Dating the oldest stars: Asteroseismology of Milky Way bulge stars from redshifts z>10

M. Asplund, L. Casagrande, A. Dotter, L. Duong, L. Howes, D. Nataf, D. Stello

Executive Summary: *The first stars and their immediate successors are predicted to have formed within the first 300 million years after the Big Bang, corresponding to redshifts z>15, with any survivors now preferentially residing in central regions of galaxies like the Milky Way. We have recently discovered for the first time a large number of extremely metal-poor stars in the Milky Way bulge, which are prime candidates for being the oldest known objects in the Universe (Howes et al., 2015, Nature, 527, 484). We propose to use the unique opportunity offered by K2 campaign 9 to obtain asteroseismic ages for some of these stars, the only way ages for these truly ancient red giant stars can be determined.*

Scientific Justification

The Population III stars are still eluding discovery. There are tremendous ongoing efforts and future facilities aimed at finding the first stars, or at least their impact on the surrounding environment at high redshift. With the highest confirmed galaxy redshift being z=8.7 (Zitrin et al. 2015, arXiv:1507.02679), the best hope for finding these stars, however, may still be to find a stellar relic lurking in our Galactic backyard. This has motivated many searches for extremely metal-poor stars in the Milky Way halo, such as the HK, Hamburg-ESO, and SEGUE/SDSS surveys (e.g. Frebel & Norris 2015, ARAA, 53, 631). So far no true Population III star has been discovered; the record-holder has [Fe/H]<-7 and [Ca/H]=-7 (Keller et al. 2014, Nature, 506, 463). In the early Universe however, there is no direct correlation between [Fe/H] and age. Indeed, the very oldest stars should typically not be in the Galactic halo.

According to cosmological models, the very first stars formed in the centers of the largest and most over-dense dark matter mini-halos, which subsequently accreted material to become the inner regions of large galaxies (e.g. Greif et al. 2012, MNRAS, 424, 399). The oldest stars should thus typically reside today in the bulges of galaxies like the Milky Way. While the typical redshift of formation for Milky Way **halo** stars with [Fe/H]<-1 is z~5, similarly metal-poor **bulge** stars formed at z>10 (**Fig. 1**, Salvadori et al. 2010, MNRAS, 401, L5). Indeed, of the bulge stars with [Fe/H]<-3, approximately 15% are predicted to have formed at z>15 (Tumlinson 2010, ApJ, 708, 1398), an otherwise completely inaccessible cosmic period. In fact the first stars likely heralded the epoch of re-ionization through their radiation and of course produced the very first elements heavier than lithium, thereby forever transforming the Universe. They thus provide a unique insight to one of the hottest topics in contemporary cosmology and astrophysics.

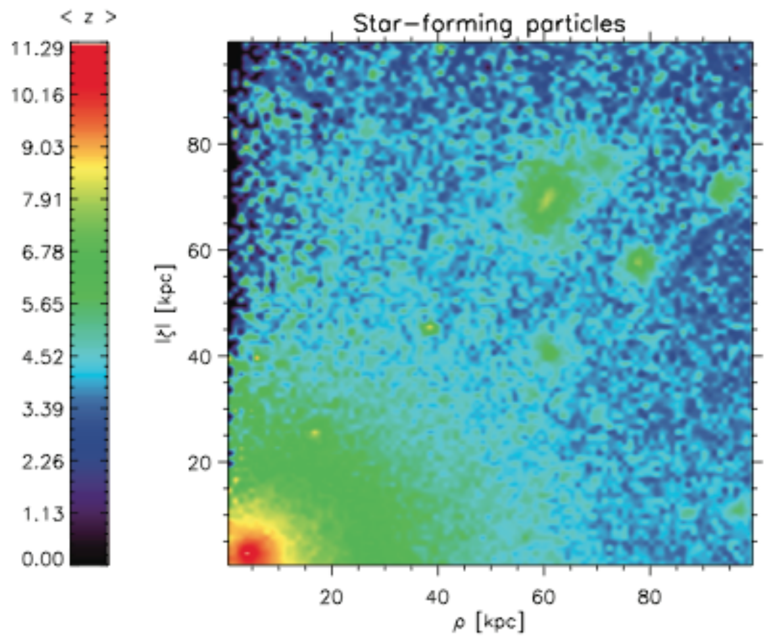

Fig. 1: *Predicted formation redshift of stars with [Fe/H]<-1 in a Milky Way-like galaxy (Salvadori et al. 2010); Galactic centre is at origin. Metal-poor bulge stars formed at z>10 while halo stars formed at z~5.*

Until recently, any search for the first stars in the bulge has been considered essentially hopeless since the overcrowding and overall metal-rich nature of the bulge makes it extremely difficult to identify these exceptionally rare objects amongst the myriad of high-metallicity stars. Our EMBLA survey has overcome this problem using SkyMapper photometry and AAOmega/AAT spectroscopy to discover hundreds of metal-poor stars in the Galactic bulge, down to [Fe/H]=-4.0 (Howes et al. 2014, MNRAS, 445, 4241). Our program has been remarkably efficient in finding metal-poor stars in addition to targeting for the first time the region where the oldest stars should reside. Using high-resolution spectra obtained with Magellan and VLT, we have determined accurate parameters and elemental abundances for some of the most metal-poor bulge stars, revealing both important chemical similarities with halo stars as well as intriguing differences, most notably related to carbon and alpha-elements (Howes et al. 2015, Nature, 527, 484). Most of these metal-poor bulge stars have tight orbits constrained to the central regions of the Galaxy, convincingly demonstrating that they are not simply halo star interlopers. Both their extremely metal-poor nature and kinematics imply that they are prime candidates for being the oldest known objects in the Universe. Asteroseismology with K2 Campaign 9 now offers the unique opportunity to date some of these stars, potentially probing for the first time the z>15 Universe.

Target Selection and Asteroseismic Analysis

We have selected all metal-poor bulge stars with [Fe/H]<-1.2 identified in our EMBLA survey that fall within the K2 Campaign 9 footprint, in total 200 stars (EMBLA mainly targeted higher Galactic latitudes in the bulge than the Campaign 9 field). According to Salvadori et al. (2010), these stars would have typically formed at redshifts z>10 (**Fig. 1**). Our target list include eight stars with [Fe/H]<-3. We have already determined reliable spectroscopic parameters ($T_{\rm eff}$, [Fe/H]) for the targets, facilitating an asteroseismic analysis of these red giant branch stars. Our sample size is driven by the expected asteroseismic age uncertainties of ~20% from K2 data for red giants (Stello et al. 2015, ApJL, 809, L3), which implies a mean statistical age uncertainty for our sample of ~200Myr, i.e. corresponding to differentiating between redshift z=15 and 10. These K2 observations will also allow a direct comparison of average formation redshift of bulge stars and halo stars with the same [Fe/H] which have been observed in previous K2 campaigns, irrespective of possible systematic errors in age determinations for metal-poor stars; the age difference between z=10 (expected for bulge stars) and z=5 (halo) is ~700Myr.

We also propose to observe 175 red giant stars covering the whole [Fe/H] range of the bulge, which are part of a spectroscopic survey with HERMES/AAT to determine their detailed chemical compositions (Duong et al., *in prep.*). The K2 observations will allow us for the first time to trace the chemical enrichment of the bulge as a function of time from the very earliest epochs until today. Currently the frequency of young (<6Gyr) bulge stars, or even their existence, is heavily debated (e.g. Bensby et al. 2013, A&A, 549,147). Accurate asteroseismic ages should settle this key issue and thus provide crucial insight to the evolution of the bulge.

The K2 light-curves will be generated using our own aperture photometry pipeline for K2 (by D. Stello). While our targets are generally faint compared to most seismic targets reported in literature, there are strong indications from new Kepler results (Mathur et al., *in prep.*) and recent analysis of K2 C5 data that K2 with its improved pointing should be able to detect oscillations in these stars. Measurements of the large frequency separation $\Delta\nu$ and frequency of maximum power $\nu_{\rm max}$ needed for the asteroseismic scaling relations to infer stellar masses and radii will be done using the SYD code (Huber et al. 2009, CoAst, 160, 74). From these, stellar ages will be determined based on grid modeling (Stello et al. 2009, ApJ, 700, 1598) using MESA stellar evolution tracks (Choi, Dotter et al., 2015, ApJS, in press).

Our team has all the necessary skills in K2 observations, asteroseismology, stellar modeling, and Galactic archaeology. We have developed all of the required state-of-art analysis codes and have already secured the spectroscopic observations of the targets to successfully execute the program in a timely manner, which is expected to yield high-impact results.