional Fermi surface, which is the locus in reciprocal space of the long-lived electronic excitations that govern their electronic properties at low temperatures. These excitations should have well-defined momenta with components in all three dimensions. The high-transition-temperature (high-T_c) copper oxide superconductors have unusual, highly two-dimensional properties above the superconducting transition[1]. This, coupled with a lack of unambiguous evidence for a three-dimensional Fermi surface, has led to many new and exotic models for the underlying electronic ground state[2]. Here we report the observation of polar angular magnetoresistance oscillations[3] in the overdoped superconductor $Tl_2Ba_2CuO_{6+\delta}$ in high magnetic fields, which firmly establishes the existence of a coherent three-dimensional Fermi surface. Analysis of the oscillations reveals that at certain symmetry points, however, this surface is strictly two-dimen-