Observational constraints on the survival of pristine stars

Mattis Magg$^{1,2}$*, Ralf S. Klessen$^{1,3}$, Simon C. O. Glover$^1$, Haining Li$^4$

$^1$Universität Heidelberg, Zentrum für Astronomie, Institut für Theoretische Astrophysik, D-69120 Heidelberg, Germany
$^2$International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD)
$^3$Universität Heidelberg, Interdisziplinäres Zentrum für Wissenschaftliches Rechnen, D-69120 Heidelberg, Germany
$^4$Key Lab of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Chaoyang, Beijing 100101, China

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ABSTRACT

There is a longstanding discussion about whether low mass stars can form from pristine gas in the early Universe. A particular point of interest is whether we can find surviving pristine stars from the first generation in our local neighbourhood. We present here a simple analytical estimate that puts tighter constraints on the existence of such stars. In the conventional picture, should these stars have formed in significant numbers and have preserved their pristine chemical composition until today, we should have found them already.

Key words: stars: Population III – stars: luminosity function, mass function – cosmology: reionization, first stars, early universe

1 INTRODUCTION

The first stars, Population III (Pop III) stars, are thought to form in cosmological minihaloes at redshifts of $z \approx 20$, a few 100 Myr after the Big Bang. Forming in the absence of metals, and therefore from gas with much higher temperature than present day giant molecular clouds, these stars were initially predicted to be very massive (e.g. Bromm et al. 1999; Abel et al. 2000). Later simulations revealed the fragmentation of protostellar disks and a formation channel for low-mass metal-free stars (Clark et al. 2011; Greif et al. 2011; Stacy & Bromm 2014). However, there is so far no consensus on the initial mass function (IMF) of pristine stars and in particular whether these fragments form and survive. Some simulations, such as those cited above, predict that the formation and survival of low-mass fragments should be relatively common. However, other simulations find that only massive Pop III protostars form and do not predict low-mass fragments to survive in significant numbers (Hosokawa et al. 2011; Hirano et al. 2014).

As these stars are born at high redshifts it is not possible to directly observe the formation of these stars. Furthermore low-mass Pop III stars exhibit only very weak feedback. As they do not explode as supernovae (SNe) they will not leave an imprint in the abundance patterns of second generation stars and are therefore invisible to the conventional stellar archaeology approach (Ishigaki et al. 2018) or searches for the first SNe (Hummel et al. 2012; Hartwig et al. 2018).

These stars are also not predicted to be very luminous making 21-cm tomography insensitive to their existence. Thus, the remaining hope for constraining the existence and abundance of low-mass Pop III stars is the prospect of observing them directly in the local Universe.

Many observational studies have targeted the most metal-poor stars to be found in our Galaxy, with the goal of understanding its early enrichment history (Beers & Christlieb 2005; Frebel & Norris 2015; Ishigaki et al. 2018). Among these stars we focus on the categories of extremely metal-poor (EMP) and ultra metal-poor (UMP) stars. We refer to stars with metallicities$^1$ of $[\text{Fe/H}]<-3$ as EMP stars and to stars of metallicities of $[\text{Fe/H}]<-4$ as UMP stars. Note that in this definition UMP stars are always EMP stars too.

2 COMPUTING DETECTION PROBABILITIES

2.1 Basic idea

The idea to constrain the existence of surviving pristine stars with non-detections is not new. Hartwig et al. (2015) and Ishiyama et al. (2016) have estimated the probability to find Pop III survivors in a blind survey and have stated required sample sizes to falsify the predicted numbers at various confidence levels. However, this approach only looks at blind

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$^1$ For denoting metallicities, we use the standard notation $[\text{Fe/H}] = \log_{10}(m_{\text{Fe}}/m_{\text{H}}) - \log_{10}(m_{\text{Fe, }\odot}/m_{\text{H, }\odot})$ where $m_{\text{Fe}}$ and $m_{\text{H}}$ are the mass abundances of iron and hydrogen, and $m_{\text{Fe, }\odot}$ and $m_{\text{H, }\odot}$ are the respective solar abundances.
surveys and does not take into account that observers are actually much better at finding metal-poor stars than a blind survey.

Our goal is to understand the implications of the non-detection of metal-free stars by the community until today. A key problem in this is the large non-uniformity in selection criteria employed by the observations. Our approach is based on the following idea: the formation sites of extremely and ultra metal-poor stars are thought to be similar to those of metal-free stars. They both are expected to form in high-redshift mini- and atomic cooling haloes. Therefore, we are not aware of any reason why their spatial distribution, ages, luminosity or magnitudes in broad band filters should be significantly different. This idea is confirmed by the simulations of Starkenburg et al. (2017), where metal-poor and metal-free stars show very similar spatial distributions. Consequently, we assume that on average extremely metal-poor stars are equally likely to be detected as Pop III survivors. The detection of each EMP star known to the community can be seen as randomly drawing a star from a sample that contains all EMP stars as well as the hypothetical metal-free stars. Therefore, the probability of metal-free stars randomly escaping detection thus far can be computed as

$$P_0 = \left(1 - \frac{N_{\text{surv}}}{N_{\text{EMP,tot}}} \right)^{N_{\text{EMP,obs}}} ,$$

where $N_{\text{EMP,tot}}$ is the total number of EMP stars in the galactic halo, $N_{\text{EMP,obs}}$ is the number of such stars that are observed and $N_{\text{surv}}$ is the total number of surviving metal-free stars in the halo. We note that $N_{\text{EMP,tot}}$ includes all stars with a metallicity below $[\text{Fe}/\text{H}] = -3$ and therefore in particular UMP stars and potential metal-free stars. A similar estimate is made for UMP stars.

### 2.2 Number of Pop III survivors

We use 30 different numbers of pristine survivors in the Milky Way (MW) presented in Fig. 1. Magg et al. (2018) computed these numbers with a semi-analytical model, which simulates early star formation in merger trees of MW-like haloes. The merger trees used for this purpose are from the high-resolution cosmological N-body simulations from the Caterpillar project (Griffen et al. 2016). The assumed IMF in this model is a logarithmically flat IMF in the mass range $0.6-150 \, M_\odot$. This IMF is very top-heavy and it gives many fewer surviving stars than, for example, a Salpeter-like IMF in the same mass range. The number-count of surviving pristine stars spans a range between 1800 and 5200 stars. It is extremely difficult to estimate the error for the survivor count in each individual of the 30 modelled haloes. We assume that the main source of errors is encompassed in the different merger histories of the 30 haloes, i.e., that the 30 survivor counts represent the probability distribution of expected survivor counts in the MW. Even the largest number of surviving pristine stars we adopt is by a factor of two smaller than the one found in Hartwig et al. (2015, 10000 survivors) on which the Magg et al. (2018) study is built. This difference is primarily caused by the significantly improved modelling of feedback and in particular by taking into account the positions of the haloes and the effects of ionizing radiation. The adopted numbers of Pop III survivors are also by more than order of magnitude smaller than the one in Ishiyama et al. (2016, around 100000 survivors). This discrepancy is mostly caused by assuming around an order of magnitude more survivors per Pop III forming minihalo. Komiya et al. (2016) predicted around 3000 Pop III survivors in the MW, similarly to our estimate. Therefore, our estimate of the number of surviving pristine stars is among the most conservative predictions that still allow for surviving Pop III stars.

### 2.3 Total number of EMP stars in the halo

To compute with which probability a number of metal-free stars could have escaped detection until now, we have to determine the size of the “haystack”, i.e., the total number of EMP/UMP stars among which we have to look for pristine survivors. In order to do this we assume that all EMP, UMP and hypothetical pristine stars are located in the stellar halo of the MW. Simulations and semi-analytical modelling confirm that most of surviving metal-free stars should be found in the stellar halo (Hartwig et al. 2015; Starkenburg et al. 2017). Sestito et al. (2019) recently found that the majority of known UMP stars indeed are observed in the stellar halo. Therefore, our estimates of the total amount should be appropriate. Furthermore this assumption only enters in our estimate of the size of the “haystack”, i.e., our model is independent of it as long as it does not lead to us significantly underestimating the total number of EMP/UMP stars in the MW.

We assume a stellar halo mass of $M_{\text{halo}} = 10^9 \, M_\odot$ (Bell et al. 2008). We convert this to a number of stars by assuming an average stellar mass of a typical old metal-poor main sequence turn-off star, i.e. $M_\star = 0.6 \, M_\odot$. This is again a conservative estimate, which probably significantly overestimates the number of EMP and UMP stars. Thus it gives a relatively large “haystack”, assuming that all stars are at the smallest mass where they can still be detected and the metallicities constrained reasonably well. For the same reason the lower limit of the pristine IMF was selected to be $0.6 \, M_\odot$ in Magg et al. (2018). Recently, Youakim et al. (2017) estimated that 1/800 of halo stars are EMP stars and...
Pristine survivors

Figure 2. Probability of not detecting metal-free stars until today, as function of halo mass. We show the probabilities derived from UMP (blue diamonds) and EMP (orange triangles) star detections separately and combined (green circles). The UMP stars give much tighter constraints than the EMP stars.

1/80000 of halo stars are UMP stars. Thus, we estimate the total number of EMP and UMP stars to be

\[ N_{\text{EMP, tot}} = \frac{M_{*, \text{halo}}}{800M_{\odot}} = 2.08 \times 10^6 \]  

(2)

and

\[ N_{\text{UMP, tot}} = \frac{M_{*, \text{halo}}}{80000M_{\odot}} = 20800. \]  

(3)

While these number are subject to large uncertainties they are the best estimates available to us. To be conservative, we also use a very pessimistic conversion factor between stellar mass and the number count of stars. One source of uncertainty is that Youakim et al. (2017) derived those number for stars in the magnitude range 14 < V < 18 and that EMP and UMP stars could be more common in the more metal-poor outer stellar halo. Therefore, we will discuss below how our results would change, if we underestimated the number of EMP and UMP stars by a factor of two.

2.4 Number of detected stars

For the number of observed UMP stars we use the \( N_{\text{UMP, obs}} = 42 \) stars from Sestito et al. (2019). We determine the number of detected EMP stars to be \( N_{\text{EMP, obs}} = 532 \) by a query of the SAGA\(^2\) database (Suda et al. 2008). Of these stars, 507 are in the metallicity range \(-4 < [\text{Fe}/\text{H}] < -3\). With this method, we are underestimating the number of detected EMP stars as we do not include e.g. the recent detections from TOPoS (François et al. 2018) or LAMOST (Li et al. 2018, Li et al. in prep.).

3 RESULTS AND DISCUSSION

By using the estimated numbers of survivors, EMP and UMP stars and their detections, we can compute the probability of the non-detection of these metal-free stars until today with Eq. (1). The probabilities for individual haloes are presented in Fig. 2. The non-detection probabilities derived from EMP stars are typically around 50 per cent, while the values derived from the UMP star sample are orders of magnitude smaller. If we remove the UMP stars from the detected EMP sample, i.e., using \( N_{\text{EMP, obs}} = 507 \), the two non-detection probabilities become independent. We can combine them by multiplication. These combined probabilities offer a slight improvement over the estimate derived from detections of UMP stars. As the 30 simulated merger trees represent our a priori distribution of survivor counts, we compute final non-detection probabilities in the MW by averaging the 30 probabilities. We find

- \( P_{0, \text{EMP}} = 0.39 \) for EMP stars,
- \( P_{0, \text{UMP}} = 0.0019 \) for UMP stars and
- \( P_{0, \text{comb}} = 0.0011 \) combined.

Thus the estimate of the number of metal-free survivors can excluded at a 99.9 per cent confidence level. At 98 per cent confidence level, this model allows for no more than 1650 metal-free stars. This also rules out the predicted number of survivors from Hartwig et al. (2015) and Ishiyama et al. (2016). The non-detection probabilities derived from EMP stars are typically around 50 per cent, while the values derived from the UMP star sample are orders of magnitude smaller. Even if we underestimate the number of EMP and UMP stars by a factor of two, the predictions from Magg et al. (2018) are still incompatible with our estimate at a confidence level of 97 per cent.

In addition to upper limits we can compute our best estimate of the number of surviving metal-free stars. At merely \( N_{\text{surv}} = 300 \) the non-detection of metal-free stars until today becomes equally likely to their detection (i.e. \( P_{0, \text{comb}} = 0.5 \)).

These findings imply either that low mass Pop III stars must be rarer than suggested by Magg et al. (2018) or a significant number of them must accrete metals from their surroundings during their life. We will briefly discuss both possibilities here.

A possible explanation for the non-detection of metal-free stars is that they could have been enriched with accreted metals from the interstellar or intergalactic medium during their lifetime, and are now detected among the metal-poor stars. Whether such accretion can occur at a sufficient level to explain the non-detection of metal-free stars is still under debate. Frebel et al. (2009) found that metal-poor stars can only very inefficiently accrete metals, while Johnson & Khochfar (2011) find accretion can be efficient, if it is not prevented by stellar winds. If enrichment is efficient, Komiyama et al. (2016) predicted that around 100 – 170 stars may escape their formation sites before being enriched and be accreted onto the MW stellar halo at later times. However, such stars may have a different distribution of orbits and can therefore not be investigated with the model presented in this study. More recently Tanaka et al. (2017) and Suzuki (2018) pointed out that magnetic winds and a hot coronae of Pop III survivors may prevent accretion of metals from the interstellar medium altogether. Accretion of compact interstellar comets has been investigated as source of metal pollution by Tanikawa et al. (2018), and the contribution was found to be negligible in most cases.

A second possible pathway that leads to the pollution of surviving Pop III stars is mass overflow in binaries. For ex-

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2 http://sagadatabase.jp, accessed on 22.01.2019
ample, Suda et al. (2004) and Lau et al. (2007) have shown that under the right conditions significant pollution with carbon can occur in Pop III binaries. Observationally, Arzoumanian et al. (2019) suggest a connection between carbon enhancement and binarity in EMP stars. Such mass transfer would be sensitive to the binarity and the separation of Pop III stars, which is so far not well constrained. However, in most cases binary mass transfer is insufficient as source of enrichment, as it cannot explain the presence of iron in these stars. Therefore, in order to explain the lack of observed surviving metal-free stars by pollution, the need for accretion from the interstellar medium remains.

The most obvious explanation for the non-detections of Pop III survivors, would be that metal-free stars with masses below 0.8 $M_{\odot}$ do not form at all or are much rarer than predicted. This would mean that the pristine IMF must either be more top-heavy or truncated towards lower masses. We perform a simplistic estimate here of how much we would need to change the IMF form the one assumed in Magg et al. (2018) in order to arrive at survivor numbers consistent with observations. Magg et al. (2018) used a logarithmically flat IMF in the mass range 0.6-150 $M_{\odot}$, Such an IMF produces on average one surviving star per 520 $M_{\odot}$ of forming Pop III stars, where we assumed that these stars survive in the range of 0.6-0.8 $M_{\odot}$. For comparison, the present day IMF from Kroupa (2001) predicts around one star in this mass range per 10 $M_{\odot}$ of stars formed. The assumed pristine IMF leads to the prediction of an average of 3750 surviving Pop III stars. At fixed star formation efficiency and feedback efficacy, to scale this number down to the above given upper limit of 1650 survivors, we would need to reduce the number of survivors to one per 1200 $M_{\odot}$ of Pop III stars. This could either be achieved by raising the lower limit of the IMF to 0.7 $M_{\odot}$ or by changing its slope from $\alpha = -1.0$ (i.e., logarithmically flat) to $\alpha = -0.8$. In particular, these constraints are strongly inconsistent with Pop III stars forming with an IMF similar to the one observed in the present day. Without pollution of almost every low-mass Pop III star, an IMF that, compared to the present day IMF, is either very top-heavy or truncated towards sub-solar masses is required.

The largest uncertainty in our method lies in our estimate of the total size of the “haystack”, i.e. the total number of EMP and UMP stars in the Milky Way and in particular in the outer stellar halo. While the numbers used in this paper are uncertain we chose a conservative estimate. Future surveys that allow to more completely and deeply explore the outer stellar halo will reduce these uncertainties. Additionally, the number of UMP and in particular EMP stars cited in this study are lower limits, as the SAGA catalogue is not entirely up-to-date and because there are more processed, but not yet published detections of EMP stars (Li et al. in prep).

In summary, we derived new upper limits on the number of surviving metal-free stars in the MW. We conclude that such stars must form very rarely or else have been polluted by metals during their lifetime. We demonstrate the ability of our approach to constrain the primordial IMF by non-detections and highlight the need for a lower mass cutoff of the IMF or an even more top-heavy functional form than adopted here, should pollution of these stars not be significant. Future surveys and individual detections of EMP and UMP stars will further strengthen constraints on the survival of metal-free stars.

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REFERENCES

Abel T., Bryan G. L., Norman M. L., 2000, ApJ, 540, 39
Arentsen A., Starkenburg E., Shetrone M. D., Venn K. A., Depagne É., McCinnachie A. W., 2019, A&A, 621, A108
Beers T. C., Christlieb N., 2005, ARA&A, 43, 531
Bell E. F., et al., 2008, ApJ, 680, 295
Bromm V., Coppi P. S., Larson R. B., 1999, ApJ, 527, L5
Clark P. C., Glover S. C. O., Smith R. J., Greif T. H., Klessen R. S., Bromm V., 2011, Science, 331, 1040
François P., et al., 2018, A&A, 620, A187
Freybel A., Norris J. E., 2015, ARA&A, 53, 631
Freybel A., Johnson J. L., Bromm V., 2009, MNRAS, 392, L5
Greif T. H., Springel V., White S. D. M., Glover S. C. O., Clark P. C., Smith R. J., Klessen R. S., Bromm V., 2011, ApJ, 737, 75
Griffin B. F., Ji A. P., Dooley G. A., Gómez F. A., Vogelsberger M., O’Shea B. W., Frebel A., 2016, ApJ, 818, 10
Hartwig T., Bromm V., Klessen R. S., Glover S. C. O., 2015, MNRAS, 447, 3882
Hartwig T., Bromm V., Loeb A., 2018, MNRAS, 479, 2202
Hirano S., Hosokawa T., Yoshida N., Umeda H., Omukai K., Chisaki G., Yorke H. W., 2014, ApJ, 781, 60
Hosokawa T., Omukai K., Yoshida N., Yorke H. W., 2011, Science, 334, 1250
Hummel J. A., Pawlik A. H., Milošavljević M., Bromm V., 2012, ApJ, 755, 72
Ishigaki M. N., Tominaga N., Kobayashi C., Nomoto K., 2018, ApJ, 857, 46
Ishiyama T., Sudo K., Yokoi S., Hasegawa K., Tominaga N., Susa H., 2016, ApJ, 826, 9
Johnson J. L., Khochfar S., 2011, MNRAS, 413, 1184
Komiyama Y., Suda T., Fujimoto M. Y., 2016, ApJ, 820, 59
Kroupa P., 2001, MNRAS, 322, 231
Lau H. H. B., Stancliffe R. J., Tout C. A., 2007, MNRAS, 378, 563
Li H., Tan K., Zhao G., 2018, ApJS, 238, 16
Magg M., Hartwig T., Agarwal B., Frebel A., Glover S. C. O., Griffin B. F., Klessen R. S., 2018, MNRAS, 473, 5308
Sestito F., et al., 2019, MNRAS
Stacy A., Bromm V., 2014, ApJ, 785, 73
Starkenburg E., Oman K. A., Navarro J. F., Crain R. A., Fattahi A., Frenk C. S., Sawala T., Schaye J., 2017, MNRAS, 465, 2212
Suda T., Aikawa M., Machida M. N., Fujimoto M. Y., Iben Icko J., 2004, ApJ, 611, 476
Suda T., et al., 2008, PASJ, 60, 1159
Suzuki T. K., 2018, PASJ, 70, 34
Tanaka S. J., Chiaki G., Tominaga N., Susa H., 2017, ApJ, 844, 137
Tanikawa A., Suzuki T. K., Doi Y., 2018, PASJ, 70, 80
Youakim K., et al., 2017, MNRAS, 472, 2963

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