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Beryllium abundances in metal-poor stars with the CUBES spectrograph

R. Smiljanic[1], R. E. Giribaldi[2] & A. R. da Silva[1]

[1] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716, Warsaw, Poland
e-mail: `rsmiljanic@camk.edu.pl`
[2] Institut d'Astronomie et d'Astrophysique, Université libre de Bruxelles, CP 226, Boulebard do Triomphe, 1050 Brussels, Belgium

Abstract. The Cassegrain U-Band Efficient Spectrograph (CUBES) is a new near-UV optimised spectrograph that is being built for the 8-meter Very Large Telescope (VLT) of the European Southern Observatory. Due to its high efficiency, at wavelengths shorter than 400 nm, CUBES at the VLT will be competitive even against the 39-m Extremely Large Telescope, which will be optimised for observations in the red and infrared. Among the science cases motivating the construction of CUBES are studies of beryllium abundances in metal-poor stars. Beryllium is a light element with one single stable isotope, ^{9}Be, which is a pure product of cosmic-ray spallation. Inside stars, Be atoms can only be destroyed. The peculiar nucleosynthetic origin of Be makes it ideal as a tracer of inhomogeneous metal mixing in the interstellar medium of the early Galaxy. In this work, we simulated the use of the instrument in investigating Be abundances in extremely metal-poor stars ([Fe/H] < -3.0) and in turn-off stars of globular clusters. Both science cases will be challenging but can only be addressed with an efficient instrument like CUBES.

Resumo. O espectrógrafo CUBES (*Cassegrain U-Band Efficient Spectrograph*, em inglês) é um novo instrumento otimizado para observações no UV próximo que está sendo construído para o *Very Large Telescope* (VLT) de 8 metros do Observatório Europeu do Sul (ESO, na sigla em inglês). Devido a sua alta eficiência, em comprimentos de onda mais curtos que 400 nm o CUBES no VLT será competitivo mesmo em comparação com o *Extremely Large Telescope* de 39 metros, que será otimizado para observações no vermelho e infravermelho. Entre os casos científicos que motivam a construção do CUBES estão os estudos de abundância de berílio em estrelas pobres em metal. O berílio é um elemento leve com um único isótopo estável, ^{9}Be, que é um produto puro de espalação de raios cósmicos. Dentro das estrelas, os átomos de Be só podem ser destruídos. A peculiar origem nucleossintética do Be o torna ideal como traçador da falta de homogeneidade de metais no meio interestelar da Galáxia primitiva. Neste trabalho, por meio de simulações, investigamos o uso deste instrumento para estudos da abundância do Be em estrelas extremamente pobres em metal ([Fe/H] $< -3{,}0$) e também em estrelas de aglomerados globulares. Ambos os casos científicos serão desafiadores, mas só poderão ser tratados com um instrumento eficiente como o CUBES.

Keywords. Instrumentation: spectrographs – Stars: abundances – Stars: Population II

1. Introduction

The Cassegrain U-Band Efficient Spectrograph (CUBES[1]) is a new spectrograph that will be installed at a Cassegrain focus of one of the Unit Telescopes of the Very Large Telescope (VLT) of the European Southern Observatory (ESO), at Cerro Paranal, Chile, in 2027 (Cristiani et al. 2022a,b). The instrument will enable observations in the near-ultraviolet (near-UV) wavelength range, dividing the spectral coverage into two arms (300-352 nm and 346-405 nm). It will have two resolution modes, R $\sim$ 6000 and R $\sim$ 22000, which are enabled by the exchange of two independent image slicers (Calcines et al. 2022a,b). Each arm will have a high-groove transmission grating that operates in first order produced by microlithography (Zeitner et al. 2022a,b). The preliminary design also includes an option for a fibre link to the UV-visual echelle spectrograph (UVES, Dekker et al. 2000), as a possibility to provide simultaneous observations at longer wavelengths (see details in Zanutta et al. 2022, but for a previous version of the design).

CUBES is being carefully designed to be an instrument of high efficiency. It will open up the possibility of obtaining near-UV spectra for objects that are two to three magnitudes fainter than what is possible with current existing spectrographs. In fact, a blue-optimised spectrograph on the VLT will be competitive against the 39-m Extremely Large Telescope (ELT) at wavelengths shorter than 400 nm (Pasquini 2014; Evans et al. 2016). This is the case because the ELT and also other giant telescopes under construction are being optimised for red- and infrared observations. As a result, they will have very low throughput in the blue part of the spectrum observable from the ground.

The CUBES consortium is led by the Italian National Institute for Astrophysics (Italy) and includes the University of São Paulo (Brazil), the University of Heidelberg (Germany), the UK Astronomy Technology Centre (UK), and the Nicolaus Copernicus Astronomical Center (Poland). The preliminary design phase of the project was conducted in 2022. The CUBES science case is broad and includes studies of solar system, Galactic, and extragalactic objects as well as transients (see a summary in Evans et al. 2022).

2. Beryllium abundances in metal-poor stars

Beryllium is a light element of atomic number Z = 4 that has a single stable isotope, ^{9}Be. An interesting aspect regarding Be is that it can only be formed as a product of cosmic-ray spallation. It is formed in the interstellar medium by the break up of heavier nuclei, in particular C, N, and O (Reeves, Fowler & Hoyle 1970; Meneguzzi, Audouze & Reeves 1971). Inside stars, Be is only destroyed. It is consumed rapidly in proton capture reactions when the temperature is greater than 3.5×10^6 K.

In spectra observed from the ground, there are only two spectral lines of Be that can be used for abundance analysis in late-type stars. These lines are in the near-UV range, at 3130.423 and 3131.067 Å. They originate from the 2s $^2S_{1/2} \rightarrow$ 2p $^2P_{1/2,3/2}$ transitions in singly ionised beryllium (Kramida 2005). Therefore,

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[1] `https://cubes.inaf.it/`

CUBES is an instrument that is expected to be very useful for studies of Be abundances in metal-poor stars.

Currently, Be abundances have been determined in the literature for about 200 different metal-poor stars. This sample is limited to stars brighter than V ∼ 12 mag, for which spectra with signal-to-noise ratio of about 100 can be obtained in a few hours using UVES at the VLT, for example. To illustrate the increase in the sample enabled by CUBES, we queried the catalogue of spectroscopic astrophysical parameters from Data Release 3 of *Gaia* (Recio-Blanco et al. 2022). We selected as potential targets those stars with a declination < +15 deg and G between 12 and 14 mag. This sample was restricted to metal-poor dwarfs or subgiants with: [Fe/H] ≤ -1.5, effective temperature ($T_{\rm eff}$) between 4500 and 6900 K, and surface gravity (log g) between 3.5 and 5.0. Quality flags were ignored for this selection. We found a sample of about 1400 stars that could be targeted by CUBES for studies of Be. For comparison, a query with the same constraints but in the interval with G magnitude between 8 and 12 returns only 357 stars.

In this contribution, we summarise the results of our simulations of the expected performance of CUBES regarding the detection of Be lines in metal-poor stars. We investigated two science cases. One is the search for star-to-star variation in Be abundances among turn-off stars of globular clusters (see a detailed discussion in Giribaldi & Smiljanic 2022). The other is the detection of weak Be lines in faint, extremely metal-poor stars with [Fe/H] < -3.0 (see a detailed discussion in Smiljanic, da Silva & Giribaldi 2022). These new simulations expand on the previous study of the same cases reported in Smiljanic (2014), which was based on an earlier study of CUBES (Barbuy et al. 2014; Bristow et al. 2014), by incorporating recent updates in the instrument design (Zanutta et al. 2022).

3. Simulations

Synthetic spectra were computed with the Turbospectrum code (Plez 2012) and adopting MARCS one-dimensional (1D) model atmospheres (Gustafsson et al. 2008). The line list used atomic data extracted from the Vienna Atomic Line Database (VALD) 3 (Ryabchikova et al. 2015), with the changes described in Giribaldi & Smiljanic (2022)[2]. The list of molecules taken into account in the synthesis, and references, is also given in Giribaldi & Smiljanic (2022). Synthetic spectra were calculated in the range 3000-7000 Å on steps of 0.02 Å.

The red part of the spectrum was used to compute the stellar magnitudes in the V band, which are needed to estimate the exposure time needed to achieve a certain signal-to-noise ratio (SNR). For these calculations, we used the CUBES exposure time calculator (ETC[3]) described in Calderone et al. (2022) and Genoni et al. (2022). The SNR of all our simulated observations was estimated assuming an airmass = 1.2 and a seeing of 1.0 arcsec at 3100 Å (which corresponds to a seeing of about 0.9 arcsec at 5500 Å; slightly worse than the median seeing in Paranal, which is approximately 0.8 arcsec). The exposure times were always taken to be 3000 s. With that choice, we wanted to simulate a standard Paranal service mode observing block, which his normally limited to 1 hour of execution. We also assumed an overhead time of about 10 min, as is the case for observations with UVES at the VLT.

Furthermore, to understand the properties of the observed spectra, we used the CUBES end-to-end simulator[4] (E2E, Calderone et al. 2022; Genoni et al. 2022). The E2E is a software that simulates the effects of the atmosphere, the telescope, and the optical elements of the instrument, including the foreoptics, the image slicers, the spectrograph, and the detector. For the simulations we discuss here, we used the E2E that reflected the design at the end of phase A (Genoni et al. 2022; Zanutta et al. 2022). According to the E2E simulations, in the region around the Be lines, CUBES can obtain spectra with R ∼ 23 000 and a sampling of ∼2.35 px (corresponding to a pixel of 0.058 Å). For our analysis, the resolution and sampling of the synthetic spectra were then adjusted to the values obtained with the E2E.

4. Discussion

4.1. Beryllium abundances in globular cluster stars

Globular clusters are large and dense agglomerations of old stars (∼ 10 Gyr). They are relics of the early star formation process in galaxies (Renzini 2017). These systems show signs of multiple stellar populations that are generally interpreted as multiple generations of stars (see Bastian & Lardo 2018, and references thein). The stars in these multiple populations show abundance variations related to proton-capture reactions in high-temperature hydrogen burning. These variations cannot originate inside the stars themselves and must come from some sort of external pollutor whose origin is not well understood (see Gratton et al. 2019, and references therein).

The key use of Be abundances in this case is as a tracer of the mixture between pristine and polluted material in the formation of second-generation stars. This is the case because the material ejected by any type of evolved star is fully depleted in beryllium. Moreover, we are more interested in measuring the star-to-star variation in Be abundances than in measuring the absolute values of those abundances. The biggest difficulty is that those measurements must be done in unevolved main-sequence turnoff stars to avoid the effects of evolutionary mixing that might affect the Be abundances in more evolved objects. Turnoff stars in globular clusters are faint, with V band magnitudes of about 17. Interested readers are referred to Giribaldi & Smiljanic (2022) for more details and references.

Such measurements have been attempted in the case of two globular clusters, NGC 6397 by Pasquini et al. (2004) and NGC 6752 by Pasquini et al. (2007). Two stars were observed in each cluster, using the UVES spectrograph. In NGC 6397, a total of 12 hours per star was used to obtain SNR ∼ 8-15 around the Be lines. In NGC 6752, a total of 15 hours per star was used and SNR ∼ 10-20 was achieved in the same region. The results were somewhat inconclusive as a clear variation in the Be abundances could not be confirmed. With CUBES, 1 hour of exposure can result in spectra with SNR ∼ 25 and 15 for stars in NGC 6397 and NGC 6752, respectively.

As an example of what will be possible with CUBES, in Fig. 1 we show the spectra of three turnoff stars in the globular cluster M4 (the closest globular cluster to the Sun, for which turnoff stars have $V = 16.5$ mag.). The abundance of Be in these simulated stars differs in steps of 0.2 dex. With 1 hour of exposure, the spectra of these stars would be obtained with SNR ∼ 25. The simulations shown in Fig. 1 have SNR = 50, therefore assuming that 4 hours were spent observing each target. The star-to-star variation can be clearly seen.

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[2] This line list is available in `https://github.com/RGiribaldi/Master-line-list-for-spectral-synthesis-with-Turbospectrum`

[3] A public version of the CUBES ETC can be found in `https://cubes.inaf.it/exposure-time-calculator`

[4] A public version of the CUBES E2E can be found in `https://cubes.inaf.it/end-to-end-simulator`

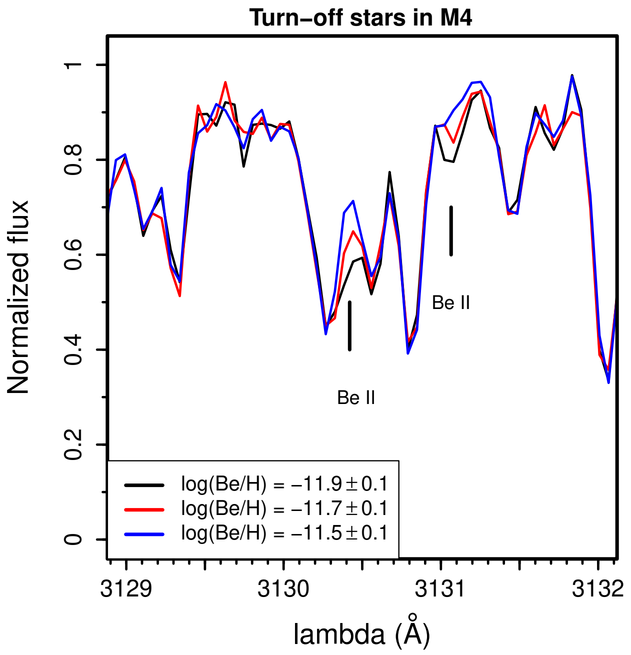

Figure 1. Simulated spectra of turn-off stars in the globular cluster M4. Three spectra are shown differing in the Be abundance in steps of 0.2 dex, according to what is given in the legend. All three spectra have SNR = 50 (simulating 4 hours of observation for each object). The location of the two Be lines is marked.

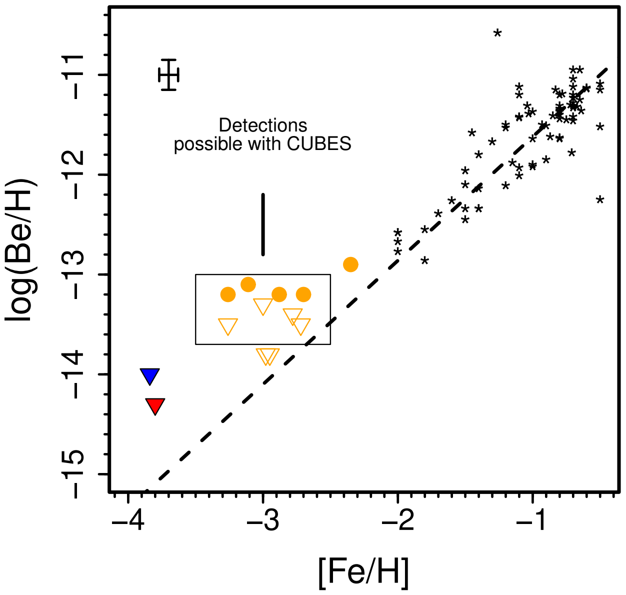

Figure 2. Relation between the Be abundance and metallicity based on the stars from Smiljanic et al. (2009), shown as star symbols. The extremely metal-poor stars from Smiljanic, Zych & Pasquini (2021) are shown in orange, as a circle for a detected Be abundance and as a triangle for an upper limit. The blue and red triangles are upper limits for the stars discussed in Spite et al. (2019) and Placco et al. (2014), respectively. The box is the region in the parameter space for which CUBES observations can be used to detect Be abundances in extremely metal-poor stars (see Smiljanic, da Silva & Giribaldi 2022, for the details).

In Giribaldi & Smiljanic (2022), we concluded that measurements of the star-to-star variation of the Be abundances will be likely possible for the 10 globular clusters that are closest to the Sun and observable from the Cerro Paranal observatory. These clusters have turnoff stars with magnitudes as low as V = 18, for which spectra with SNR = 10 can be obtained with 1 hour of exposure. The exception in the list is probably, NGC 6397. For this metal-poor cluster ([Fe/H] = −2.0), the Be lines are expected to be quite weak and hard to detect.

However, we remark that the science case will still be challenging. CUBES is a single object spectrograph and a total of at least four hours of observation might be needed per target. Building a large sample for a statistical study, even in one single cluster, will be time consuming. Moreover, at the resolution of CUBES, the Be lines are not free of blends and must be carefully analysed. Nevertheless, this seems to be a science case that can only be explored when an efficient instrument like CUBES becomes available.

4.2. Beryllium abundances in extremely metal-poor stars

In the second series of simulations (see Smiljanic, da Silva & Giribaldi 2022, for details), we attempted to investigate whether CUBES spectra can be used to determine Be abundances in extremely metal-poor stars (those with [Fe/H] $\lesssim -3.0$). Smiljanic, Zych & Pasquini (2021) recently presented results for a sample of 11 such stars, showing that there is a clear deviation from the linear relation between Be and [Fe/H] defined by stars of higher metallicities, suggestive of a plateau (see Fig. 2). That there is no plateau, however, seems clear from several upper limits located below that apparent plateau level (including here also results from Placco et al. 2014; Spite et al. 2019). Smiljanic, Zych & Pasquini (2021) suggested that what is observed is actually an increase in the abundance scatter which is related to inhomogeneous metal mixing in the early stages of Galactic chemical enrichment (see also Molaro, Cescutti & Fu 2020). Our goal with the simulations was to investigate whether it will be possible to improve the observations in this metallicity region, transforming some of the upper limits into detections and increasing the number of stars that have been analysed.

We simulated spectra for the case of warm main-sequence stars with ($T_{\rm eff}$, log g) = (6300 K, 4.30) and for a the case of cooler more evolved subgiants with ($T_{\rm eff}$, log g) = (5600 K, 3.40). For each case, we investigated two metallicity values, [Fe/H] = −3.0 and −3.5. The Be abundances in the simulations varied between log(Be/H) = −12.9 and −14.1 in steps of 0.05 dex. Furthermore, for defining the SNR of the observations, we studied simulations of brighter and fainter targets, defined as stars with V band magnitude of 12.5 and 14, respectively. We implemented statistical tests to decide when a detection or an upper limit was obtained (see Smiljanic, da Silva & Giribaldi 2022, for the details).

An example is shown in Fig. 3 for a simulated subgiant star with [Fe/H] = −3.0. In this case, a SNR = 340 can be obtained observing a star of V = 12.5 with CUBES for exposures of 3000s. Our analysis returns a detection with the same Be abundance used to simulate the object. This is a clear case where a detection is possible. Indeed, it can be seen from the figure that even lower Be abundances would be possible to detect.

For these extremely metal-poor stars, the Be lines are always very weak and therefore very challenging to be measured. The simulations show that with CUBES, there is a chance to make those measurements if signal-to-noise ratio per pixel obtained

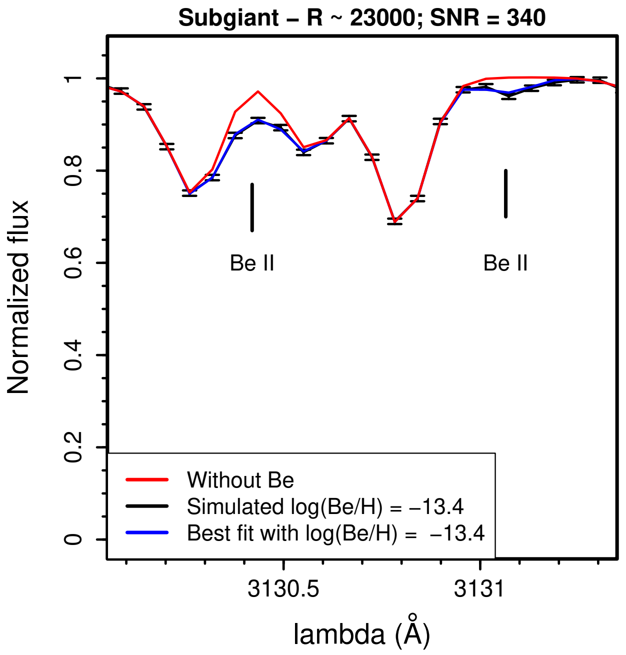

Figure 3. Example of spectrum around the Be lines for a extremely metal-poor subgiant star. The red line in the figure is the spectrum of the same subgiant computed without Be. The simulated observation, with SNR = 340, is shown in black and the best fitting spectrum (without noise) from a library of comparison spectra in blue. The error bars show the level of uncertainty in the spectrum because of the noise.

in the region around the Be lines is of at least 400. Depending on the atmospheric parameters of observed stars, Be abundances between $\log(\mathrm{Be/H}) = -13.1$ and -13.6 can be detected with an uncertainty of ±0.15 dex. For stars with V band magnitude of 12.5, this level of SNR can be obtained with 4-5 hours of exposure. For fainter targets, with V band magnitude of 14, this would require about 16 hours of exposure. There are about 20 known stars with $[\mathrm{Fe/H}] \lesssim -3.0$ in this magnitude range that could be targeted for such analysis. This is, again, a very challenging science case that can only be explored with an efficient near-UV spectrograph like CUBES.

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