



Back to the Lithium Plateau with the $[\text{Fe}/\text{H}] < -6$ Star J0023+0307*

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Abstract

We present an analysis of the Ultraviolet and Visual Echelle Spectrograph (UVES) high-resolution spectroscopic observations at the 8.2 m Very Large Telescope of J0023+0307, a main-sequence extremely iron-poor dwarf star. We are unable to detect iron lines in the spectrum but derive $[\text{Fe}/\text{H}] < -6.1$ from the Ca II resonance lines assuming $[\text{Ca}/\text{Fe}] \geq 0.40$. The chemical abundance pattern of J0023+0307, with very low $[\text{Fe}/\text{Mg}]$ and $[\text{Ca}/\text{Mg}]$ abundance ratios but relatively high absolute Mg and Si abundances, suggests J0023+0307 is a second generation star formed from a molecular cloud polluted by only one supernova in which the fallback mechanism played a role. We measure a carbon abundance of $A(\text{C}) = 6.2$ that places J0023+0307 on the low band in the $A(\text{C})$ – $[\text{Fe}/\text{H}]$ diagram, suggesting no contamination from a binary companion. This star is also unique having a lithium abundance $A(\text{Li}) = 2.02 \pm 0.08$, close to the level of the lithium plateau, in contrast with lower Li determinations or upper limits in all other extremely iron-poor stars. The upper envelope of the lithium abundances in unevolved stars spanning more than three orders of magnitude in metallicity ($-6 < [\text{Fe}/\text{H}] < -2.5$) defines a nearly constant value. We argue that it is unlikely that such uniformity is the result of depletion processes in stars from a significantly higher initial Li abundance, but suggests instead a lower primordial production, pointing to new physics such as decaying massive particles, varying fundamental constants, or nuclear resonances, that could have affected the primordial ${}^7\text{Li}$ production.

Key words: cosmology: observations – Galaxy: halo – primordial nucleosynthesis – stars: abundances – stars: individual (J0023+0307) – stars: Population II

1. Introduction

The study of most ancient stars in the Milky Way allows us to infer early properties of the Galaxy, its chemical composition, and assembly history. The number of ultra metal-poor stars (i.e., $[\text{Fe}/\text{H}] < -4.0$) has increased strikingly in the past few years. A large observational effort has enlarged the sample of such rare objects, thanks to new search techniques (see, e.g., Christlieb et al. 2001; Frebel et al. 2005; Caffau et al. 2011; Keller et al. 2014; Bonifacio et al. 2015; Hansen et al. 2016; Starkenburg et al. 2018). The main sources of metal-poor candidates are large spectroscopic surveys such as the Hamburg/European Southern Observatory (ESO; Christlieb et al. 2001), Sloan Digital Sky Survey (SDSS; York et al. 2000), or Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST; Deng et al. 2012), and photometric ones like Skymapper (Keller et al. 2007) or Pristine (Starkenburg et al. 2017).

Metal-poor stars are invaluable messengers that carry information from early epochs and an important key to understand the primordial production of lithium and the processes responsible for the possible meltdown (see, e.g., Aoki et al. 2009; Sbordone et al. 2010) of the lithium plateau (Spite & Spite 1982; Rebolo et al. 1988). All of the stars with metallicities below $[\text{Fe}/\text{H}] < -3.0$ and lithium abundances lower than $A(\text{Li}) = 2.2 \pm 0.1$ are considered to be likely affected by destruction in the stars. Several explanations have been discussed (see, e.g., Richard et al. 2005; Piau et al. 2006; González Hernández et al. 2009; Meléndez et al. 2010;

Sbordone et al. 2010; Molaro et al. 2012; Bonifacio et al. 2015; Matsuno et al. 2017), including lithium depletion in stellar atmospheres due atomic diffusion, high rotational velocities during the earlier star formation, astration by Population III stars, destruction in the pre-main-sequence phase, and the presence of enhanced fragmentation in the formation of ultra metal-poor stars.

New or poorly measured nuclear reaction resonances could affect the lithium production predicted in big bang nucleosynthesis (BBN; e.g., Cyburt & Pospelov 2012), although recent experiments make this nuclear fix to the BBN unlikely (O’Malley et al. 2011). Processes injecting neutrons at the relevant temperatures of the primordial plasma can also alter the primordial ${}^7\text{Li}$ abundance, for instance, decaying massive particles (well-motivated candidates such as weakly interacting massive particles are provided by supersymmetry) are a natural source for a neutron excess (Peskin 2008), which injected at the appropriate level may reduce the primordial production of ${}^7\text{Li}$. In addition, time-varying fundamental constants may lead to a significantly lower value for primordial ${}^7\text{Li}$, which is particularly sensitive to changes in the deuteron binding energy (see, e.g., Fields 2011). Lithium observations in stars at the lowest observed metallicities are specially important to bring insight on the processes of potential lithium depletion in stars and, ultimately, to establish if any non-standard physics may have played a role during or after BBN.

J0023+0307 was discovered and first observed by Aguado et al. (2018a). François et al. (2018) observed it with X-shooter on the 8.2 m Very Large Telescope (VLT), providing for first time individual abundances of carbon, magnesium, and silicon. Most recently, using the Magellan Inamori Kyocera Echelle

* Based on observations made with Very Large Telescope (VLT) at Paranal Observatory, Chile.

(MIKE) on the *Magellan* telescope, Frebel et al. (2019) added additional elemental abundances and claimed a lithium detection. Here, we measure with high precision many elemental abundances that confirm most of the results from the literature and provide a reliable lithium abundance determination of J0023+0307. These observations allow us to explore the lower-metallicity end of the $A(\text{Li})$ – $[\text{Fe}/\text{H}]$ diagram.

2. Observations

J0023+0307 ($g = 17.90 \pm 0.01$, R.A. = $00^{\text{h}}23^{\text{m}}14^{\text{s}}00$, decl. = $+03^{\circ}07'58''07$ J2000) was observed under the ESO program 0101.D-0149(A) with the UVES spectrograph on the 8.2 m Kueyen VLT at Cerro Paranal Observatory, in the Atacama desert, Chile. The observations were taken in 12 observing blocks (OBs), 1 hr each on 2018 July 22–23, August 8–12, and October 7–8. The total on-target integration time was 10 hr. A $1''.4$ slit was used with 2×2 binning in dark sky conditions. Our settings used dichroic #Dic1 and provided a spectral coverage between 390 and 580 nm. The data were reduced by the ESO staff, and retrieved through the Phase 3 query form. We corrected each spectrum for the barycentric velocity, coadded and combined them. The signal-to-noise per $0.018 \text{ \AA}/\text{pixel}$ in the combined spectrum was ~ 30 , 55, and 80 at 380, 510, and 670 nm, respectively. The nominal resolving power for this set up is $R \sim 31,220$ for the blue part of the spectrum (330–452 nm) and $R \sim 31,950$ for the red (480–680 nm). The seeing was $0''.91$ during the first OB and between $0''.40$ and $0''.65$ during the rest of the run, thus the actual R value is somewhat higher. We performed a fit using an automated fitting tool based on the IDL MPFIT routine (with continuum location, global shift, abundance, and global FWHM as free parameters) of all individual, isolated, detected spectral lines with a high-resolution model and obtained an average global (including instrumental and macroturbulent broadening and assuming no rotation) Gaussian broadening of $7.4 \pm 0.6 \text{ km s}^{-1}$ (equivalent to $R \sim 40,500$). From a cross-correlation of the J0023+0307 spectrum with a extremely metal-poor (EMP) F-type star template we derive a radial velocity of $v_{\text{rad}} = -195.5 \pm 1.0 \text{ km s}^{-1}$, in perfect agreement with the value reported by Frebel et al. (2019), $v_{\text{rad}} = -194.6 \pm 1.2 \text{ km s}^{-1}$. No signal of v_{rad} variation has been observed in the observations spanning four months, suggesting that the star may be single. The *Gaia* DR2 (Gaia Collaboration et al. 2018) provides a parallax of $\varpi = 0.27 \pm 0.14 \text{ mas}$. A detailed calculation of the Galactocentric orbit has been recently carried out by Sestito et al. (2019), who find that the orbit of J0023+0307 is confined to the Galactic plane within $|Z| < 2.3 \text{ kpc}$.

3. Stellar Parameters

Aguado et al. (2018a) reported effective temperatures from the analysis of the Baryon Oscillation Spectroscopic Survey (BOSS; $T_{\text{eff}} = 6295 \pm 36 \text{ K}$), the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS; $T_{\text{eff}} = 6140 \pm 132 \text{ K}$), and the Intermediate-dispersion Spectrograph and Imaging System (ISIS; $T_{\text{eff}} = 6188 \pm 84 \text{ K}$) low-/mid-resolution spectra. After that, François et al. (2018) derived a value of $T_{\text{eff}} = 6160 \pm 100 \text{ K}$ from the $(g-z)$ color calibrations. By fitting the wings of the H_{α} Balmer line we find a higher temperature ($T_{\text{eff}} = 6400 \pm 150 \text{ K}$; see Figure 1). In addition, we used the color calibrations based on the infrared

Table 1
All of the T_{eff} Derived Values Considered in This Work and Explained in Section 3

Source	References	T_{eff}	δT
BOSS spectrum	(1)	6295	36
OSIRIS spectrum	(1)	6140	132
ISIS spectrum	(1)	6188	84
$(g-z)$	(2)	6160	100
H_{α}	(3)	6400	150
H_{β}	(3)	6165	62
IRFM	(4)	6482	224
$(V-J)$	(5)	6481	156
$(V-H)$	(5)	6335	186
$(V-K_s)$	(5)	6615	212
Mean $V-X$	(5)	6474	145
$(V-I)$	(5)	5992	157
$(V-I)$	(6)	5997	130

References. (1) Aguado et al. (2018a), (2) François et al. (2018), (3) this work, (4) González Hernández & Bonifacio (2009), (5) Casagrande et al. (2010), and (6) Frebel et al. (2019).

flux method presented in González Hernández & Bonifacio (2009) with 2*MASS* and *V* Johnson magnitudes transformed from UKIDSS *J*, *H*, *K*, and SDSS *g*, *r* filters. This approach also led to a higher temperature ($T_{\text{eff}} = 6482 \pm 224 \text{ K}$). On the other hand, using color–temperature–metallicity calibrations by Casagrande et al. (2010) we arrive at three very different temperatures from different colors, $V-J$, $V-H$, and $V-K$, giving an average of $T_{\text{eff}} = 6441 \pm 158 \text{ K}$.

Finally, Frebel et al. (2019) use a lower value ($T_{\text{eff}} = 5997 \pm 130 \text{ K}$) from the $V-I$ color. The dispersion found along the several methods performed by different authors reflects how difficult it is to derive a robust effective temperature in EMP stars (see, e.g., Sbordone et al. 2010). We decided to adopt the T_{eff} value from François et al. (2018), $T_{\text{eff}} = 6160 \pm 100 \text{ K}$, which is essentially the same as that derived by Aguado et al. (2018a) from a high signal-to-noise ratio (S/N) ISIS spectrum and also very close to the weighted mean temperature of the values given in Table 1.

The surface gravity derived by Aguado et al. (2018a), $\log g = 4.9 \pm 0.5$, confirms that J0023+0307 is a dwarf star. François et al. (2018) assumed $\log g = 4.5 \pm 0.5$ arguing that the star is not bright enough to be considered a subgiant based on the distance derived from the *Gaia* DR2 parallax. In addition, Sestito et al. (2019) carried out a kinematical study and concluded that the subgiant solution implies an unbound orbit, favoring the dwarf against the subgiant solution at an 88% confidence level. Since there are no detectable iron lines in the UVES spectrum of J0023+0307, we adopt the value from Sestito et al. (2019), $\log g = 4.6 \pm 0.1$, which is consistent with all of the other estimates. Following the method explained in Allende Prieto et al. (2006), based on the comparison of the main stellar parameters with different sets of isochrones from Bertelli et al. (1994), we find a Galactocentric distance of $\sim 2.6 \text{ kpc}$. The obtained value is in agreement with those derived by Sestito et al. (2019), $d = 2.7 \pm 1.4 \text{ kpc}$, using *Gaia* DR2 data.

Finally, the microturbulence has been fixed at 2 km s^{-1} . The errors introduced using this value instead of a value more appropriate for a dwarf of 1.5 km s^{-1} are small ($< 0.1 \text{ dex}$), as

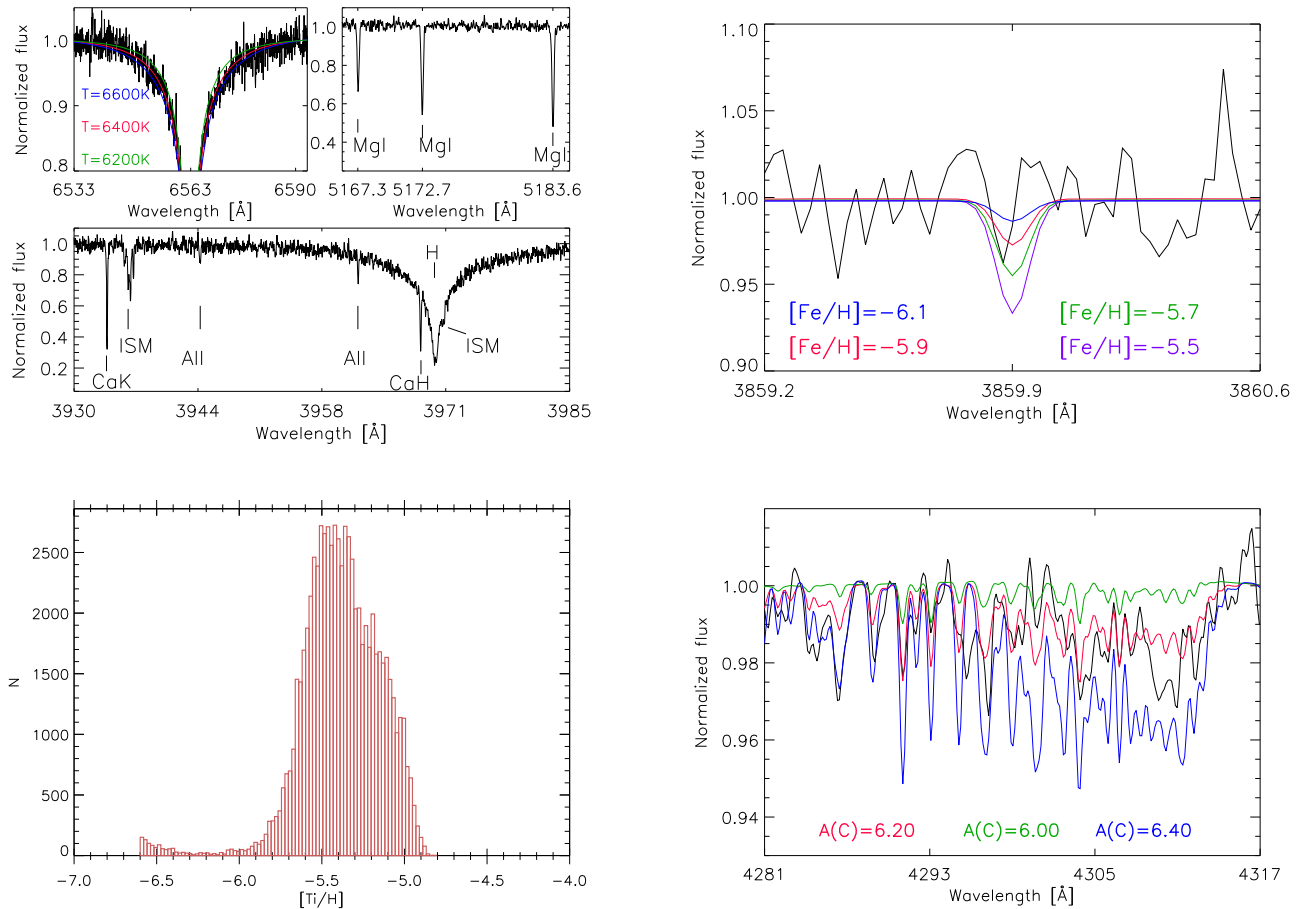


Figure 1. Upper-left panel: the first subpanel shows the UVES J0023+0307 spectrum (black line) in the H_α region around 6563 Å together with the best fit (red line) and the upper and lower limit values (blue and green lines). For fitting purposes the H_α core has been excluded from the χ^2 calculation. The other two subpanels show a detail of the J0023+0307 UVES spectrum in the vicinity of the magnesium triplet and calcium H&K. Upper-right panel: a detail of the J0023+0307 UVES spectrum in the vicinity of the strongest iron line at 3859.9 Å. A synthetic spectra of four different iron ratios ($[\text{Fe}/\text{H}] = -6.1, -5.9, -5.7, -5.5$) are plotted. Lower-left panel: the number of Markov chain Monte Carlo (MCMC) experiments vs. $[\text{Ti}/\text{H}]$ (15 lines) computed with FERRE. Lower-right panel: the G -band area of the UVES J0023+0307 spectrum (black line), smoothed to a 10,000 resolution, compared with ASSET synthetic spectra for the best-fit carbon abundance (red line) together with upper and lower values (blue and green lines).

discussed in Aguado et al. (2018b) and Starkenburg et al. (2018), and included in our quoted derived abundance uncertainties in this work. In the metallicity regime $[\text{Fe}/\text{H}] < -5.0$, the analysis is performed with model atmospheres computed with $[\text{Fe}/\text{H}] = -5.0$.

4. Analysis

A grid of synthetic spectral models has been computed with the code ASSET (Koesterke et al. 2008) using stellar models from Kurucz ATLAS 9 (Mészáros et al. 2012) and following the recipe explained in Allende Prieto et al. (2014) and Aguado et al. (2017). The grid contains models spanning $-7 \leq [\text{Fe}/\text{H}] \leq -4$; $-1 \leq [\text{C}/\text{Fe}] \leq 7$, $4750 \text{ K} \leq T_{\text{eff}} \leq 7000 \text{ K}$, and $1.0 \leq \log g \leq 5.0$. This grid extends the one used by Starkenburg et al. (2018) to reach lower metallicities. Both grids have been smoothed to $R \sim 40,500$ and normalized. We have performed an MCMC analysis based in self-adaptive randomized subspace sampling (Vrug et al. 2009) implemented in the FERRE code⁵ (Allende Prieto et al. 2006). The MCMC algorithm samples the probability distribution to estimate

⁵ FERRE is available from <http://github.com/callendeprieto/ferre>.

Table 2
Absolute Abundances for Individual Lines

Element	λ (Å)	$\log gf$ (dex)	EW(mÅ)	$A(X)$
Li I	6707.8	...	19.3 ± 1.1	2.02
C (CH)	G -band	...	...	6.20
Na I	5889.95	0.11	9.2 ± 1.0	1.94
Na I	5895.92	-0.18	12.9 ± 0.9	2.22
Mg I	3829.35	-0.23	79.7 ± 2.0	4.66
Mg I	3832.30	0.12	83.3 ± 2.0	4.50
Mg I	3838.29	0.39	92.2 ± 2.0	4.63
Mg I	5167.32	-1.03	63.7 ± 1.2	4.78
Mg I	5172.68	-0.40	89.2 ± 1.4	4.54
Mg I	5183.60	-0.18	94.7 ± 1.2	4.48
Al I	3944.00	-0.62	24.2 ± 1.4	2.36
Al I	3961.52	-0.32	24.3 ± 1.4	2.34
Si I	3905.52	-1.09	36.7 ± 1.8	4.05
Ca II	3933.66	0.13	92.82 ± 1.9	0.68
Ca II	3968.47	-0.16	55.9 ± 2.3	0.65
Fe I	3859.92	-0.68	...	<2.02

central values and uncertainties. Further details about the use of FERRE with high-resolution spectroscopy are presented in Starkenburg et al. (2018).

Table 3
Abundances for Individual Species J0023+0307

Species	$\log \epsilon_{\odot} (X)^a$	This Work				François et al. (2018)				Frebel et al. (2019)			
		$\log \epsilon (X)$	$[X/H]^a$	σ	N	$\log \epsilon (X)$	$[X/H]^b$	σ	N	$\log \epsilon (X)$	$[X/H]^b$	σ	N
Li I	1.05	2.02	...	0.05	1	...	...	...	...	1.70	...	0.20	1
CH	8.39	6.20	-2.19	0.20	...	6.40	-1.99	0.30	...	5.89	-2.50	0.20	...
Na I	6.17	2.08	-4.09	0.21	2	...	...	...	...	2.24	-3.93	0.30	2
Mg I	7.53	4.60	-2.93	0.11	7	5.10	-2.43	0.23	3	4.63	-2.90	0.10	8
Al I	6.37	2.35	-4.02	0.12	2	...	...	...	...	2.30	-4.07	0.20	2
Si I	7.51	4.05	-3.46	0.10	1	4.20	-3.31	0.23	1	3.94	-3.57	0.20	1
Ca II	6.31	0.66	-5.65	0.09	2	0.60	-5.71	0.20	1	0.57	-5.74	0.20	1
Ti II	4.95	-0.42	-5.37	0.23	15	...	...	...	...	<0.6	<-4.35	...	...
Cr I	5.64	<1.54	<-4.1	...	...	...	...	...	...	<1.4	<-4.24	...	...
Fe I	7.45	<1.95	<-5.5	...	...	<3.5	<-3.95	...	...	<1.9	<-5.55	...	...
Ni I	6.23	<2.93	<-3.3	...	...	...	...	...	...	<2.2	<-4.03	...	...
Sr II	2.92	<-1.68	<-4.6	...	...	<0.0	<-2.92	...	...	<-1.5	<-4.42	...	...
Ba II	2.17	<-1.33	<-3.5	...	...	...	...	...	...	<-1.3	<-3.47	...	...

Notes.

^a Solar abundances from Asplund et al. (2005).

^b Solar abundances converted to Asplund et al. (2005).

4.1. Iron and Titanium

Similarly to SMSS J0313-6708 (Keller et al. 2014) or J1035+0641 (Bonifacio et al. 2015), no iron lines have been detected in the UVES spectrum. We are able to provide an upper limit of $[Fe/H] < -5.5$ (see Figure 1, upper-right panel) only from the strongest iron line in the spectrum at 385.9 nm. The S/N in the blue region of the spectrum is ~ 35 , where no clear iron features are present. However we have analyzed simultaneously 20 regions of 0.08 nm (between 372 and 405 nm) corresponding to wavelengths of 20 isolated iron lines, and we have sampled the probability distribution by launching 10 Markov chains of 10,000 experiments each. We arrive at $[Fe/H] = -6.92 \pm 0.23$ but we cannot consider this result final due to the proximity of the grid limit and the extremely low signal we are trying to measure. Frebel et al. (2019) performed an analysis using only the Fe line at 385.9 nm and provided an upper limit of $[Fe/H] < -5.6$ (see Tables 2 and 3). On the other hand, we have found a more robust and reliable result with the same FERRE-MCMC analysis on 15 Ti lines. In Figure 1 (lower-left panel), we plot the probability distribution from the MCMC experiments (right). With this methodology we are able to recover information hidden in the noise by performing this analysis simultaneously over 15 Ti lines, arriving at $[Ti/H] = -5.37 \pm 0.15$. Frebel et al. (2019) arrived at $[Ti/H] < -4.3$ (1 line) and $[Ti/H] < -4.5$ (8 lines).

4.2. Carbon

The moderate S/N in the *G*-band region forces us to perform a careful continuum determination. Even in carbon-enhanced metal-poor (CEMP) stars, especially with $T > 6000$ K, it is hard to distinguish CH features from the noise. We have pre-normalized the J0023+0307 UVES spectrum using a low-order polynomial and then normalized both the observed and synthetic spectra using a running mean filter with a 200 pixel window. Since we are only comparing neighboring pixels, i.e., relative fluxes, our methodology partially solves the problem of the continuum determination. The best FERRE fit leads to $A(C) = 6.20 \pm 0.2$. An additional test was done after

smoothing the spectrum to $R \sim 10,000$ resolution (see Figure 1, lower right panel). The abundances inferred at full and reduced are within <0.05 dex, and some CH features are now detectable by eye. François et al. (2018) found $A(C) = 6.40 \pm 0.2$ consistent with our value, and Frebel et al. (2019) derived $A(C) = 5.89 \pm 0.2$ but with an effective temperature ~ 170 K lower. The three values are in a reasonable agreement and match with the first upper limit derived by Aguado et al. (2018a), $A(C) < 6.3$, using the medium-resolution ($R \sim 2500$) ISIS spectrum.

4.3. Other Elements

J0023+0307 exhibits relatively high abundances of some elements compared to iron or calcium (see Table 3). The spectrum presents strong Mg I absorptions in the blue (~ 383 nm) and also in the magnesium triplet Mg Ib at 516-518 nm. Six very clear features (see Table 2) have been identified and fitted giving an abundance of $A(Mg) = 4.60 \pm 0.11$ corresponding to $[Mg/H] = -2.93$. Si also shows an absorption at (390.5 nm) leading us to derive $A(Si) = 4.05 \pm 0.05$ ($[Si/H] = -3.46$). The shape of the aluminum features at 394.4 and 396.1 nm is not so well defined, however the derived abundances are the same, $A(Al) = 2.35 \pm 0.08$ ($[Al/H] = -4.02$). The calcium H&K analysis is significantly improved compared to that presented in Aguado et al. (2018a). Both resonance lines are resolved and a complex interstellar medium (ISM) structure is present (see Figure 1, upper left panel). We find $A(Ca) = 0.66 \pm 0.09$ ($[Ca/H] = -5.65$), which is ~ 0.5 dex higher than Aguado et al. (2018a), from a significantly lower resolution ($R \sim 2500$) spectrum, which is fully compatible with François et al. (2018) and Frebel et al. (2019). Assuming a $[Ca/Fe] \geq 0.40$, we use the calcium abundance to set a metallicity upper limit of $[Fe/H] \leq -6.1$. Finally the two sodium lines around ~ 589.2 nm present broader line profiles than expected and moderate quality. The best FERRE fits allow us to derive $A(Na) = 2.08 \pm 0.21$ ($[Na/H] = -4.09$). Some of the derived upper limits are shown in table.

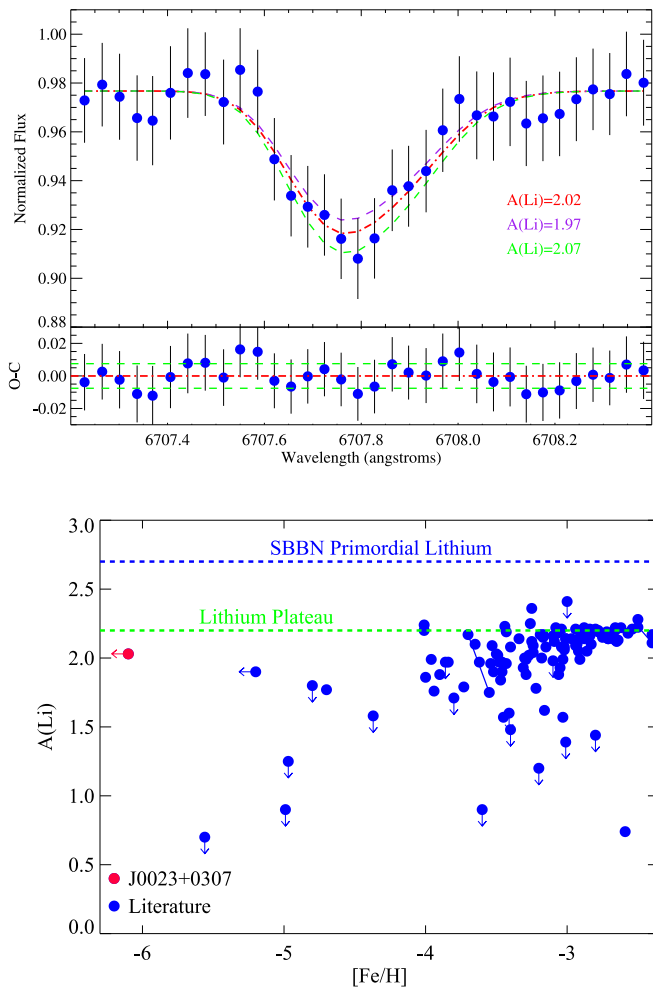


Figure 2. Upper panel: Li doublet of J0023+0307 rebinned to $0.035 \text{ \AA}/\text{pixel}$ ($1.6 \text{ km s}^{-1}/\text{pixel}$) together with the best-fit model ($A(\text{Li}) = 2.02$, $\sigma = 0.05$) and the fit residual, providing an S/N of ~ 130 . We also show for comparison two additional synthetic spectra at about 3σ from the best fit. Lower panel: Li abundance, $A(\text{Li})$, vs. metallicity, $[\text{Fe}/\text{H}]$, of J0023+0307 compared with other dwarf—turn-off stars ($\log g \geq 3.7$) with Li abundance values from Bonifacio et al. (2018) and references therein. The blue filled circles connected with a solid line indicate the spectroscopic binaries in González Hernández et al. (2008) and Aoki et al. (2012). The lithium plateau (also called the Spite plateau) reference is shown as a solid line at a level of $A(\text{Li}) = 2.20$ dex. The blue dashed line represents the primordial lithium value ($A(\text{Li}) \sim 2.7$) from Wilkinson Microwave Anisotropy Probe (WMAP; Spergel et al. 2003).

4.4. Lithium

We have been able to clearly detect the Li doublet (see Figure 2) in the rebinned spectrum of the extremely iron-poor star J0023+0307. We measure an S/N of 130 with a bin of $0.035 \text{ \AA}/\text{pixel}$ near the Li doublet. We fit the lithium profile with our automated fitting tool (see Section 2), using a grid of model spectra for three different Li abundances ($A(\text{Li}) = 2.4, 2.0, 1.6$ dex), and with $A(\text{Li})$, continuum location and global shift of the line as free parameters, and we fix the global FWHM to 7.4 km s^{-1} (see Section 2). We derive an $\text{EW}(\text{Li}) = 19.3 \pm 1.1 \text{ m\AA}$ (see Table 2). To evaluate the statistical uncertainty, we perform a Monte Carlo simulation with 10,000 realizations by injecting noise, corresponding to the actual S/N near the Li line, in the best-fit synthetic spectrum. We measure a Li abundance in the star J0023+0307 of $A(\text{Li}) = 2.02 \pm 0.08$, including the error due to the uncertainty

of the adopted T_{eff} (see, e.g., González Hernández et al. 2008). The difference of ~ 0.3 dex in the Li abundance with respect to the value reported in Frebel et al. (2019) cannot be simply attributed to our hotter adopted T_{eff} . A 160 K lower T_{eff} translates into about a 0.1 dex lower Li abundance, so a 0.2 dex difference still remains to be explained. We believe that our better quality data allow us to provide a robust Li abundance determination.

Our Li abundance measurement is almost at the level of the lithium plateau but at metallicity level of $[\text{Fe}/\text{H}] < -6$, which is significantly lower than any previous measurement. In Figure 2 we also display the lithium abundances of extremely metal-poor unevolved stars including main-sequence and turn-off field stars with available Li measurements or upper limits. Matsuno et al. (2017) suggested that no stars with $[\text{Fe}/\text{H}] < -3.5$ show Li abundances at the level of the lithium plateau ($A(\text{Li}) = 2.2 \pm 0.1$), apart from three stars (González Hernández et al. 2008; Bonifacio et al. 2018). Recently, Bonifacio et al. (2018) have been able to measure the Li abundance of the iron-poor star J1035+0641 ($A(\text{Li}) = 1.9$, $[\text{Fe}/\text{H}] < -5.2$). Both stars are suggested to be CEMP-no stars, but J0023+0307 has a lower C abundance of roughly 1 dex. Other unevolved CEMP stars at $[\text{Fe}/\text{H}] < -4.5$ have either no Li detected or $A(\text{Li}) < 1.8$, which may suggest that Li is not connected with the C content (Matsuno et al. 2017).

5. Discussion and Conclusions

J0023+0307 is a dwarf star with $[\text{Fe}/\text{H}] < -6.1$, $A(\text{Li}) = 2.02$ and very large overabundances of carbon ($[\text{C}/\text{Fe}] > 3.9$), magnesium ($[\text{Mg}/\text{Fe}] > 3.2$), and silicon ($[\text{Si}/\text{Fe}] > 2.6$). These chemical abundance ratios provide a strong argument against ISM pollution by a pair-instability supernova (PISN), since similar shortages of Ca–Fe and Mg–Si should be expected. In particular Takahashi et al. (2018) found the ratios $[\text{Na}/\text{Mg}] \sim 1.5$ and $[\text{Ca}/\text{Mg}] \sim 0.5\text{--}1.3$ as the most robust discriminant of PISN. For J0023+0307, both $[\text{Na}/\text{Mg}] = -1.1$ and $[\text{Ca}/\text{Mg}] = -3.2$ are quite far from those values. The low Fe abundance of J0023+0307 is fully compatible with a Population III supernova scenario. The high $[\text{C}/\text{Fe}]$ together with Mg and Si derived abundances may point to fallback (Umeda & Nomoto 2003), returning Fe and Ca to the black hole. J0023+0307 is in the low band of the absolute carbon abundance (Bonifacio et al. 2015; Yoon et al. 2016) and does not show radial velocity variations, discarding the scenario of mass transfer from a binary companion. Hartwig et al. (2018) present complementary criteria to disentangle different second generation star formation scenarios, mono-enriched or multi-enriched. The proposed methodology uses two different criteria, a semi-analytical model to determine the formation sites and the other based on the divergence of the chemical displacement (DCD), for further details see Hartwig et al. (2018, 2019). In particular, the chemical signatures of J0023+0307 may fit well in the most likely mono-enriched area of the $[\text{Mg}/\text{C}]$ versus $[\text{Fe}/\text{H}]$ diagram presented in Hartwig et al. (2018). SDSS J1035+0641 (with a metallicity of $[\text{Fe}/\text{H}] < -5.2$) discovered by Bonifacio et al. (2015) also presents a high probability of being a second generation mono-enriched star (Hartwig et al. 2019).

Bonifacio et al. (2018) has recently detected lithium ($A(\text{Li}) = 1.9$) in J1035+0641 close to the lithium plateau. J0023+0307 with an Li abundance of $A(\text{Li}) = 2.02$ surprisingly nearly recovers the same level of the lithium plateau at about 1 dex less iron content. The presence of lithium in this extremely iron-poor star at $[\text{Fe}/\text{H}] \lesssim -6$ reinforces the

production of lithium at the big bang and places a stringent constraint to any theory aiming at explaining the cosmological Li problem. The fact that no star in this large metallicity regime ($-6 < [\text{Fe}/\text{H}] < -2.5$) has been detected to show an Li abundance between that inferred from SBBN and the lithium plateau makes this upper boundary of the Li abundance (or extended Li plateau) at low metallicities difficult to explain by destruction in the stars, and may support a lower primordial Li production, driven by non-standard nucleosynthesis processes.

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