

Astro2020 Science White Paper

Extremely metal-poor stars: the need for UV spectra

Thematic Areas:

- Star and Planet Formation
- Cosmology and Fundamental Physics
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments

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1 Introduction

Our current understanding of the chemical evolution of the Universe is that a first generation of stars was formed out of primordial material, completely devoid of metals (Pop III stars). This first population of stars comprised massive stars that exploded as supernovae disseminating the metals they synthesised in the interstellar medium. These massive stars are long dead and cannot be observed in the local Universe. Among very metal poor stars (metallicity below -2.0) we expect to find the direct descendants of these pristine metal factories. The chemical composition of these stars provides us indirect information on the nature of the Pop III stars, their masses, luminosities and mode of explosion. The constraints are stronger if the chemical inventory is more complete, more chemical elements and isotopic ratios are measured for each star. Unfortunately the lower the metallicity of the star, the weaker the lines. Access to the space UV spectral range gives us crucial supplementary information. To start with, it allows access to some very strong Fe lines that may allow to measure the abundance of this element in stars for which this was not possible from the ground-accessible UV spectra. The number of such stars is steadily increasing. Next the UV range allows us to measure elements that cannot be measured from ground-based spectra like P, Ge, As, Se, Cd, Te, Lu, Os, Ir, Pt, Au. In addition it is fundamental for measuring other elements that can be accessed from earth, but with great difficulty, like C, S, Cu, Zn, Pb. The Hubble space telescope, with its limited collecting power made this possible only for very few stars. Old metal poor stars are cool, of spectral types F,G,K, and their UV flux is low. The availability of a UV high resolution spectrograph fed by a large area space telescope will open an unprecedented window on the early evolution of our Galaxy.

2 Carbonicity: a path to understand star formation at very low metallicity ?

Star formation in the pristine Universe takes place under conditions very different from what happens in the present day Universe. As a gas-cloud collapses its temperature increases, and its pressure tends to counter-balance the gravitational pull. In present day gas there are two main mechanisms that allow a contracting gas-cloud to cool, while collapsing, thus ensuring that the collapse may continue: collisional excitation and radiative recombination of atomic and molecular levels and collisional heating of dust particles with successive emission of far-IR photons. In both cases the produced photons can escape the collapsing cloud without further interacting with the gas, thus effectively subtracting energy from the system and allowing the collapse to continue. In a gas that is totally devoid of metals, there is no dust and the available atoms and molecules (H, ^2H , ^3He , ^4He , ^7Li , H_2 , LiH) either do not have low-lying levels that can easily be excited collisionally or are too rare to provide an efficient source of cooling. From these simple physical considerations one expects that the first generation of stars would be made only by massive stars, that result from the collapse of clouds that are massive enough that the pull of gravity cannot be counter-balanced by the increase of temperature during the collapse. Such stars would be long dead and not observable in the local Universe. Only low-mass stars have long enough lifetimes, that, if formed in the first generations of stars, would still be shining today. The discovery of the first star with $[\text{Fe}/\text{H}] < -5$, HE 0107-5240 (Christlieb et al. 2002), came as a big surprise, because the record deficiency in Fe was accompanied by a large overabundance in C, N

(later it was clear that also O is largely overabundant in this star Bessell et al. 2004). The review by Palla (2003) describes very well the state-of-the art of our understanding of star formation at very low metallicity. Most of the community assumed that the peculiar chemical composition of HE 0107-5240 was the composition of the gas cloud out of which it was formed and was the result of enrichment of one or several SNe (Umeda & Nomoto 2003; Bonifacio et al. 2003; Limongi et al. 2003). The formation of low-mass stars from such gas was explored (Schneider et al. 2003). In a very influential paper Bromm & Loeb (2003) showed that the low lying levels of CII and OI can provide a very efficient cooling mechanism, through collisional excitation and radiative recombination, provided the carbon or oxygen abundance is at least 0.01% to 0.1% of that found in the Sun. A condition satisfied by HE 0107-5240. The peculiar chemical composition would then not be surprising, but the result of the fact that such a chemical composition is necessary to allow the formation of low-mass stars. It was thus not a surprise that when in the following years other stars of this very low metallicity were found they all turned out to be highly enhanced in carbon (Frebel et al. 2005; Norris et al. 2007). For several years it was generally accepted that below $[\text{Fe}/\text{H}] \lesssim -4.5$ one should find only C-enhanced stars. In spite of the fact that a part of the community privileged an interpretation of the C-enhancement in these stars as the result of mass-transfer from a former AGB companion (Suda et al. 2004; Lau et al. 2007; Cruz et al. 2013), a line of thought that has been reinforced by the recent discovery by Arentsen et al. (2018) that HE 0107-5240 is, after all, a binary system. Nevertheless the real shock in the field came by the discovery of SDSS J1029+1729 by Caffau et al. (2011) a star with $[\text{Fe}/\text{H}] \approx -5$ but no evidence of carbon enhancement. Showing that low-mass stars can be found even below the minimum amount of C and O required by the Bromm & Loeb (2003) scenario. This finding has recently been reinforced by the discovery of Pristine_221.8781+9.7844 by Starkenburg et al. (2018), a star with similar properties to those of SDSS J1029+1729, making it unlikely that these stars are the result of some highly contrived evolutionary scenario.

Nevertheless the supporters of the need for C enhancement for the formation of low-mass stars argue that SDSS J1029+1729 and Pristine_221.8781+9.7844 are in reality C-enhanced, simply the C abundance cannot be measured because of the weakness of the G-band in these warm Turn-Off (TO) and Sub Giant (SG) stars (e.g Placco et al. 2016). This claim is very difficult to confute, in spite of the fact that the claim of C-enhancement in the TO stars G64-12 and G64-37 by Placco et al. (2016), based on a 1D analysis of the G-band, is not supported by the 3D-NLTE analysis of IR atomic lines in these stars by Amarsi et al. (2019). The reason is that the TO stars, based on evolutionary time-scales, are certainly much more numerous than cooler giant stars and, at the same time, considerably brighter than cooler MS stars. It is thus likely that other examples of carbon-normal extremely metal-poor stars will be found among TO stars, where the G-band is weaker, for any given C abundance, with respect to what observed in cooler stars. The IR C atomic lines observed by Amarsi et al. (2019) weaken with decreasing C abundance to a level where they become not observable in stars like SDSS J1029+1729 and Pristine_221.8781+9.7844 with current and future observational facilities. If we wish to measure a C abundance in SDSS J1029+1729 and Pristine_221.8781+9.7844 and their siblings, rather than mere upper limits, we have to turn to the vacuum UV. The CI line at 193.09 nm is so strong that it would be measurable in SDSS J1029+1729 and Pristine_221.8781+9.7844, even if they had $[\text{C}/\text{Fe}]=0.0$ (e.g. Spite et al. 2017). Currently the instrumentation on board of HST cannot tackle these faint cool stars ($V \approx 17$). A space telescope with a large collecting area (e.g. LUVOIR) equipped with a high-resolution UV spectrograph should give us a definite answer on the question: do

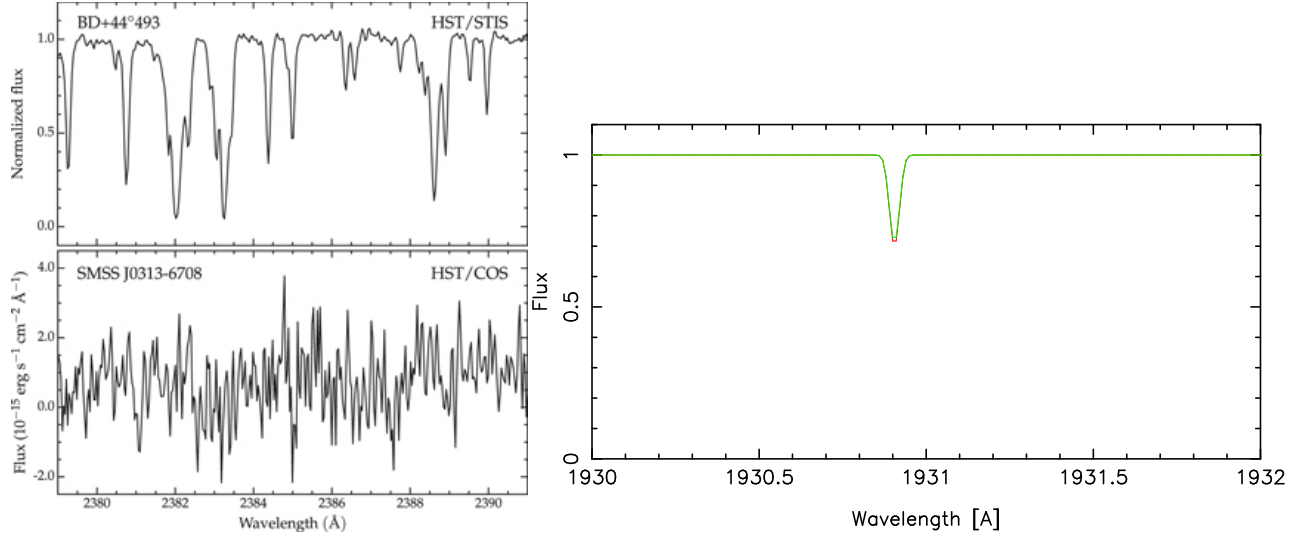


Figure 1: Left: the HST COS spectrum of SMSS 0313-6708, compared to the HST STIS spectrum of the metal-poor star BD +44 493 ($[\text{Fe}/\text{H}]=-3.7$) around the strong Fe II line at 2382 \AA (Roederer 2017). Right: synthetic computation of the UV CI line for a turn-off stars with $A(\text{C})=1.3$, correspondent to about $[\text{C}/\text{Fe}]=-7$.

carbon-normal stars exist with $[\text{Fe}/\text{H}] < -4.5$?

3 What is the iron abundance ?

As we find stars that are more and more metal-poor it occurs that we are not able to measure any Fe line from optical or near-UV spectra. Currently there are four stars for which no iron line could be measured: SMSS 0313-6708 ($[\text{Fe}/\text{H}] < -7.10$ Keller et al. 2014), SDSS J1035+0641 ($[\text{Fe}/\text{H}] < -5.20$ Bonifacio et al. 2018), SDSS J0023+0307 ($[\text{Fe}/\text{H}] < -6.0$ Aguado et al. 2018b), SDSS J0815+4729 ($[\text{Fe}/\text{H}] < -5.8$ Aguado et al. 2018a). In these stars only Ca and C can be measured. We expect several more to be discovered by the on-going and planned surveys and it would be of paramount importance to determine their Fe abundance. Roederer (2017) integrated with HST COS 32 114 s, spread over 10 orbits, on SMSS 0313-6708, but was unable to detect any measurable line. This example illustrates very well the need for a larger collecting power than HST (e.g. LUVOIR) and spectral performances, at least at the level of COS.

4 Phosphorus a shy element

Phosphorus is a relatively abundant element in the Universe. Its two closest elements in the periodic table of elements (Si and S) are well investigated while P remains mysterious because only few P lines (in the infra-red and in the UV) can be detected in a stellar spectrum. The PI lines in the infra-red are relatively weak and can provide the P abundance in stars with a P abundance from over-solar down to about 1/10 the solar P (see e.g. Caffau et al. 2011). Some PI lines in the UV allow to derive P abundances at metal-poor regime (see Roederer et al. 2014) so to

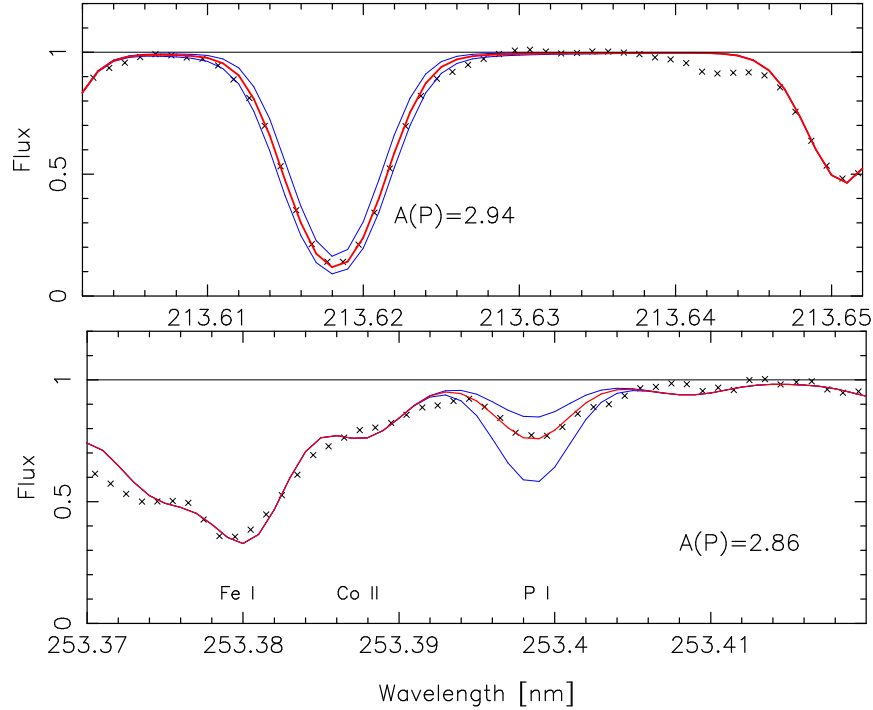


Figure 2: From figure 6 of Spite et al. (2017): two PI lines in the HST spectrum of HD 84937 (black crosses), compared to the synthetic spectra (solid red and blue lines) in the range of four PI lines.

allow the investigation of the Galactic evolution of phosphorus. Roederer et al. (2014) investigated ten PI lines in the UV at metal-poor regime, but only few were useful to derive abundances. Spite et al. (2017) selected five PI UV lines (two are shown in Fig. 2) to derive the P abundance of the metal-poor star HD 84937 and obtained a good agreement in $A(P)$ from the lines she investigated. A high-resolution UV spectrograph with large effective area, able to investigate metal-poor stars will allow to finally understand the Galactic chemical evolution of phosphorus.

5 Heavy elements

It is believed that in the very old, very metal-poor stars, born in the first Gyr of our Galaxy, most of the neutron capture elements were produced by the main r-process in neutron star mergers (e.g. Pian et al. 2017). But this process is clearly not able to explain the abundance of all the heavy elements and in particular the abundance of the lightest of these elements like Ge, As, Se (e.g. Spite et al. 2018). It is very important to compare the complete distribution of the abundance of the heavy elements to the predictions of the different processes: main-r- process, weak-r processes, i(intermediate) process, neutron-rich neutrino winds in core-collapse supernovae etc... Up to now no process is able to explain the pattern of the heavy elements in metal-poor stars (see Fig. 3). Many neutron capture elements are impossible to detect in the spectral range accessible to ground-based telescopes. Their abundance can be deduced only from the UV lines between 190 and 300 nm (e.g. Ge, As, Se, Cd, and also Lu, Pt and Au), hence a high-resolution UV spectrograph is required.

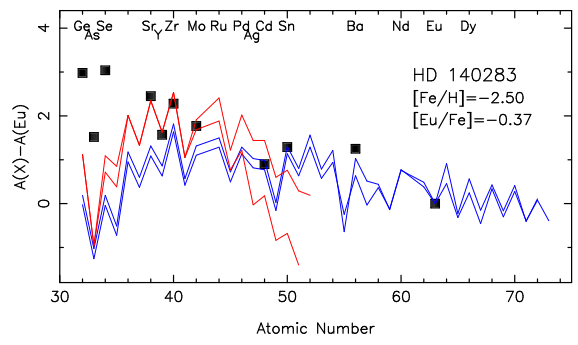


Figure 3: The chemical pattern of HD 140283 compared to theoretical models.

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