The minimum stellar metallicity observable in the Galaxy

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ABSTRACT
The first stars fundamentally transformed the early Universe through their production of energetic radiation and the first heavy chemical elements. The impact on cosmic evolution sensitively depends on their initial mass function (IMF), which can be empirically constrained through detailed studies of ancient, metal-poor halo stars in our Galaxy. We compare the lowest magnesium and iron abundances measured in Galactic halo stars with theoretical predictions for the minimum stellar enrichment provided by Population III stars under the assumption of a top-heavy IMF. To demonstrate that abundances measured in metal-poor stars reflect the chemical conditions at their formation, and that they can thus be used to derive constraints on the primordial IMF, we carry out a detailed kinematic analysis of a large sample of metal-poor stars drawn from the SDSS survey. We assess whether interstellar accretion has altered their surface abundances. We find that accretion is generally negligible, even at the extremely low levels where the primordial IMF can be tested. We conclude that the majority of the first stars were very massive, but had likely masses below $\sim 140 M_\odot$.

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

1 INTRODUCTION
The first stars, the so-called Population III (Pop III), were the key drivers of early cosmic evolution. Their copious production of hydrogen-ionizing radiation initiated the reionization of the Universe, and the first supernova (SN) explosions seeded the pristine intergalactic medium (IGM) with the first heavy elements (Ciardi & Ferrara 2005; Barkana & Loeb 2007). The character of this stellar feedback sensitively depends on the initial mass function (IMF) of the first stars. The current theoretical model of their formation, based on numerical simulations, suggests that the Pop III IMF was top-heavy (Bromm & Larson 2004). In the context of modern cold dark matter (CDM) cosmology, there are two physically distinct sites of early star formation. The very first stars are predicted to have formed in so-called minihaloes at redshift $z \sim 30 - 20$. The subsequent SNe dispersed the first heavy elements into the surrounding gas, thus setting the initial conditions for the formation of the second-generation of already slightly metal-enriched (Pop II) stars. If the prediction of a top-heavy IMF is correct, of order one Pop III star would form per minihalo, whereas a small cluster of predominantly low-mass Pop III stars would arise in the alternative case of a normal, Salpeter-like IMF. The second site for the formation of stars at high redshift are the atomic cooling haloes, with of order a 100 times the mass of the minihaloes. Their dark matter potential wells are sufficiently deep to induce the collapse of the material that was affected by the SN feedback from the Pop III stars in minihaloes. These systems are therefore the sites for the formation of the second generation (Pop II) stars. Due to their predominantly low masses they may still be found today as the most metal-poor stars.

Each galaxy thus exhibits a certain minimum metallicity, reflecting the pre-enrichment from Pop III stars. We here explore the fundamental question of the minimum Fe and Mg abundances observable in the Milky Way to derive constraints on early galaxy formation and on the Pop III IMF. We pursue a “near-field cosmology” approach (Freeman & Bland-Hawthorn 2002), established over the past decade by large objective-prism surveys (Beers & Christlieb 2005) of metal-poor stars as vital tracers of Galactic chemical evolution and the early Universe. These stars carry the fossil record of the physical conditions in the first star forming systems (“stellar archaeology”). To successfully retrieve any such signatures, it is crucial that the atmospheric composition of the observed stars has not been altered either intrinsically by the products of nuclear burning in the stellar interior, or externally by accretion of interstellar material during their long lifetimes. Mass transfer across a binary system may also change the abundances of certain elements (e.g. C), but not the ones that are of interest.

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2 A. Frebel, J.L. Johnson and V. Bromm

in this study (Fe, Mg). The first effect can be accounted for by selecting relatively unevolved main-sequence and giant stars. Regarding the second issue, only a few approximate calculations are available (Talbot & Newman 1977; Yoshii 1981; Ibata 1983), based on the idealized assumption that all stars have the same velocity. We therefore revisit the issue of accretion with a full stellar kinematic analysis of a large sample of metal-poor stars, so that we can assign individual velocities to them. A more realistic modeling of accretion is crucial because stellar archaeology pre-supposes a negligible contribution to the observed abundances from such pollution, so that it is possible to derive constraints on the early Universe and the Pop III IMF. Testing the prediction of a top-heavy IMF is one of the main goals of the upcoming James Webb Space Telescope (JWST), but it is important to also utilize complementary probes that are already accessible now, such as the most metal-poor stars.

2 MINIMUM STELLAR METALLICITY

A fundamental characteristic of the Milky Way is the minimum observable metal-enrichment in its stars. The existence and level of such a “metallicity floor” is governed by the Pop III IMF. If the first stars were formed with a normal, Salpeter-like IMF, contrary to the current consensus view, there would be no minimum stellar metallicity, and truly metal-free, low-mass stars would exist. In this case, significant interstellar accretion could masquerade such putative primordial abundances in those stars. Without detailed knowledge of their accretion history, this would prevent us from identifying them as such low-mass Pop III stars. Hence, any information about the IMF would be irretrievably lost.

For a top-heavy IMF, the situation is very different. Recent numerical simulations of the assembly process of atomic cooling haloes, which are often thought to constitute the first galaxies, have shown that Pop III star formation only occurs in a few of the progenitor minihaloes that eventually merge into the atomic cooling halo (Johnson et al. 2008). For simplicity, we here assume that only one minihalo hosted a Pop III star that ended its life in a SN explosion. This accommodates the possibility that a fraction of the minihalo Pop III stars formed massive black holes by direct collapse, without any concomitant metal enrichment. Under this assumption, we can now derive an estimate for the “bedrock enrichment” from Pop III stars with a top-heavy IMF, which would in turn set the minimum stellar metallicity observable in the Galaxy’s oldest Pop II stars. Current simulations predict the typical Pop III mass to only within a factor of 10. Consequently, within the general top-heavy paradigm, a number of qualitatively very different SN pathways for the first stars are still possible (Heger & Woosley 2002; Iwamoto et al. 2002), and it is important to consider these. If the progenitor Pop III star had a mass in the range 140−260 M☉, an energetic pair-instability SN (PISN) would occur, which is characterized by extremely large metal yields (Heger & Woosley 2002). The Mg yield is almost constant over the entire PISN mass range; assuming that the Mg yield from a single PISN is well-mixed in an atomic cooling halo containing a total gas mass of 10⁷ M☉ leads to the narrowly confined prediction of [Mg/H]min ≃ −3.2

Since this overlaps with the range of observed stellar Mg abundances, a fraction of Pop II stars could carry the signature of PISN nucleosynthesis. However, this fraction is likely very small since no clear PISN “odd-even” effect has thus far been found among metal-poor stars. No useful PISN prediction can be made in the case of Fe, since the corresponding yields range from zero to very high values, depending on the precise progenitor mass (Heger & Woosley 2002). Alternatively, if the Pop III progenitor had a less extreme mass, but still in the black hole forming range of Ms > 25M☉, a peculiar class of “faint”, core-collapse (CC) SNe becomes possible. The class of such low explosion-energy SNe, experiencing mixing and fallback onto a nascent black hole, was introduced to produce very low Fe yields (Umeda & Nomoto 2002; Iwamoto et al. 2002) in order to explain the two hyper Fe-poor stars with [Fe/H] < −5.0. Higher explosion energies are required to explain the abundance pattern of metal-poor stars with [Fe/H] > −4.5. We use these observationally calibrated nucleosynthesis calculations to constrain the likely range in Fe and Mg abundances that would result if the first stars died as such faint CC SNe. The different pre-enrichment levels are indicated in Fig. 1 for comparison with the observational data.

Based on these SN yield considerations, we have derived typical values for the Pop III pre-enrichment. We now wish to place extreme lower limits on the observable stellar Mg and Fe abundances in the Galaxy that result from assuming a top-heavy Pop III IMF. It is often argued that the transition from a top-heavy to a normal, Salpeter-like IMF for the subsequent generations of Pop II/I stars (including those considered here) is governed by a “critical metallicity” (Bromm & Larson 2004). Its value is still rather uncertain, depending on whether fine-structure line cooling is dominant (Bromm & Loeb 2003; Frebel et al. 2007), or dust cooling (Schneider et al. 2006). To arrive at a robust estimate that does not depend on the detailed nature of the critical metallicity, we consider a range that extends from typical fine-structure to dust predictions. Within the fine-structure model (Bromm & Loeb 2003), carbon is the most important coolant, leading to a critical abundance of [C/H]min = −3.5. Combining this with the empirically determined maximum carbon-to-magnesium and carbon-to-iron ratios found in metal-poor stars, i.e. in HE 0107−5240 ([C/Mg]max = 2.5; Collet et al. 2006) and HE 1327−2326 ([C/Fe]max = 3.8; Frebel et al. 2008), we estimate the minimum Mg and Fe abundances to be [Mg/H]min = −6.0 and [Fe/H]min = −7.3. Dust cooling models typically result in lower critical abundances, [C/H]min = −4.5, and the minimum observable Fe and Mg abundances are reduced accordingly. Our predictions for the minimum Fe and Mg values are shown in Fig. 1 (yellow regions).

The level of our predicted metallicity floor is particularly interesting for the goals of current and future surveys with regard to identifying the most metal-poor stars. Some of the recently discovered metal-poor stars have extremely low Mg and Fe abundances that begin to approach our theoretical predictions for the metallicity floor. These objects suggest that additional examples of such stars can be found

1 [A/B] = log10(N_A/N_B) − log10(N_A/N_B)⊙, for elements A, B.
with current observational techniques, potentially even with abundances below the current record holders. Based on spectrum synthesis calculations, we estimate that suitably cool giants should have at least one detectable Mg and Fe line at abundances as low as $[\text{Mg/H}] \sim -6.5$ and $[\text{Fe/H}] \sim -8.0$, respectively. Technological limitations should therefore not prevent us from reaching abundances that are within our predicted minimum metallicity ranges.

3 DATA ON METAL-POOR STARS

In order to explore whether the most metal-poor stars used here to constrain the minimum stellar abundances, or other metal-poor halo stars in general, are possibly affected by accretion, we reconstruct their individual accretion histories by carrying out a detailed kinematical analysis. Our sample stars are selected from the Sloan Digital Sky Survey (SDSS), which provides the necessary input data (radial velocities, distances, proper motions, abundances) for such an analysis. Studies based on the kinematics from SDSS have already led to groundbreaking results (e.g. Carollo et al. 2007). A full description of the data products used here can be found elsewhere (Munn et al. 2004; Lee et al. 2007; Adelman-McCarthy 2008). We note though that we employed $[\text{Fe/H}]$ abundances derived from the Ca K line and selected 565 stars with $[\text{Fe/H}] < -2.5$. The spectra of all stars with $[\text{Fe/H}] < -3.4$ were inspected because the majority of them turned out to be spectral artifacts or misclassified objects, and not real metal-poor stars. This leaves 474 stars in the sample. To obtain $[\text{Mg/H}]$, we set the available $[\alpha/\text{Fe}]$ equal to $[\text{Mg/Fe}]$. Based on temperature estimates from the H $\delta$ line, we find that the sample contains 472 turnoff (dwarf) stars with known proper motions; the remaining two appear to have unrealistically low temperatures so we exclude them from the sample. Reliable proper motions are not available for most of the well-studied metal-poor giants since their distances are very large, and hence uncertain. Future missions such as GAIA will enable us to extend this work by providing accurate proper motions, especially for all the metal-poor giants. Since our diagnostic is based on readily obtainable medium-resolution spectra, it will be straightforward to apply it to the extensive data sets from future large-scale surveys.

4 ROLE OF ACCRETION

We assume that a given star moves in a rigid, three-component Milky Way potential, adopted from Johnston (1998), for 10 Gyr. Using a standard orbit integrator (D. Lin, priv. comm. 2008; see Fulbright 2000 for further details), we determine the orbital parameters, such as $U, V, W$ velocities and eccentricity, for all sample stars. For simplicity, accretion is assumed to take place only during disk crossings. The density structure in the disk interstellar medium (ISM) is highly inhomogeneous, such that every star will encounter regions of different density at each disk crossing. Since the accretion rate depends only linearly on density (see Sec. 4), as opposed to the inverse-cubed scaling with velocity, we here for simplicity work with an average ISM density. Using the empirically determined volume filling fraction as a function of density (Taibot & Newman 1977), we find for the average disk density, $n \approx 5 \text{ cm}^{-3}$ and assume a disk height of $\sim 100 \text{ pc}$.

We estimate the amount of accreted gas onto a low-mass star that passes through interstellar gas assuming Bondi-Hoyle accretion (Bondi 1952):

$$\dot{M} \approx 2 \pi (GM)^2 \rho / (c_s^2 + c_e^2)^{3/2},$$

(1)

See http://www.sdss.org/dr6/
where $M$ is the mass of the star, $\rho \simeq m_p n$ the gas density, $v_{\text{rel}}$ the stellar velocity relative to the gas, and $c_s \simeq 5 \, \text{km s}^{-1}$ the sound speed in the general Milky Way ISM. We calculate the relative velocity of a star during each disk crossing according to $v_{\text{rel}} = \sqrt{(U, V - v_0, W)^2}$, where $v_0 \simeq 200 \, \text{km s}^{-1}$ is the average speed of the disk. For the ISM abundances, we assume a solar distribution with the overall metallicity evolving according to:

$$Z_{\text{ISM}}(t) = (1 + t/t_\text{H})^{-4} \left[ 10^{-3} + 0.67 \times \left( 1 + t/t_\text{H} \right)^5 - 1 \right] Z_\odot,$$

(2)

where $t_\text{H} = 13.7 \, \text{Gyr}$ is the Hubble time, such that $Z_{\text{ISM}} \sim Z_\odot$ at the time of the formation of the Sun $\sim 5 \, \text{Gyr}$ ago. This relation follows from detailed homogeneous chemical enrichment models [Page 1997]. As halo stars will pass through the Milky way disk between 50 and 80 times, the average density and metallicity of the accreted gas is likely to be similar for all stars. However, the stellar velocities at disk crossing can vary widely, thus dominating the accretion rate because of the strong dependence on relative velocity in equ. (1). Stars with the highest velocity relative to the disk will experience the least pollution by the Milky Way ISM, and are therefore most likely to display a surface metallicity endowed at the earliest epochs of star formation.

We specifically choose to investigate the accretion history of Mg and Fe, which are easily measurable abundances in metal-poor stars. Also, these abundances are not affected by potential mass transfer across a binary system. We calculate the total amount of accreted Mg and Fe by summing up the contributions from every disk crossing. To finally arrive at surface abundances, we assume that $10^{-3}$ of the stellar mass is contained in the convective outer layer for dwarfs. We specifically choose to investigate the accretion history of Mg and Fe, which are easily measurable abundances in metal-poor stars. Also, these abundances are not affected by potential mass transfer across a binary system. We calculate the total amount of accreted Mg and Fe by summing up the contributions from every disk crossing. To finally arrive at surface abundances, we assume that $10^{-3}$ of the stellar mass is contained in the convective outer layer for dwarfs. For giants this fraction would rise to $\sim 0.1$ [Yoshii 1983].

In Fig. 1 we compare the resulting accreted Mg and Fe abundances for every star (all dwarfs) with its observed values. All stars have lower “accreted abundances” than their observed values. If a star were to have an accreted abundance larger than the currently observed one, it might indicate that such a star never entered a dense GMC during its lifetime. Our GMC “maximum accretion” scenario thus provides a robust upper limit to the total accreted abundance for each star. We note that in our accretion estimates the potential role of stellar winds has been neglected. The presence of a wind would likely balance any accretion or prevent it altogether [Talbot & Newman 1977]. Since wind strength scales with stellar mass and metallicity, the low-mass, metal-poor stars considered here should have little or no wind. Hence, the accreted [Fe/H] and [Mg/H] abundances are likely an upper limit. We thus conclude that stellar archaeology is not hampered by interstellar accretion, even for our maximum accretion scenario. Furthermore, we demonstrate that kinematic information is vital for the identification of the lowest-metallicity stars.

Finally, we compare our results with the “pollution limit” derived previously by [Iben 1983]. This limit was calculated in an attempt to explain the paucity of low-metallicity stars (G-dwarf problem), within the framework of a normal, Salpeter-like IMF for the first stars. The estimated Fe pollution of [Fe/H]_{cc} = −5.7 (one value for all stars) would in this interpretation naturally prevent the discovery of any stars with lower metallicities. However, we show that the “accretion limit” is a strong function of stellar kinematics, and that there is therefore no such universal limit. Our result thus suggests that the traditional, pollution-based, explanation for the absence of surviving low-mass Pop III stars needs to be revisited. Furthermore, with the latest Fe abundance measurement for HE 1327−2326 of [Fe/H] = −5.9 [Frebel et al. 2008], the Iben pollution limit has already been reached. This star, however, is currently thought to be a second generation object displaying the nucleosynthetic yields of a metal-free CC SN with a mass $\sim 25 M_\odot$ [Iwamoto et al. 2003], and not a masqueraded, low-mass Pop III star. In addition, HE 1327−2326 does not exhibit scaled-down solar abundances, contrary to the expectation that a star with an accretion-dominated signature should show a solar abundance pattern.

5 IMPLICATIONS

As an interesting consequence from the proceeding analysis, we can derive some observational constraints on the underlying Pop III IMF that determined the level of pre-enrichment. From Fig. 1 we infer that select stars with high velocities and correspondingly low accreted abundances (gray region) are useful probes of the Pop III IMF. Accretion alone would not have been able to push them above the minimum levels predicted for a top-heavy IMF. If these stars had formed...
from extremely low-metallicity gas, their observed present-day surface abundances should still have reflected this. The fact that these low-accretion stars all have abundances above the minimum floor predicted for a top-heavy Pop III IMF supports the notion that the first stars were very massive (see also Tumlinson 2006; Salvadori et al. 2007). We here would like to repeat that such tests can only be carried out if proper attention is given to the individual accretion history of each star.

To make this test fully convincing, we need to address possible observational biases. In particular, the apparent lack of IMF-sensitive stars below the top-heavy prediction could simply reflect their small numbers. However, current survey sizes reach levels of completeness that render such an interpretation increasingly unlikely. To gauge the putative number of low-mass Pop III stars in the Galaxy, assuming a Salpeter-like primordial IMF, we begin with the approximate number of minihaloes that formed before the redshift of reionization, and that eventually merged to become part of the Milky Way. Using standard extended Press-Schechter (EPS) theory (Lacey & Cole 1993), we estimate that ~10^4 Milky Way progenitor minihaloes hosted Pop III star formation. The ~100M_⊙ in cold, dense gas avalable to form stars, as found in numerical simulations, would then result in ~100 low-mass Pop III stars. The total number of such hypothetical Pop III fossils in the Galaxy would be ~10^6. Given that the Galactic halo today contains ~10^9 stars, one low-mass Pop III star should be found per ~10^3 stars surveyed (Oey 2003). In the Hamburg/ESO Survey, each of the two stars with [Fe/H] < −5 was found in a sample of ~2000 selected metal-poor stars, which in turn comprise ~10% of a subset of halo stars with no metallicity selection. To first order, this seems unlikely that a selection effect would significantly affect our results. This argument is further strengthened by SDSS, which has spectroscopically measured metallicities for several hundred thousand stars.

Our results (see Fig. 1, panel B) finally also suggest that only a small fraction of the first stars died as PISNe because a number of stars have observed [Mg/GeV] ratios below the abundance floor predicted for PISN enrichment. We thus conclude that the majority of the first stars were very massive, but had masses below ~140 M_⊙. Current data and simulations are not yet precise enough to determine the PISN fraction with any certainty, but our diagnostic can in principle be extended to constrain this important quantity (see also Karlsson et al. 2008).

We have thus shown that stellar archaeology can provide crucial observational constraints on the primordial IMF, given that the metal-poor stars of interest have sufficiently high space velocities to avoid significant accretion. Together with our prediction that stars with abundances below the currently known lowest values can be found in ongoing and future discovery efforts, stellar archaeology becomes directly relevant for the science goals of the next generation of 30m-class optical telescopes such as the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Future surveys will continue to provide us with local constraints on star formation at the edge of the observable Universe. Selecting suitable candidates for this task will increasingly rely on our ability to combine chemical abundance analyses with kinematic information.

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