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Metal poor stars

The role of CUBES

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Abstract In this contribution I provide an overview of the study of metal poor stars, with an emphasis on the efforts that are on-going to find large number of these rare objects. These efforts will provide, in the next few years, an interesting number of targets for which it will be desirable to have a chemical inventory, as complete as possible. In this respect CUBES, providing access to the near-UV region provides a unique opportunity to access some abundance indicators that have no counterparts in other spectral regions available from ground-based observations. I also take the opportunity to encourage the community to reflect on the possibility of placing a copy of CUBES on a telescope in the northern hemisphere. This contribution is not intended to be an exhaustive review of the field, but aims at stimulating interest in near-UV observations of metal poor stars.

Keywords Stars: abundances · Stars: Population II · Techniques: spectroscopic

1 Introduction

Both theory and observations have made us aware that the Universe is evolving both dynamically and chemically. The pillars of this notion are the expansion of the Universe (Hubble, 1929; Riess et al., 1998), Cosmic Microwave Background (Penzias and Wilson, 1965; Planck Collaboration et al., 2020), and the primordial nucleosynthesis (Wagoner et al., 1967; Pitrou et al., 2018). The latter tells us that the majority of the helium in the Universe was created by primordial nucleosynthesis and that no heavier element, except a small amount of ^{7}Li, was created at that time. This implies that the rich chemical

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composition of the present Universe is the result of the subsequent evolution. It is now well understood that the main factories where chemical elements are synthesised, are stars. The exceptions are Be and B, that are formed in the interstellar medium through spallation of nuclei of carbon, nitrogen and oxygen. In this framework it is obvious to expect that the most ancient stars are also the ones that are the most metal poor and, that the first generation of stars must have been formed from material that was devoid of metals.

The formation of stars from a metal-free gas does not proceed in the same way as in a metal-enriched gas (see Bromm, 2013, for a review). In particular the lack of cooling via either dust or metal lines can prevent the formation of low mass stars. In a primordial gas the only path for the formation of low mass stars is fragmentation (Greif et al., 2011). The extremely low metallicity (say below 10^{-3} of the Solar metallicity) stars are the descendants of the first generation of stars or, at most, the very first few generations of stars. Therefore their chemical composition is a result of the metals ejected by the first Supernovae and can, through appropriate modelling, be used to derive the mass distribution of the first generations of stars (see for example Ishigaki et al., 2018, and references therein). This is important both to understand the early chemical evolution of the Universe and reionisation, since the flux of ionising photons depends on the masses and numbers of massive stars. The low mass and high mass ends of the Initial Mass Function are more difficult to constrain, however they are also being actively investigated by studying low metallicity stars.

2 Metal poor stars. How many are there ? How to find them ?

The importance of metal poor stars to understand the formation and evolution of our Galaxy was understood already in the 1950's and the situation was summarised at the Vatican Conference on stellar populations in 1957 (O'Connell, 1958). It was quickly realised that the metal poor stars were a minority population and required special efforts to find them. At the same time a wide effort began to determine the Metallicity Distribution Function (MDF) of our Galaxy (see Bonifacio et al., 2021, for a synthetic historical account).

Before proceeding on this topic I would like to warn the reader on the different usages of the word "metallicity" found in the literature. In the papers dealing with stellar evolution the word refers almost always to Z, the mass fraction of all elements other than H and He. While simple to compute for a theoretical model, this quantity is often difficult to determine observationally. The most abundant metal is generally oxygen, followed by carbon, neon and nitrogen, of these elements only carbon is accessible with relative ease from stellar spectra. In observational papers that determine chemical abundances from spectra, one refers most often to the quantity $[\mathrm{Fe/H}] = \log[\mathrm{N(Fe)/N(H)}] - \log[\mathrm{N(Fe)_\odot/N(H)_\odot}]$, where the abundances are abundances in number of atoms, not in mass. A question that is often posed is: "Why Fe ?" Part of the answer is provided in Fig. 1, where I show a set of extremely metal poor

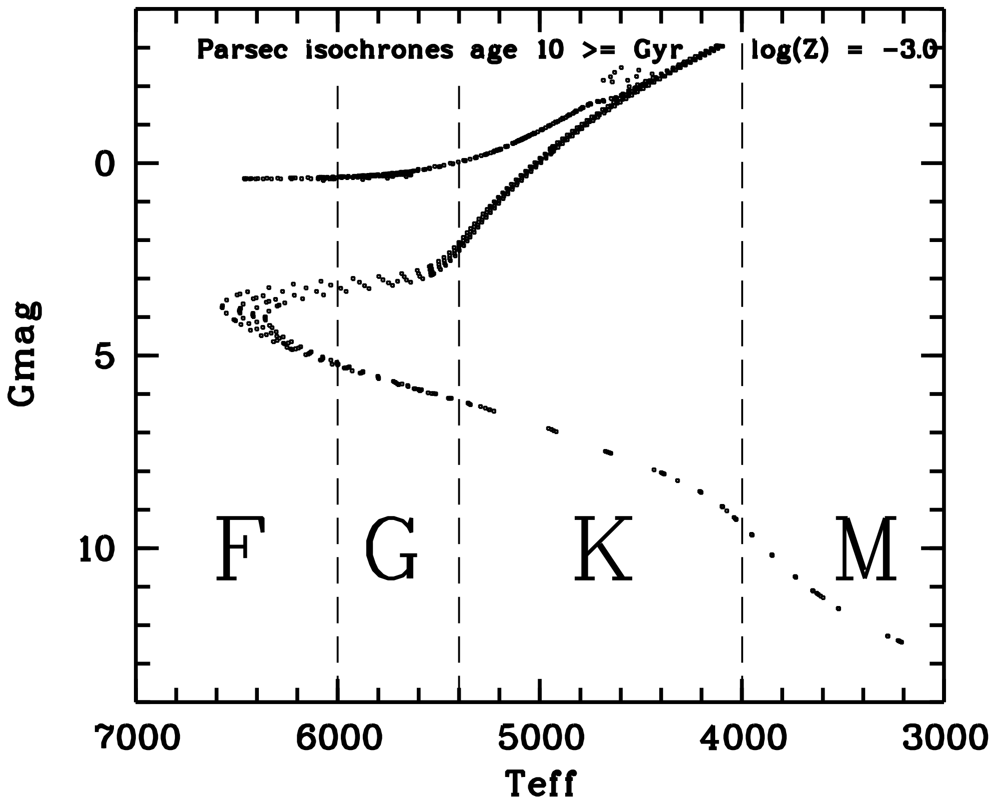

Fig. 1 Parsec isochrones (Bressan et al., 2012) for metallicity –3.0 and ages of 10 to 13 Gyr (steps of 1 Gyr). The spectral types corresponding to each temperature interval are marked at the bottom of the plot.

isochrones for old populations. All the brightest stars, both dwarfs and giants are of spectral types FGK. The tip of the Red Giant Branch never reaches type M, as is the case at solar metallicity. In the near-UV to optical spectra, that are the ones most readily observable from ground based facilities, of FGK stars of any metallicity the FeI lines are by far the most numerous and easily measurable, thus the FeI abundance is what can be measured with greatest ease and robustness. If all the stars had chemical abundances in which all the elements scale by a constant factor with respect to a reference star (e.g. the Sun) there would be a simple one-to-one correspondence between Z and [Fe/H]. This is, however, not the case. It is well known that with decreasing [Fe/H] we observe an increase in [O/Fe] and also of other elements that are formed by captures of α particles. Furthermore at very low metallicity we observe an increase in the fraction of Carbon Enhanced Metal-Poor stars (CEMP), in which [C/Fe]$>$ 1.0 (see Beers and Christlieb, 2005). It is thus clear that to pass from [Fe/H] to Z a complete chemical inventory is necessary, or at least of the most abundant elements. Since this is hardly ever available in practice one often resorts to some hypothesis on the unknown [X/Fe] ratios. Two more caveats on the use of metallicity. In the first place there are observational alternatives to [Fe/H], one is [C/H], since carbon is measured with relative ease, in K giants, even at extremely low metallicity, another is [Ca/H] that is again relatively easily available even at low resolution from both the CaII K line and the CaII IR triplet, in some cases "metallicity" is defined by an average of [X/H] of available elements. In the second place, when [Fe/H] and [X/Fe] are mentioned one should always be careful to make sure the adopted solar abundances are understood and taken into account when comparing abundances with models or among different observational sources. Unfortunately there is a large number of papers that do not provide this crucial information, making it impossible to compare the results to models or to other observations. The bottom line is to make sure to compare the same quantity when extracting data from different papers.

In a fundamental paper Roger Cayrel (1986), in response to the paucity of the extremely metal poor stars observed, showed that if the first stars are born in clusters of mass of the order of $10^6 M_\odot$, rather than in isolation, the gravitational potential is sufficient to retain the metals produced and ejected by the first SNe and a metallicity Z of 0.25 the solar metallicity is reached in a few millions of years. This scenario is still considered valid today, modulo the notion that the mass of the system may contain a large fraction of dark matter. In a hierarchical scenario of galaxy formation, as implied by a Λ-Cold-Dark-Matter cosmology, these systems are called "mini-halos" and are the bricks that allow the formation of large galaxies (like the Milky Way), through mergers.

Our group at GEPI has been actively searching for extremely metal poor stars in the last twenty years. One of the most successful projects was the TOPoS survey (Caffau et al., 2013), that selected candidates using SDSS spectra analysed with a specific pipeline. It used a selection of 33 lines and line blends that were strong enough to be measured on an SDSS spectrum of a Turn-Off star of metallicity –2.0. These included CaII H&K lines, the three CaII infra-rd triplet lines, two of the MgI b triplet lines (the third is blended with FeII. The derived "metallicity" is a mean of Mg, Ca, Ti, Mn, and Fe (Bonifacio et al., 2021). This selection was very successful, it allowed to detect six of the 14 currently know stars with [Fe/H]< -4.5 (see Table 1 of Bonifacio et al. 2020), two of which (SDSS J0023+0307 Aguado et al. 2018a and SDSS J0815+4729 Aguado et al. 2018b) were discovered in parallel by the IAC group, who also used SDSS spectra to select their candidates. In Fig. 2 I show the metallicity histogram of all the extremely metal poor (EMP) stars discovered thanks to a selection on SDSS stars, of these 102 out of 103 were observed in the course of the TOPoS Survey. One of the by-products of the TOPoS survey is that the metallicities derived from the SDSS spectra allowed a precise definition of the metal-weak tail of the Galactic MDF down to a metallicity of –4.0 (Bonifacio et al., 2021), as shown in Fig. 3. To derive this MDF it was necessary to correct the observed MDF for the metallicity bias present in the SDSS spectroscopic sample, that is clearly boosted in metal

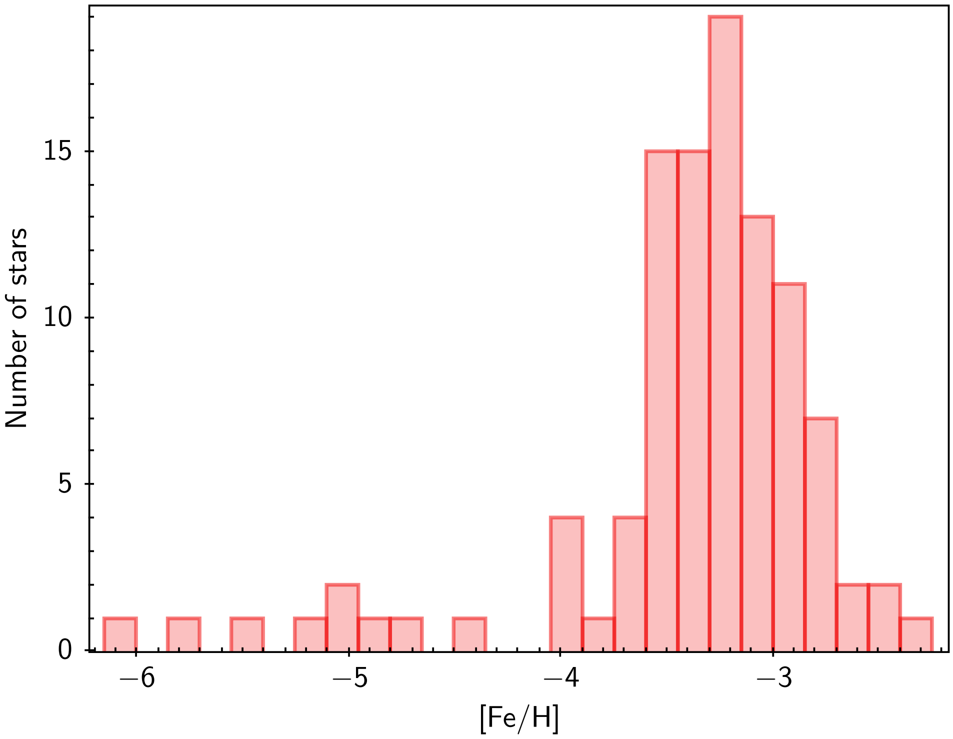

Fig. 2 Histogram of the EMP stars selected from SDSS, in this case upper limits are treated like detections. [Fe/H] values are from (Caffau et al., 2011, 2012; Bonifacio et al., 2012, 2015; Caffau et al., 2011; Allende Prieto et al., 2015; Caffau et al., 2016; Bonifacio et al., 2018; Aguado et al., 2018a,b,a; François et al., 2018a,b, 2020).

poor stars. Once this correction made, it turns out that the metal-weak tail of the MDF derived from the SDSS spectra is almost identical to that derived from the Hamburg-ESO Survey follow-up (Schörck et al., 2009) and of the H3 Survey (Naidu et al., 2020). In Fig. 3 I show the average of the metal-weak tail of Bonifacio et al. (2021) and Schörck et al. (2009), without including also Naidu et al. (2020), because the latter only extends to a metallicity –3.0. Thanks to this averaging procedure we may now assign an error to each bin in the MDF, this information is crucial to allow a comparison with theoretical models. The conclusion is that the extremely metal poor stars are very few, for each 1000 stars at metallicity –2.0 there are about 30 at metallicity –3.0 and only one at metallicity –4.0. This explains why wide and large surveys are needed to find these unique objects. However thanks to Gaia coupled to the ground-based spectroscopic (e.g. GALAH De Silva et al. 2015, WEAVE Dalton et al. 2020, 4MOST de Jong et al. 2019, MOONS Cirasuolo et al. 2020), and narrow-band photometric surveys (e.g. SkyMapper, Keller et al. 2007, Pristine, Starkenburg et al. 2017, S-Plus, Mendes de Oliveira et al. 2019) we can expect the numbers of the known EMP stars will be boosted by a

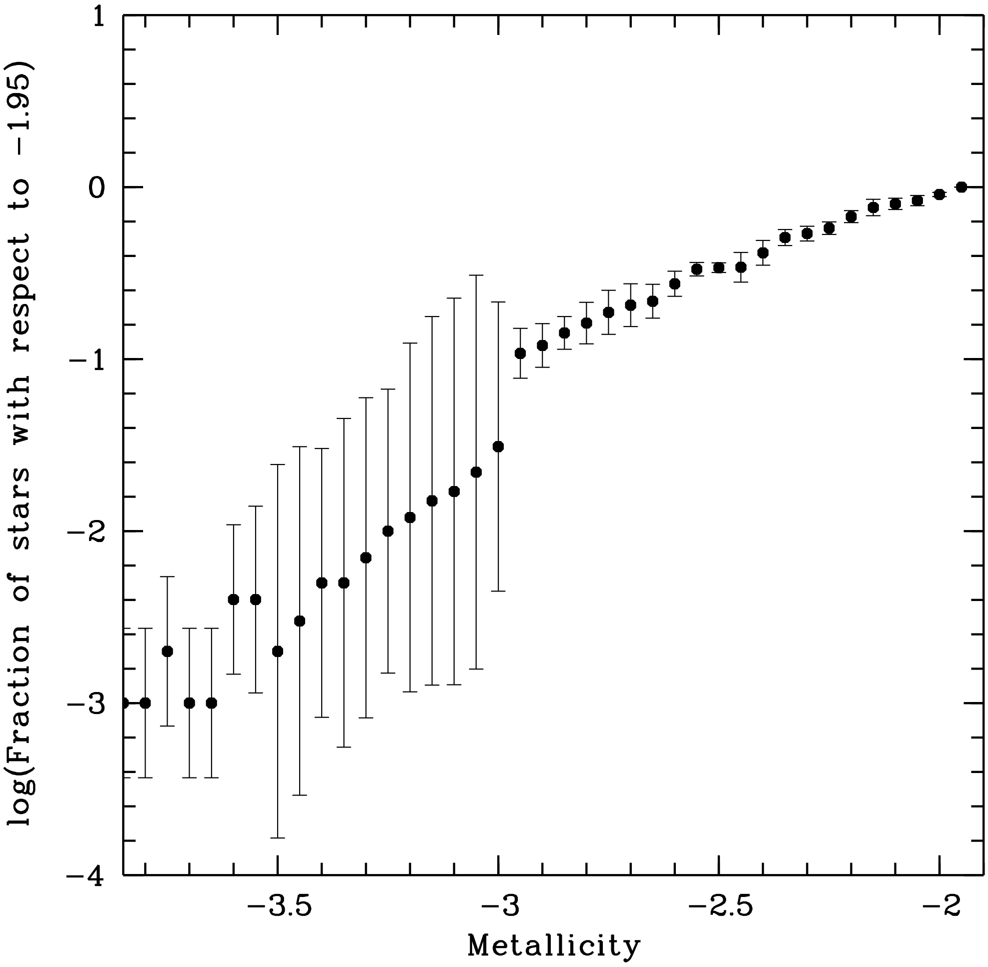

Fig. 3 The average metal-weak tail of the Galactic MDF from Bonifacio et al. (2021).

factor of 100, we shall thus be capable to perform statistics on their properties and especially on their chemical composition.

A classical method to select metal poor stars is kinematics, selection of high speed, high proper motion or high radial velocity stars results in selecting a high fraction of metal poor stars. This was realised very early by Roman (1950) and has since formed part of the "common wisdom" of all astronomers. The availability of accurate parallaxes, proper motions, and for the brightest stars also radial velocities has revived this kind of selection. Our group has been using FORS at the VLT to explore the chemical properties of stars with transverse velocities in excess of 500 $\mathrm{km\,s^{-1}}$(Caffau et al., 2020). This allowed to select stars with extreme kinematics, including five formally unbound stars, more than half of the sample turned out to be on retrograde orbits. However from the chemical point of view none of the stars appeared to be extreme, the mean metallicity of the sample is $\overline{[\mathrm{Fe/H}]} = -1.5$ with a dispersion of 0.4 dex. Another unexpected finding is the apparently high fraction, 12.5% of stars apparently younger than 8 Gyrs, i.e. at least 4 Gyrs younger than the observed age of the Halo (see e.g. Haywood et al., 2016, and references therein). Whether these stars belong to a young metal poor population or are simply Blue Stragglers is still an open question. An investigation on this issue is on-going. The kinematical selection allows to select stars that have orbits very different from the Sun, that is to say, that they do not belong to the thin disc. The Gaia data allowed us to realise that there are stars of any metallicity that are on thin disc orbits (see e.g. Di Matteo et al., 2020, and references therein). The most extreme case being that of SDSS J102915+172927, that with a global metallicity $Z \approx 4.9 \times 10^{-5} Z_{\odot}$ (Caffau et al., 2012) is on a thin disc orbit. A kinematical selection totally misses such stars.

In the next decade we can expect a large number of metal poor stars to be be robustly identified by spectroscopy, photometry and kinematics. By metal poor I mean all stars stars with metallicity below –1.0. While certainly the most metal poor stars hold a special interest, as descendants of the first generation(s) of stars, stars in the metallicity range $-2.5 \leq [\mathrm{Fe/H}] \leq -1.0$ hold the promise to distinguish between competing models of Galactic chemical evolution (see e.g. Cescutti and Chiappini, 2014). Furthermore it is in this metallicity range that one can expect to find the stars formed from gas polluted by the ejecta of Pair Instability Supernovae (Salvadori et al., 2019), allowing us to probe the high mass end of the Initial Mass Function of the first generation(s) of stars.

3 The role of CUBES

In the coming years an instrument like CUBES (Ernandes et al., 2020) can play a strategic role in our capability of measuring the chemical abundances of metal poor and in particular of extremely metal poor stars. The metallic lines in the optical wavelength range become weaker with decreasing metallicity, to the point that for warm Turn-Off stars below metallicity of –3.0 there are often no measurable metallic lines in the optical range, except the Mg I b triplet. Many of the metallic lines in the UV range 300–400 nm, instead remain measurable down to extremely low metallicity. I will make below a list of crucial spectral features in this wavelength range that will allow CUBES to provide unique additions to the chemical inventory of metal poor stars.

3.1 Beryllium

Beryllium can only be measured from the resonance Be II doublet at 313 nm. It is interesting that with existing spectrographs it has been possible to determine tight upper limits on the Be abundance in two stars with $[\mathrm{Fe/H}] \sim -4$ (Ito et al., 2009; Spite et al., 2019). Quite surprisingly in both stars the Be upper limit is well below the Be-O trend defined by other stars. These observations have only been possible because both stars are very bright (BD +44 493 has G=8.9, 2MASS J18082002-5104378 has G= 11.8). CUBES, with its higher efficiency could perhaps transform the upper limit on 2MASS J18082002-5104378 into a measurement and open up the possibility to study Be in fainter stars at comparable metallicity. At these very low metallicities blending is not an issue for measuring Be, since the redmost line of the doublet is always clean, thus the resolving power achievable with CUBES is adequate. The flat-fielding precision (of the order of 5%, see Ito et al. 2009 and Spite et al. 2019) achieved by current UV-capable spectropgraphs like HDS at Subaru (Noguchi et al., 1998) and UVES at VLT (Dekker et al., 2000) seems adequate. The limiting factor to go to fainter objects is the S/N ratio, that can be improved by CUBES.

3.2 Nitrogen

In spite of the fact that it is one of the most abundant elements in the Universe, nitrogen is quite difficult to measure in stars. The atomic lines of neutral nitrogen in the near infra-red become not measurable at metallicities below –0.5. A significant amount of measurements in the literature have been done using CN bands, however below metallicity −1.0 the violet band at 420 nm becomes not measurable (see e.g. Carretta et al., 2005, and references therein) and one is left with the 388.3 nm band, which, however is formed in conditions of non thermodynamic equilibrium (Mount and Linsky, 1975) and suffers from severe granulation effects (Gallagher et al., 2017). As an abundance indicator it is very difficult to model. The fact that it is a bi-metallic molecule is less of a nuisance, on the one hand because carbon can often be determined from the G-band (except for non C-enhanced extremely metal poor stars), on the other hand because in any case the use of molecular bands requires the knowledge of the abundances of at least C and O, and possibly N, since all three elements are connected via the chemical reaction network that rules the formation and dissociation of molecules (see e.g. Gallagher et al., 2017, for a discussion of this point). The use of the NH $A^3\Pi_i - X^3\Sigma^-$ band at 336 nm is a much better choice (see e.g. Israelian et al., 2004; Spite et al., 2005; Bonifacio et al., 2013), at the cost of having access to the near UV range, with all the difficulties annexed.

3.3 Oxygen

In spite of being the most abundant metal in the Universe, oxygen is difficult to measure in extremely metal poor stars. The [OI] line at 630 nm is measurable in giant stars, down to [O/H]~ -3 (see e.g. Cayrel et al., 2004), and it is in any case difficult because the region in contaminated by telluric absorption lines. The strongest line of the permitted OI triplet at 777 nm can be measured down to [O/H]~ -2.8 (in 3D-NLTE analysis) in metal poor Turn-Off stars (see e.g. Israelian et al., 2001; Amarsi et al., 2019), but below it becomes very difficult to measure. An attractive alternative is offered by the OH UV lines of the $A^2\Sigma^+ - X^2\Pi$ bands that are found in the wavelength range 308 nm – 330 nm (see e.g. Israelian et al., 2001; Bessell et al., 2004, 2015). The lines are known to suffer from strong granulation effects (Collet et al., 2007; González Hernández et al., 2010; Gallagher et al., 2017; Prakapavičius et al., 2017; Collet et al., 2018), but, in principle, these can be modelled. Again the price to pay is accessibility to the near-UV range, in fact quite close to the atmospheric cut-off.

3.4 Copper

The copper abundance in giant stars can be measured from the high excitation lines of Mult.2 at 510.5 nm and 587.2 nm (e.g. Cohen, 1980; Sneden et al., 1991; Shetrone et al., 2001; Pancino et al., 2002; Mishenina et al., 2002; Cunha et al., 2002; Shetrone et al., 2003; Simmerer et al., 2003; Yong et al., 2005), however these lines become vanishingly small at [Fe/H] < -3.0. The alternative is to use the resonance lines of Mult. 1 at 324.7 nm and 327.3 nm (Bihain et al., 2004; Andrievsky et al., 2018). The strongest of the two lines, 324.6 nm, has been detected in the extremely metal poor giant CD −38 245 (Andrievsky et al., 2018). These lines are known to suffer from strong granulation effects (Bonifacio et al., 2010), as well as deviations from thermodynamic equilibrium (Andrievsky et al., 2018). Although up to now a full 3D-NLTE analysis of these lines does not exist, it is reasonable to expect it will be available in the next few years. The study of the vacuum UV Cu II lines, that are supposed to be little affected by either NLTE or granulation effects, by Roederer and Barklem (2018) support the 1D NLTE computations of Andrievsky et al. (2018), suggesting that there are also some granulation effects, that tend to lower the abundance with respect to the 1D NLTE results.

3.5 Neutron capture elements

Many elements that are formed by neutron capture have useful lines in the CUBES range. Rather than providing an line list I point to the reader the extensive analysis of the r-process rich metal poor giant CS 31082-001 by Hill et al. (2002, see their Table A.1). That line list is an excellent starting point for the study of neutron capture elements in metal poor stars. One of the worries is that many of these lines are not only weak, but also blended with other atomic or molecular lines. In this respect the foreseen resolving power of CUBES (R$\sim$ 20 000) may prove to be a limiting factor. One should be however aware that in metal poor stars the line broadening is generally dominated by macroturbulence, corresponding typically to a resolving power of 40 000. Therefore increasing the instrumental resolving power above this value allows for a a better sampling of the line profile, which is always desirable when performing line-fitting, but does not allow to resolve blends.

4 Conclusion

I hope I have convinced the reader of the importance of obtaining a chemical inventory, as complete as possible, for metal poor stars. In the coming years many interesting targets will be available as a result of selection based on spectra, narrow band photometry or kinematics in a magnitude range that is relevant for CUBES observations. For these stars the near-UV range covered by CUBES will provide access to a unique set of abundance diagnostics, that are simply not available at longer wavelengths. Although for some elements, noticeably the neutron capture elements, it would be desirable to have the possibility to observe with a higher resolving (ideally above 60 000, that corresponds more or less to the thermal broadening of spectral lines in stars of G type), the trade-off with the efficiency of the instrument has found a sweet spot around $R = 20\,000$. The prospects for CUBES to prove an extremely useful instrument are good, to the point that I believe it would be an excellent idea to have a copy of CUBES on a 8-10m telescope in the northern hemisphere. A possibility would be the GTC telescope (Alvarez et al., 1998) , on which some of the bent-Cassegrain foci are still not claimed for, and they could be used for a copy of CUBES.

Conflict of interest

The author declares to have no conflict of interest concerning the contents of this paper.

References

Aguado DS, Allende Prieto C, González Hernández JI, Rebolo R (2018a) J0023+0307: A Mega Metal-poor Dwarf Star from SDSS/BOSS. ApJ854(2):L34, DOI 10.3847/2041-8213/aaadb8, 1802.06240

Aguado DS, González Hernández JI, Allende Prieto C, Rebolo R (2018b) J0815+4729: A Chemically Primitive Dwarf Star in the Galactic Halo Observed with Gran Telescopio Canarias. ApJ852(1):L20, DOI 10.3847/2041-8213/aaa23a, 1712.06487

Allende Prieto C, Fernández-Alvar E, Aguado DS, et al (2015) An equatorial ultra iron-poor star identified in BOSS. A&A579:A98, DOI 10.1051/0004-6361/201525904, 1505.05555

Alvarez P, Rodríguez Espinosa JM, Sánchez F (1998) The Gran Telescopio Canarias (GTC) project. New A Rev.42(6-8):553–556, DOI 10.1016/S1387-6473(98)00071-2

Amarsi AM, Nissen PE, Skúladóttir Á (2019) Carbon, oxygen, and iron abundances in disk and halo stars. Implications of 3D non-LTE spectral line formation. A&A630:A104, DOI 10.1051/0004-6361/201936265, 1908.10319

Andrievsky S, Bonifacio P, Caffau E, et al (2018) Galactic evolution of copper in the light of NLTE computations. MNRAS473(3):3377–3384, DOI 10.1093/mnras/stx2526, 1709.08619

Beers TC, Christlieb N (2005) The Discovery and Analysis of Very Metal-Poor Stars in the Galaxy. ARA&A43(1):531–580, DOI 10.1146/annurev.astro.42.053102.134057

Bessell MS, Christlieb N, Gustafsson B (2004) On the Oxygen Abundance of HE 0107-5240. ApJ612(1):L61–L63, DOI 10.1086/424443, astro-ph/0401450

Bessell MS, Collet R, Keller SC, et al (2015) Nucleosynthesis in a Primordial Supernova: Carbon and Oxygen Abundances in SMSS J031300.36-670839.3. ApJ806(1):L16, DOI 10.1088/2041-8205/806/1/L16, 1505.03756

Bihain G, Israelian G, Rebolo R, Bonifacio P, Molaro P (2004) Cu and Zn in the early Galaxy. A&A423:777–786, DOI 10.1051/0004-6361:20035913, astro-ph/0405050

Bonifacio P, Caffau E, Ludwig HG (2010) Cu I resonance lines in turn-off stars of NGC 6752 and NGC 6397. Effects of granulation from CO5BOLD models. A&A524:A96, DOI 10.1051/0004-6361/200912935, 1009.1848

Bonifacio P, Sbordone L, Caffau E, et al (2012) Chemical abundances of distant extremely metal-poor unevolved stars. A&A542:A87, DOI 10.1051/0004-6361/201219004, 1204.1641

Bonifacio P, Caffau E, Ludwig HG, et al (2013) Molecular bands in extremely metal-poor stars: Granulation effects. Memorie della Società Astronomica Italiana Supplementi 24:138–145, 1305.2065

Bonifacio P, Caffau E, Spite M, et al (2015) TOPoS . II. On the bimodality of carbon abundance in CEMP stars Implications on the early chemical evolution of galaxies. A&A579:A28, DOI 10.1051/0004-6361/201425266, 1504.05963

Bonifacio P, Caffau E, Spite M, et al (2018) TOPoS. IV. Chemical abundances from high-resolution observations of seven extremely metal-poor stars. A&A612:A65, DOI 10.1051/0004-6361/201732320, 1801.03935

Bonifacio P, Molaro P, Adibekyan V, et al (2020) ESPRESSO highlights the binary nature of the ultra-metal-poor giant HE 0107-5240. A&A633:A129, DOI 10.1051/0004-6361/201935833

Bonifacio P, Monaco L, Salvadori S, et al (2021) TOPoS. VI. The metal-weak tail of the metallicity distribution functions of the Milky Way and the Gaia-Sausage-Enceladus structure. A&A651:A79, DOI 10.1051/0004-6361/202140816

Bressan A, Marigo P, Girardi L, et al (2012) PARSEC: stellar tracks and isochrones with the PAdova and TRieste Stellar Evolution Code. MNRAS427(1):127–145, DOI 10.1111/j.1365-2966.2012.21948.x, 1208.4498

Bromm V (2013) Formation of the first stars. Reports on Progress in Physics 76(11):112901, DOI 10.1088/0034-4885/76/11/112901, 1305.5178

Caffau E, Bonifacio P, François P, et al (2011) X-Shooter GTO: chemical analysis of a sample of EMP candidates. A&A534:A4, DOI 10.1051/0004-6361/201117530, 1109.0992

Caffau E, Bonifacio P, François P, et al (2012) A primordial star in the heart of the Lion. A&A542:A51, DOI 10.1051/0004-6361/201118744, 1203.2607

Caffau E, Bonifacio P, Sbordone L, et al (2013) TOPoS. I. Survey design and analysis of the first sample. A&A560:A71, DOI 10.1051/0004-6361/201322488, 1310.6963

Caffau E, Bonifacio P, Spite M, et al (2016) TOPoS. III. An ultra iron-poor multiple CEMP system. A&A595:L6, DOI 10.1051/0004-6361/201629776, 1610.04106

Caffau E, Monaco L, Bonifacio P, et al (2020) High-speed stars: Galactic hitchhikers. A&A638:A122, DOI 10.1051/0004-6361/202038057

Carretta E, Gratton RG, Lucatello S, Bragaglia A, Bonifacio P (2005) Abundances of C, N, O in slightly evolved stars in the globular clusters NGC 6397, NGC 6752 and 47 Tuc. A&A433(2):597–611, DOI 10.1051/0004-6361:20041892, astro-ph/0411241

Cayrel R (1986) And if population III were population II? A&A168:81–88

Cayrel R, Depagne E, Spite M, et al (2004) First stars V - Abundance patterns from C to Zn and supernova yields in the early Galaxy. A&A416:1117–1138, DOI 10.1051/0004-6361:20034074, astro-ph/0311082

Cescutti G, Chiappini C (2014) Explaining the Ba, Y, Sr, and Eu abundance scatter in metal-poor halo stars: constraints to the r-process. A&A565:A51, DOI 10.1051/0004-6361/201423432, 1403.8070

Cirasuolo M, Fairley A, Rees P, et al (2020) MOONS: The New Multi-Object Spectrograph for the VLT. The Messenger 180:10–17, DOI 10.18727/0722-6691/5195, 2009.00628

Cohen JG (1980) Abundances in globular cluster red giants. III. M 71, M 67, and NGC 2420. ApJ241:981–1000, DOI 10.1086/158412

Collet R, Asplund M, Trampedach R (2007) Three-dimensional hydrodynamical simulations of surface convection in red giant stars. Impact on spectral line formation and abundance analysis. A&A469(2):687–706, DOI 10.1051/0004-6361:20066321, astro-ph/0703652

Collet R, Nordlund Å, Asplund M, Hayek W, Trampedach R (2018) The benchmark halo giant HD 122563: CNO abundances revisited with three-dimensional hydrodynamic model stellar atmospheres. MNRAS475(3):3369–3392, DOI 10.1093/mnras/sty002, 1712.08099

Cunha K, Smith VV, Suntzeff NB, et al (2002) The Evolution of Copper in the Globular Cluster ω Centauri. AJ124(1):379–388, DOI 10.1086/340967, astro-ph/0203408

Dalton G, Trager S, Abrams DC, et al (2020) Integration and early testing of WEAVE: the next-generation spectroscopy facility for the William Herschel Telescope. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol 11447, p 1144714, DOI 10.1117/12.2561067

de Jong RS, Agertz O, Berbel AA, et al (2019) 4MOST: Project overview and information for the First Call for Proposals. The Messenger 175:3–11, DOI 10.18727/0722-6691/5117, 1903.02464

De Silva GM, Freeman KC, Bland-Hawthorn J, et al (2015) The GALAH survey: scientific motivation. MNRAS449(3):2604–2617, DOI

10.1093/mnras/stv327, 1502.04767

Dekker H, D'Odorico S, Kaufer A, Delabre B, Kotzlowski H (2000) Design, construction, and performance of UVES, the echelle spectrograph for the UT2 Kueyen Telescope at the ESO Paranal Observatory. In: Iye M, Moorwood AF (eds) Optical and IR Telescope Instrumentation and Detectors, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol 4008, pp 534–545, DOI 10.1117/12.395512

Di Matteo P, Spite M, Haywood M, et al (2020) Reviving old controversies: is the early Galaxy flat or round?. Investigations into the early phases of the Milky Way's formation through stellar kinematics and chemical abundances. A&A636:A115, DOI 10.1051/0004-6361/201937016, 1910.13769

Ernandes H, Evans CJ, Barbuy B, et al (2020) Stellar astrophysics in the near-UV with VLT-CUBES. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol 11447, p 1144760, DOI 10.1117/12.2562497, 2102.02205

François P, Caffau E, Bonifacio P, et al (2018a) TOPoS. V. Abundance ratios in a sample of very metal-poor turn-off stars. A&A620:A187, DOI 10.1051/0004-6361/201834375, 1811.00035

François P, Caffau E, Wanajo S, et al (2018b) Chemical analysis of very metal-poor turn-off stars from SDSS-DR12. A&A619:A10, DOI 10.1051/0004-6361/201833824, 1808.09918

François P, Wanajo S, Caffau E, et al (2020) Detailed abundances in a sample of very metal-poor stars. A&A642:A25, DOI 10.1051/0004-6361/202038028, 2007.03994

Gallagher AJ, Caffau E, Bonifacio P, et al (2017) An in-depth spectroscopic examination of molecular bands from 3D hydrodynamical model atmospheres. II. Carbon-enhanced metal-poor 3D model atmospheres. A&A598:L10, DOI 10.1051/0004-6361/201630272, 1701.09102

González Hernández JI, Bonifacio P, Ludwig HG, Caffau E, Behara NT, Freytag B (2010) Galactic evolution of oxygen. OH lines in 3D hydrodynamical model atmospheres. A&A519:A46, DOI 10.1051/0004-6361/201014397, 1005.3754

Greif TH, Springel V, White SDM, et al (2011) Simulations on a Moving Mesh: The Clustered Formation of Population III Protostars. ApJ737(2):75, DOI 10.1088/0004-637X/737/2/75, 1101.5491

Haywood M, Lehnert MD, Di Matteo P, et al (2016) When the Milky Way turned off the lights: APOGEE provides evidence of star formation quenching in our Galaxy. A&A589:A66, DOI 10.1051/0004-6361/201527567, 1601.03042

Hill V, Plez B, Cayrel R, et al (2002) First stars. I. The extreme r-element rich, iron-poor halo giant CS 31082-001. Implications for the r-process site(s) and radioactive cosmochronology. A&A387:560–579, DOI 10.1051/0004-6361:20020434, astro-ph/0203462

Hubble E (1929) A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae. Proceedings of the National Academy of Science

15(3):168–173, DOI 10.1073/pnas.15.3.168

Ishigaki MN, Tominaga N, Kobayashi C, Nomoto K (2018) The Initial Mass Function of the First Stars Inferred from Extremely Metal-poor Stars. ApJ857(1):46, DOI 10.3847/1538-4357/aab3de, 1801.07763

Israelian G, Rebolo R, García López RJ, et al (2001) Oxygen in the Very Early Galaxy. ApJ551(2):833–851, DOI 10.1086/320225, astro-ph/0101032

Israelian G, Ecuvillon A, Rebolo R, et al (2004) Galactic evolution of nitrogen. A&A421:649–658, DOI 10.1051/0004-6361:20047132, astro-ph/0405049

Ito H, Aoki W, Honda S, Beers TC (2009) BD+44 493: A Ninth Magnitude Messenger from the Early Universe; Carbon Enhanced and Beryllium Poor. ApJ698(1):L37–L41, DOI 10.1088/0004-637X/698/1/L37, 0905.0950

Keller SC, Schmidt BP, Bessell MS, et al (2007) The SkyMapper Telescope and The Southern Sky Survey. PASA24(1):1–12, DOI 10.1071/AS07001, astro-ph/0702511

Mendes de Oliveira C, Ribeiro T, Schoenell W, et al (2019) The Southern Photometric Local Universe Survey (S-PLUS): improved SEDs, morphologies, and redshifts with 12 optical filters. MNRAS489(1):241–267, DOI 10.1093/mnras/stz1985, 1907.01567

Mishenina TV, Kovtyukh VV, Soubiran C, Travaglio C, Busso M (2002) Abundances of Cu and Zn in metal-poor stars: Clues for Galaxy evolution. A&A396:189–201, DOI 10.1051/0004-6361:20021399, astro-ph/0209401

Mount GH, Linsky JL (1975) A new solar carbon abundance based on non-LTE CN molecular spectra. ApJ202:L51–L54, DOI 10.1086/181978

Naidu RP, Conroy C, Bonaca A, et al (2020) Evidence from the H3 Survey That the Stellar Halo Is Entirely Comprised of Substructure. ApJ901(1):48, DOI 10.3847/1538-4357/abaef4, 2006.08625

Noguchi K, Ando H, Izumiura H, Kawanomoto S, Tanaka W, Aoki W (1998) High-dispersion spectrograph (HDS) for SUBARU Telescope. In: D'Odorico S (ed) Optical Astronomical Instrumentation, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol 3355, pp 354–362, DOI 10.1117/12.316771

O'Connell DJK (1958) Stellar populations. Ricerche Astronomiche 5

Pancino E, Pasquini L, Hill V, Ferraro FR, Bellazzini M (2002) High-Resolution Spectroscopy of Metal-rich Giants in ω Centauri: First Indication of Type Ia Supernova Enrichment. ApJ568(2):L101–L105, DOI 10.1086/340378, astro-ph/0202397

Penzias AA, Wilson RW (1965) A Measurement of Excess Antenna Temperature at 4080 Mc/s. ApJ142:419–421, DOI 10.1086/148307

Pitrou C, Coc A, Uzan JP, Vangioni E (2018) Precision big bang nucleosynthesis with improved Helium-4 predictions. Phys. Rep.754:1–66, DOI 10.1016/j.physrep.2018.04.005, 1801.08023

Planck Collaboration, et al. (2020) Planck 2018 results. VI. Cosmological parameters. A&A641:A6, DOI 10.1051/0004-6361/201833910, 1807.06209

Prakapavičius D, Kučinskas A, Dobrovolskas V, et al (2017) Three-dimensional hydrodynamical CO^{5}BOLD model atmospheres of red giant stars. V. Oxygen abundance in the metal-poor giant HD 122563 from OH UV lines.

A&A599:A128, DOI 10.1051/0004-6361/201629306, 1611.03283

Riess AG, et al. (1998) Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. AJ116(3):1009–1038, DOI 10.1086/300499, astro-ph/9805201

Roederer IU, Barklem PS (2018) A New Test of Copper and Zinc Abundances in Late-type Stars Using Ultraviolet Cu II and Zn II Lines. ApJ857(1):2, DOI 10.3847/1538-4357/aab71f, 1803.09763

Roman NG (1950) A Correlation Between the Spectroscopic and Dynamical Characteristics of the Late F - and Early G - Type Stars. ApJ112:554, DOI 10.1086/145367

Salvadori S, Bonifacio P, Caffau E, et al (2019) Probing the existence of very massive first stars. MNRAS487(3):4261–4284, DOI 10.1093/mnras/stz1464, 1906.00994

Schörck T, Christlieb N, Cohen JG, et al (2009) The stellar content of the Hamburg/ESO survey. V. The metallicity distribution function of the Galactic halo. A&A507(2):817–832, DOI 10.1051/0004-6361/200810925, 0809.1172

Shetrone M, Venn KA, Tolstoy E, et al (2003) VLT/UVES Abundances in Four Nearby Dwarf Spheroidal Galaxies. I. Nucleosynthesis and Abundance Ratios. AJ125(2):684–706, DOI 10.1086/345966, astro-ph/0211167

Shetrone MD, Côté P, Sargent WLW (2001) Abundance Patterns in the Draco, Sextans, and Ursa Minor Dwarf Spheroidal Galaxies. ApJ548(2):592–608, DOI 10.1086/319022, astro-ph/0009505

Simmerer J, Sneden C, Ivans II, et al (2003) A Comparison of Copper Abundances in Globular Cluster and Halo Field Giant Stars. AJ125(4):2018–2028, DOI 10.1086/373926, astro-ph/0303176

Sneden C, Gratton RG, Crocker DA (1991) Trends in copper and zinc abundances for disk and halo stars. A&A246:354

Spite M, Cayrel R, Plez B, et al (2005) First stars VI - Abundances of C, N, O, Li, and mixing in extremely metal-poor giants. Galactic evolution of the light elements. A&A430:655–668, DOI 10.1051/0004-6361:20041274, astro-ph/0409536

Spite M, Bonifacio P, Spite F, et al (2019) Be and O in the ultra metal-poor dwarf 2MASS J18082002-5104378: the Be-O correlation. A&A624:A44, DOI 10.1051/0004-6361/201834741, 1902.11048

Starkenburg E, Martin N, Youakim K, et al (2017) The Pristine survey - I. Mining the Galaxy for the most metal-poor stars. MNRAS471(3):2587–2604, DOI 10.1093/mnras/stx1068, 1705.01113

Wagoner RV, Fowler WA, Hoyle F (1967) On the Synthesis of Elements at Very High Temperatures. ApJ148:3, DOI 10.1086/149126

Yong D, Grundahl F, Nissen PE, Jensen HR, Lambert DL (2005) Abundances in giant stars of the globular cluster NGC 6752. A&A438(3):875–888, DOI 10.1051/0004-6361:20052916, astro-ph/0504283