Probing the Formation of the First Low-Mass Stars with Stellar Archaeology

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ABSTRACT
We investigate the conditions under which the first low-mass stars formed in the Universe by confronting theoretical predictions governing the transition from massive Population III to low-mass Population II stars with recent observational C and/or O abundance data of metal-poor Galactic stars. We introduce a new “observer-friendly” function, the transition discriminant $D_{\text{trans}}$, which provides empirical constraints as well as a powerful comparison between the currently available data of metal-poor halo stars and theoretical predictions of the formation of the first low-mass stars ($\lesssim 1M_\odot$). Specifically, we compare the empirical stellar results with the theory that fine-structure lines of C and O dominate the transition from Pop III to Pop II in the early Universe. We find the currently-available data for halo stars as well as for dwarf galaxies and globular clusters to be consistent with this theory. An explanation for the observed lack of metal-poor stars in dwarf galaxies and globular clusters is also suggested. Finally, we predict that any star to be found with $[\text{Fe}/H] \lesssim -4$ should have enhanced C and/or O abundances. The high C and O abundances of the two most iron-poor stars are in line with our prediction.

Key words: cosmology: early Universe — stars: abundances — stars: Population II — Galaxy: halo — Galaxy: stellar content — techniques: spectroscopic

1 INTRODUCTION
One of the most intriguing aspects of modern cosmology is the formation of the first stars and galaxies. It is now widely believed that these first stars were very massive; numerical simulations show that the collapse and fragmentation of primordial gas, where cooling relies on molecular hydrogen only, leads to Pop III stars with masses $\geq 100M_\odot$ (e.g. Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006). With few cooling mechanisms available, low mass star formation appears to have been initially suppressed. To enable the formation of low mass ($\lesssim 1M_\odot$) Pop II stars, additional metal coolants, generated in the first supernovae, are required (e.g. Omukai 2000; Bromm et al. 2001). Little is known about the initial chemical enrichment of the Universe. However, the onset of metal-pollution in the early Universe must have played an important part in the transition from massive Pop III to low-mass Pop II objects observable today.

Currently, two general classes of competing models for the Pop III – Pop II transition are discussed in the literature: (i) atomic fine-structure line cooling (Bromm & Loeb 2003; Santoro & Shull 2006); and (ii) dust-induced fragmentation (e.g. Schneider et al. 2006). Within the fine-structure model, CII and OI have been suggested as main coolants (Bromm & Loeb 2003), such that low-mass star formation can occur in gas that is enriched beyond critical abundances of $[\text{C}/\text{H}]_{\text{crit}} \approx -3.5 \pm 0.1$ and $[\text{O}/\text{H}]_{\text{crit}} \approx -3 \pm 0.2$.

The dust-cooling model, on the other hand, predicts critical abundances that are typically smaller by a factor of $10^{-100}$. This order-of-magnitude difference is much larger than the uncertainties within the fine-structure line model itself, which are still substantial, regarding the precise value of the critical abundances. Also, elements other than C and O (such as Si and Fe) might contribute to the cooling (e.g. Santoro & Shull 2006), but are unlikely to exceed a factor of a few in the overall cooling rate.

Without metals, the primordial gas converges to the characteristic, or ‘boiling’, state of $T_{\text{char}} \approx 200$ K and $n_{\text{char}} \approx 10^4$ cm$^{-3}$. Numerical simulations identify this state as the main reason for the high mass-scale of Pop III stars, because the gas undergoes a phase of slow, quasi-hydrostatic contraction during which any inhomogeneities that could seed further subfragmentation are wiped out by pressure.

$[X/Y] = \log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$, for elements X, Y.  

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forces (see Bromm & Larson 2004 for details). Cooling from dust, rather than metals in the gas phase, would only become important at higher densities, without influencing the evolution toward the loitering state, and hence the high mass-scale of Pop III star formation (Bromm & Loeb 2003).

Ultimately, this theoretical debate has to be decided empirically. A way forward is to extensively test the fine-structure line model with observational data of C and O abundances found in old Galactic metal-poor stars. In order to find the oldest, most “primordial” low mass stars, Bromm & Loeb (2003) suggested to search for the most C- and O-poor objects. Such abundances should reflect the level of a star’s primordiality independent of the abundances of heavier elements (e.g. Fe). They may thus provide an important and feasible observational tool to constrain the formation mechanisms of the first low-mass stars in the high-redshift Universe (e.g. Salvadori et al. 2007) while also offering an empirical discrimination between the two cooling models. Such constraints, in turn, should also provide clues to the relevance of the first generations of stars to cosmic reionization (e.g. Tumlinson et al. 2004). Detailed knowledge about the first epoch of star formation will also allow improved predictions for future high-redshift observations (e.g. Barkan & Loeb 2007). Together with the currently available data, the imminent arrival of large samples of metal-poor stars such as from SEGUE or LAMOST (Beers & Christlieb 2005), and the Southern Sky Survey in the near future, provides an ideal test bed to empirically constrain and possibly differentiate between different cooling theories.

2 THE TRANSITION DISCRIMINANT

To facilitate this test, we first note that we need a criterion for low-mass star formation that combines cooling due to C II and O I. Our discussion is based on the theory presented in Bromm & Loeb (2003), and we here only summarize the main points of that theory in an idealized and simplified way for the convenience of the reader. To this extent, let us consider the balance between fine-structure line cooling and adiabatic compression heating:

$$\Lambda_{\text{tot}} = \Lambda_{\text{CII}} + \Lambda_{\text{OI}} \geq \Gamma_{\text{ad}},$$

where all terms have to be evaluated at $n_{\text{char}}$, $T_{\text{char}}$. Heating due to adiabatic compression is given by

$$\Gamma_{\text{ad}} \approx 1.5 n_{\text{char}} \frac{k B T_{\text{char}}}{t_{\text{ff}}} \sim 2 \times 10^{-23} \text{ ergs s}^{-1} \text{ cm}^{-3},$$

where $t_{\text{ff}} \sim 5 \times 10^5$ yr is the free-fall time at the characteristic state. The cooling terms are (e.g. Stahler & Palla 2003):

$$\Lambda_{\text{OI}} \approx 2 \times 10^{-29} \text{ ergs s}^{-1} \text{ cm}^{-3} \left( \frac{n_{\text{O}}}{n_{\text{H}}} \right) / \left( \frac{n_{\text{O}}}{n_{\text{H}}} \right)_{\odot},$$

and

$$\Lambda_{\text{CII}} \approx 6 \times 10^{-29} \text{ ergs s}^{-1} \text{ cm}^{-3} \left( \frac{n_{\text{C}}}{n_{\text{H}}} \right) / \left( \frac{n_{\text{C}}}{n_{\text{H}}} \right)_{\odot}. \quad (4)$$

Equation (1) can then be written as

$$10^{[\text{C/H}]} + 0.3 \times 10^{[\text{O/H}]} \gtrsim 10^{-3.5}. \quad (5)$$

We thus introduce a new function, the ‘transition discriminant’:

$$D_{\text{trans}} \equiv \log_{10} \left( 10^{[\text{C/H}]} + 0.3 \times 10^{[\text{O/H}]} \right),$$

such that low-mass star formation requires $D_{\text{trans}} > D_{\text{trans, crit}} \approx -3.5 \pm 0.2$. This function reproduces the critical values in Bromm & Loeb (2003) for the cases where only C or O are contributing to the cooling at the loitering state, and approximates the case where both are present by assuming that the individual cooling rates are simply added. The theoretical uncertainty estimated here again approximately reflects the analysis in Bromm & Loeb (2003). However, the true error could be significantly higher, but is difficult to reliably estimate without carrying out sophisticated three-dimensional simulations that incorporate all the relevant microphysics. Such a comprehensive investigation is beyond the scope of this paper.

We note here that Bromm & Loeb (2003) attempted to test their fine-structure model with (rather limited) observational data for C and O available at the time. The $D_{\text{trans}}$ function now has the important advantage that cosmologically relevant measurements can be obtained from stellar C and/or O abundances; in particular also from the common cases where only one of the two abundances is known.

3 DATA ON METAL-POOR STARS

We collected data for C and/or O abundances for a wide range of metal-poor stars in the cases where only one of the two abundances is available, $D_{\text{trans}}$ is a lower limit. Since we are searching for stars with the lowest C and O abundances, knowledge of only one abundance is already sufficient to discriminate whether the star lies above $D_{\text{trans, crit}}$. We are limited, in most cases, to the observations of metal-poor giants. As these stars ascend the red giant branch (RGB), internal mixing takes place that changes the surface C abundance. A consequence of CNO processing is an increase of the N abundances at the expense of C. Hence, such mixed objects appear to have low(er) C abundances that do not reflect the chemical composition with which they were born.

In the absence of information of the N abundance it is difficult to assess the degree of mixing the star has undergone. A rough estimate, however, can be obtained from the luminosity of the objects. Gratton et al. (2000) investigated abundances of moderately metal-poor stars of different evolutionary stages, traced by luminosity. At log $L/L_\odot \sim 2$ they find a decline of C abundances in line with the star ascending the giant branch beyond the RGB-bump (Charbonnel et al. 1998) that is responsible for extra mixing processes. According to Figure 10 and Table 7 in Gratton et al. (2000), we thus correct the C abundances of stars with luminosities log $L/L_\odot > 2$ by simply applying an appropriate offset. Spite et al. (2005) have available CNO abundances which allowed them to extensively test their sample of giants for signs of mixing. We corrected their “mixed” giants in the same way as the other giants with no available “mixing” information. For comparison, we also calculated C-depletion-corrected lower limits of $D_{\text{trans}}$ for objects that are enhanced.

2 The data table is available on request from the first author.
in C (but have no O data available). As expected, the C-rich objects are separated from the “C-normal” stars. Amongst those stars are the two most iron-poor stars (Christlieb et al. 2002; Frebel et al. 2005) which have large C and O over-abundances.

In Figure 1 (top panel) we test $D_{\text{trans}}$ with halo data. We remind the reader that most of the data are lower limits because of missing C or O abundances. The C-based lower limits, however, are much more robust than those derived from O because $D_{\text{trans}}$, by definition, is dominated by the C abundance. All stars lie above the “forbidden zone” (as marked in Figure 1) or within a typical observational error (0.2 to 0.3 dex) to the critical limit of $D_{\text{trans}}$ (solid line). There appears to be a lower envelope of the overall distribution of the data. Keeping in mind that most of the values are lower limits, this envelope depicts the solar C and O abundances.

In the lower panel of Figure 1 we show globular cluster and dSph galaxy data collected from the literature. Most of the stars only have an O abundance available. With one exception, none of them has a metallicity less than $[\text{Fe/H}] \sim -2.5$. This finding has recently been investigated by Helmi et al. (2006) who consistently find a significant lack of metal-poor stars with $[\text{Fe/H}] < -3.0$ in several dSph galaxies. In the absence of low metallicity stars these dSph systems must have had available sufficient amounts of at least C and O at an early time to avoid the formation of very metal-poor stars.

4 DISCUSSION AND IMPLICATIONS

4.1 Selection Effects

We caution that the sample of collected data is not complete. The attempt was rather to populate the diagram with different groups of objects to study the overall stellar behaviour. Purposely, we included stars with normal and enhanced C. Any currently seen “substructure” (e.g. the two groups that appear to be well separated) within the data results from our limited selection. Hence, further data should be added to fully map the diagram to clearly identify the “observable” $D_{\text{trans}}$ region(s).

Despite our interest in stars with low C and O abundances, we note that there is a simple observational bias against C and O deficient objects. Obviously, it is easier to measure high abundances resulting in strong spectral features rather than weak ones. In particular, it is difficult, if not impossible, to detect features from elements of low abundances in warmer, unevolved main-sequence stars. Insufficient data quality may lead to additional non-detections against C and O deficient objects. Obviously, it is easier to measure high abundances resulting in strong spectral features rather than weak ones. In particular, it is difficult, if not impossible, to detect features from elements of low abundances in warmer, unevolved main-sequence stars. Insufficient data quality may lead to additional non-detections.

For the region $-4 \lesssim [\text{Fe/H}] \lesssim -3.0$, close to the “forbidden zone” (see Figure 1), we attempted to collect as much data as possible to avoid missing any extremely C-O deficient objects. Since no stars are currently known with $-5 \lesssim [\text{Fe/H}] \lesssim -4$ no data are missing from this region. If C and O indeed played such an important role in the formation of the first low-mass stars, it is crucial to obtain further information by means of more objects (particularly main sequence stars) with C and O deficiencies. These stars can provide the most accurate picture of the chemical conditions in the early Universe in terms of the availability of cooling agents. It is not clear at this point what the lower end of C and O underabundances may be, and the current data, strictly speaking, only provide an observational upper limit on the critical level of $D_{\text{trans}}$. We therefore encourage observers to search for more objects with C and O deficiencies to obtain good measures of $D_{\text{trans}}$ as close as possible to the critical value, or even below it.

Regardless of observational difficulties, it has been sug-
gested that the most metal-poor objects are more likely to reside in the bulge rather than in the halo of the Galaxy (Diemand et al. 2005). This may imply an additional selection effect of our sample. However, recent work by Scannapieco et al. (2006) has shown that the fraction of metal-poor stars in the halo may not differ greatly from that in the bulge (see also Brook et al. 2006), suggesting that the halo abundances shown in Figure 4 may indeed be representative of the most metal-poor stars in the Milky Way (but see Greif & Bromm 2006).

4.2 Constraints on Early Low-Mass Star Formation

We use stellar archaeology to observationally constrain theoretical ideas concerning the formation of the first low-mass stars. In particular, our literature sample of halo stars provides a firm observational test for the critical metallicity as predicted by Bromm & Loeb (2003). No star is lying in the forbidden zone. This behaviour is consistent with fine-structure line cooling of C and O governing the transition from PopIII to PopII stars in the early Universe. It is also consistent with the theory based on dust cooling (Schneider et al. 2006), which predicts a much lower critical metallicity. However, this latter theory cannot easily explain the complete absence of any stars with $\frac{\text{Fe}}{\text{H}} < -4$ with the exception of two objects that display rather exotic, non-solar-scaled, abundance patterns. Their unusual behaviour is clearly reflected in our diagram. If they were to have solar-scaled abundances at $\frac{\text{Fe}}{\text{H}} < -5$, they would need to follow the trend given by all the other stars and would fall right into the forbidden zone. This would have been in conflict with our prediction. We note though, that stars with $D_{\text{trans}} < -3.5$ might have formed in the early Universe. However, according to the Bromm & Loeb (2003) theory, they would not have been of low-mass, and hence would have already died a long time ago, rendering them unobservable in present-day surveys. As a consequence, any stars with iron abundances lower than $\frac{\text{Fe}}{\text{H}} < -4$ should not display scaled-down solar abundance patterns as already found in the two stars with $\frac{\text{Fe}}{\text{H}} < -5$. The chemical behaviour, at least concerning C and O, should be very different, in line with a $D_{\text{trans}}$ value above the critical threshold.

4.3 Dwarf Galaxy and Globular Cluster Populations

The paucity of stars with $\frac{\text{Fe}}{\text{H}} < -2.5$ in dSph galaxies and globular clusters, as compared to those in the Galactic halo, suggests that the most metal-poor stars in these systems formed in a different environment (e.g. Helmi et al. 2006). Many globular clusters are likely to have formed in merging galaxies, (e.g. Ashman & Zepf 1992, 2001). Likewise, it has been suggested that some dwarf galaxies may form in the tidal tails of merging galaxies (Barnes & Hernquist 1992, Elmegreen et al. 1993). Wetzstein et al. (2003). Also, interestingly, the oldest populations of stars in local dwarf galaxies appear to be very similar in age to the oldest Galactic globular clusters (Grebel & Gallagher 2004), consistent with these systems having formed through mergers in the early evolution of the Milky Way and the Local Group.

If globular clusters and dwarf galaxies do indeed form in the mergers of previous-generation galaxies, then the initial metallicity of the gas in these systems would have been that of the larger, merging galaxies responsible for their formation. The most metal-poor globular cluster and dwarf galaxy stars would then have formed from gas enriched by previous episodes of star formation that occurred in their parent merging galaxies. The merging galaxies themselves would, in turn, contain halo stars that formed at earlier epochs characterised by gas of lower metallicity. This may explain the lack of stars with $\frac{\text{Fe}}{\text{H}} \lesssim -3$ observed in local dSph galaxies, as well as the difference between the metal-poor tail of the metallicity distribution of these systems and that of the Galactic halo (Helmi et al. 2006; Metz & Kroupa 2007).

Recent simulations of the formation of dwarf galaxies from primordial gas at high redshift (e.g. Ricotti & Gnedin 2003, Kawata et al. 2006; Ripamonti et al. 2004) predict a metal-poor tail of the metallicity distribution that extends well below $\frac{\text{Fe}}{\text{H}} < -3$. Clearly, this is not observed for the nearby dSph galaxies observed by Helmi et al. (2006). This may be further evidence that some dwarf galaxies are formed in the mergers of pre-enriched larger galaxies, as opposed to being formed from primordial gas in the early Universe.

4.4 Low-mass Star Formation at High Redshift

While the enrichment of the primordial gas to levels of $D_{\text{trans}} \gtrsim -3.5$ may be required for the formation of low-mass stars, this may not be a sufficient requirement on its own. It has been suggested that the temperature floor set by the cosmic microwave background, $T_{\text{CMB}} = 2.7 \text{K (1+z)}$, may imply a redshift dependent characteristic mass of stars formed in the early Universe (e.g. Uehara & Inutsuka 2000; Clarke & Bromm 2003; Johnson & Bromm 2004; but see also Omukai et al. 2000). Gas cannot radiatively cool to below $T_{\text{CMB}}$, hence, the fragmentation mass in collapsing gas clouds may be larger, in general, at higher redshifts. Thus, low-mass stars ($\lesssim 1 M_\odot$) that can survive until today may not readily form above a certain redshift, $z_{\text{trans}}$, above which only higher mass stars are likely to form, regardless of the metallicity of the gas.

This scenario suggests an explanation for the observed lack of scatter in the abundance ratios of homogeneously analysed low metallicity stars (Cayrel et al. 2004; see also Karlsson & Gustafsson 2003). While the formation of massive stars likely begins at redshifts $z \gtrsim 20$, stars with masses $\lesssim 1 M_\odot$ may not be able to form until later times when the $T_{\text{CMB}}$ is sufficiently low, at redshifts $z \lesssim z_{\text{trans}}$. This delay between the onset of high-mass and low-mass star formation may have given ample time for the ejecta from many supernovae to become mixed in the build-up of the Galaxy before low-mass stars were finally able to form. If indeed there is an explicit redshift dependence on the minimum mass of stars that may form, then future observations of high redshift systems should find that only massive stars form at redshifts $z \gtrsim z_{\text{trans}}$, largely independent of the degree of metal-en-
richment in these systems. The recent discovery of a massive post-starburst galaxy at $z \sim 0.5$ by Mobasher et al. (2005) allows to place a firm limit of $z_{\text{trans}} \gtrsim 7$.

5 CONCLUSION

Our literature collection of metal-poor abundance data supports the notion that fine-structure C and O line cooling predominantly drives the transition from PopIII to PopII stars in the early Universe. To refine or refute this theory, more abundances of existing and future metal-poor star data should be added to Figure 1. The ultimate goal is to understand the details of when and how the first low-mass stars formed. Detailed knowledge of this cosmic milestone will provide insight into the earliest history of galaxy formation, and the nature of the first stars and supernovae.

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