The most metal-poor dwarfs of the binary CS 22876-032: Abundances and 3D effects

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ABSTRACT

Unevolved extremely metal-poor stars offer us a unique tool to infer knowledge of the first generation of stars. We have analysed the UVES high-resolution spectra of the double-lined spectroscopic binary CS 22876–032 which comprises the two most metal-poor dwarfs known. In particular we determine the oxygen (from OH lines in the near-UV) and lithium abundances, taking into account 3D effects. The long-time baseline radial velocity measurements and photometric data available allowed us to determine the orbital elements as well as stellar parameters of both components. We use OSMARCS 1D models and the TURBOSPECTRUM spectral synthesis code to determine the abundances of Li, O, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Fe, Co and Ni. We also use the CO^{5}BOLD code to predict the 3D abundance corrections, mainly for Li, O and Fe. We find a metallicity of [Fe/H]~-3.6 for both stars using 1D models with 3D corrections from horizontal and temporal average 3D models around -0.1 dex. We find α-elements consistent with those found for metal-poor giants with similar iron content although Ca and Si show rather low values [X/Fe]$\simeq$ 0. A significantly high 1D abundance ratio [O/Fe]~2 has been obtained for both stars although 3D models predict large abundance corrections of roughly -1 dex and -1.5 dex for the secondary and primary stars respectively. The Li abundance seems to be consistent with the Spite plateau although the secondary star shows a slightly lower abundance. These abundances have been discussed in the context of the chemical evolution of the Galaxy at the lowest metallicities in comparison with the most recent results.

INTRODUCTION

Metal-poor stars constitute the fossil record of the early Galaxy and offer us an opportunity to improve our understanding of the first generation of stars, especially unevolved stars, which should not have changed their chemical composition since their birth, a condition not necessarily fulfilled by giants. We have studied the chemical composition of the most metal-poor dwarfs which belong to the spectroscopic binary CS 22876–032, focusing on the oxygen (from OH bands in the near-UV) and lithium abundances, including 3D effects.

OBSERVATIONS

Spectroscopic observations of the target were carried out with the UVES spectrograph at the VLT on 2000 July, August and October, and 2001 November, covering the spectral range λλ3000–10400 Å at resolving power $\lambda/\delta\lambda \sim 43{,}000$. Using the radial velocities extracted from the UVES spectra and the long-time baseline radial velocity measurements of this binary reported in Norris et al. (2000), we determined the best orbital solution which is displayed in Fig. 1. The orbital elements are shown in Table 1.

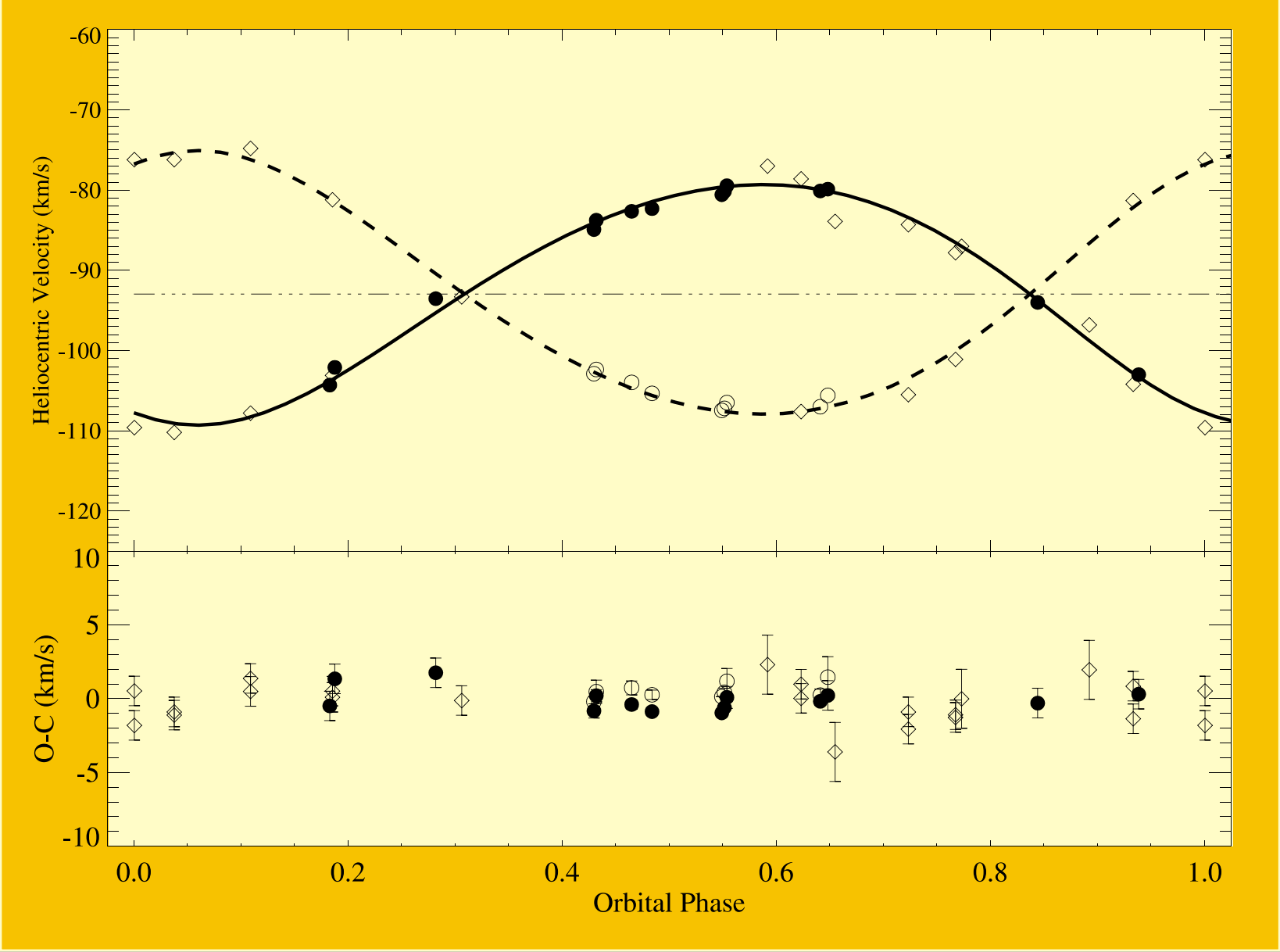
TABLE 1

NOTES.-Orbital parameters of CS 22876-032

Parameter	This paper	Norris et al. (2000)
P (days)	425.04 ± 0.14	424.71 ± 0.60
T_0 (JD−2,440,000 days)	$8,586.94 \pm 12.17$	$8,576.37 \pm 13.51$
e	0.10 ± 0.01	0.12 ± 0.03
w (deg)	153.90 ± 9.87	144.96 ± 12.40
V_0 (km s^{-1})	-92.96 ± 0.10	-93.36 ± 0.28
K_A (km s^{-1})	14.98 ± 0.15	15.13 ± 0.51
K_B (km s^{-1})	16.46 ± 0.15	17.06 ± 0.56
M_B/M_A	0.91 ± 0.02	0.89 ± 0.04

FIGURE 1

NOTES.-Upper panel: Radial velocities of CS 22876–032A (filled circles) and CS 22876–032B (open circles) folded on the orbital solution for the Primary (solid line) and secondary (dashed line) presented in Table 1. Open diamonds represent the data from Norris et al. (2000, and references therein). Lower panel: Relative difference between the radial velocity points and the model.



STELLAR PARAMETERS

The atmospheric parameters of each star in CS 22876–032 were estimated by comparing the photometric data available in the literature with theoretical isochrones of Chieffi & Limongi (private communication). The stellar parameters can be derived from the best fit to the observed colours which also satifies the mass ratio determined from the orbital solution. In Fig. 2 we displayed the result which corresponds to a primary star with $T_{\mathrm{eff}A}$=6500±100 K and log g_A=4.4±0.1 and a secondary star with $T_{\mathrm{eff}B}$=5900±150 K and log g_B=4.6±0.1. The uncertainties on the stellar parameters were estimated using Monte Carlo techniques, by injecting noise to the observed colours and mass ratio. An example of the results of these simulations for the effective temperature of both components is shown in Fig. 3.

FIGURE 2

NOTES.-Position of the two components of CS 22876–032 on the isochrone of Chieffi & Limongi (private communication) of 14 Gyr and $Z=10^{-6}$. For comparison, two more isochrones have also been displayed with 14 Gyr and $Z=10^{-5}$ (dashed line), and 12 Gyr and $Z=10^{-6}$ (dotted line).

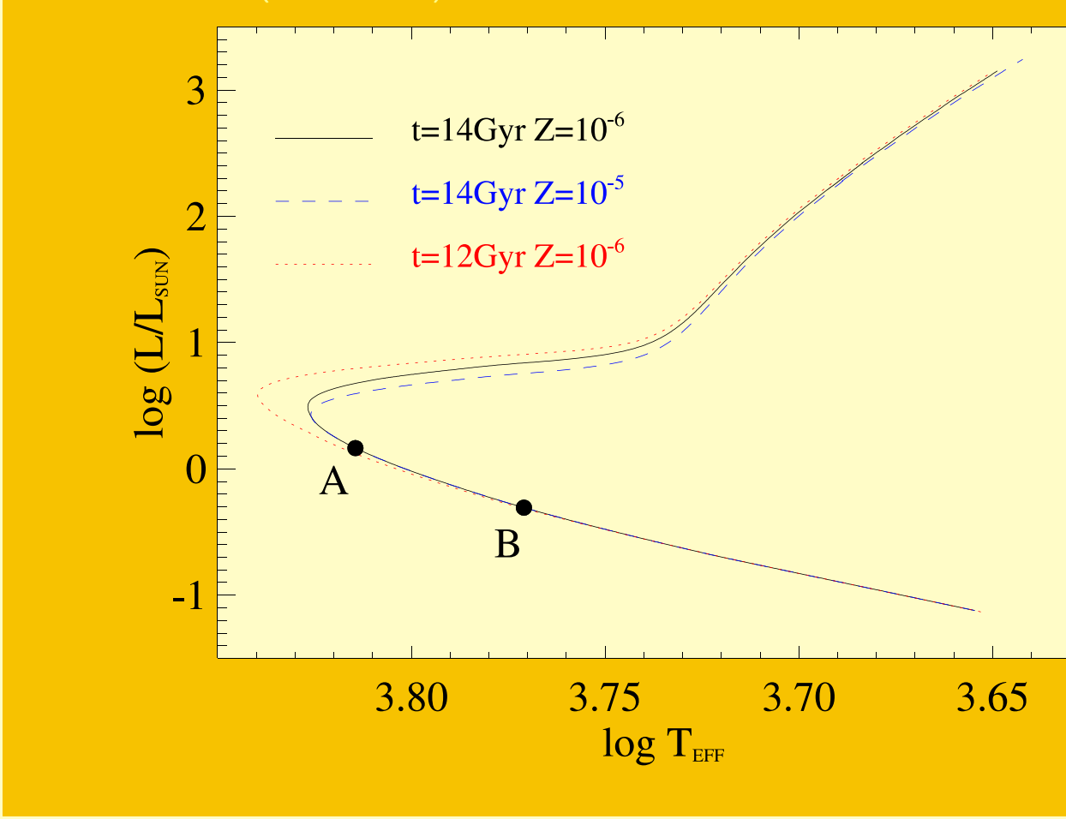
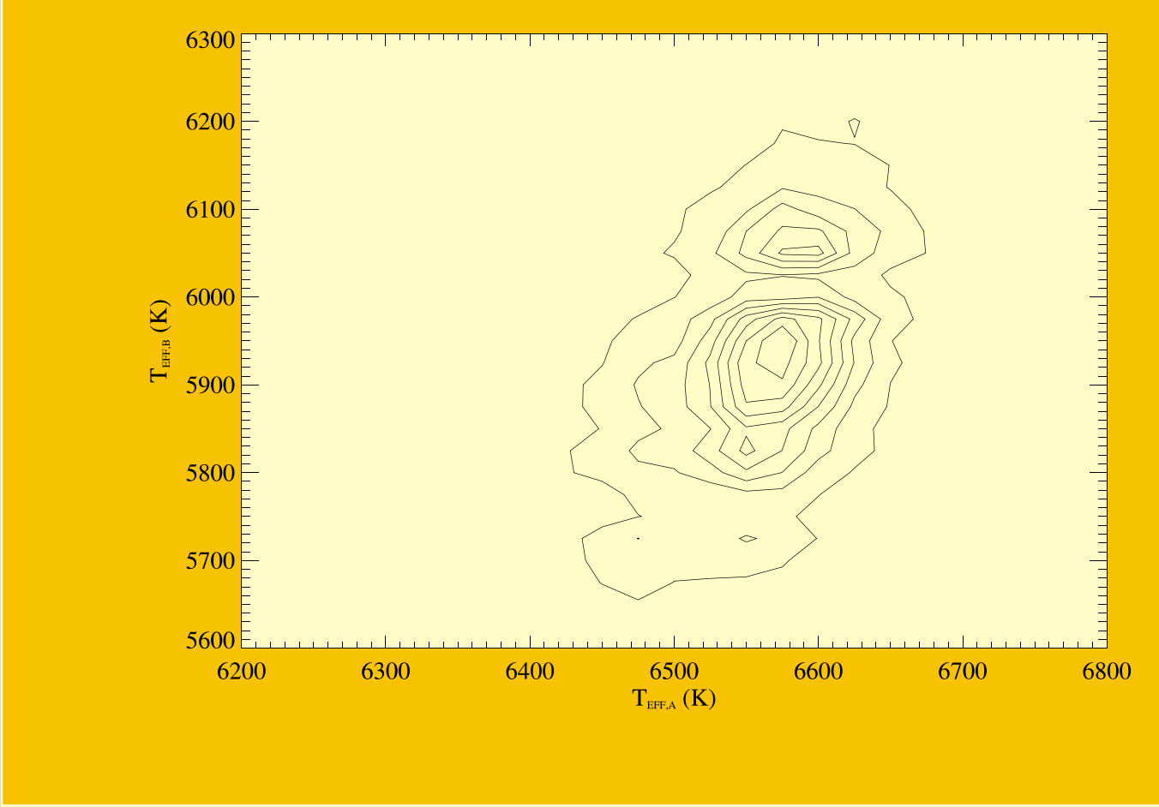


FIGURE 3

NOTES.- Distribution of effective temperatures for CS 22876–032A, B obtained with the Monte Carlo simulations by comparing the binary colours with those given by the isochrone showed in Fig. 2, assuming a mass ratio of M_B/M_A=0.91±0.02. The lower contour line encloses 95.4% of the 10,000 simulations.

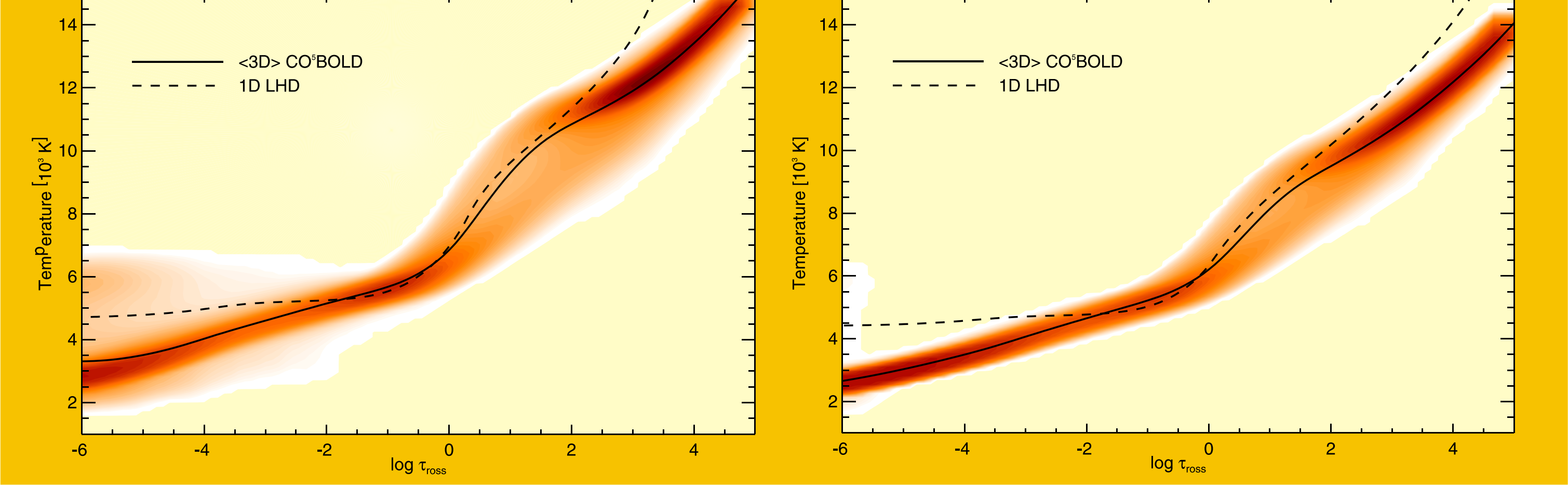


3D CORRECTIONS

3D models for both binary components have been computed with the CO^{5}BOLD code (Freytag et al. 2002, Wedemeyer et al. 2004). Their stellar parameters are close to the stellar parameters T_{eff}/ logg/ [Fe/H]: 6550/4.50/-3.0 and 5920/4.50/-3.0, for primary and secondary, respectively. In Fig. 4, we displayed the temperature structure of each model in comparison with a temporal and horizontal average of the 3D model structure, the ⟨3D⟩ model, and a hydrostatic 1D model, the 1D$_{\mathrm{LHD}}$ model, with the same micro-physics as CO^{5}BOLD. The average temperature profile provided by a hydrodynamical simulation is different from that of a 1D atmosphere assuming radiative equilibrium. In particular, in the external photosphere layers, the ⟨3D⟩ model is cooler than the 1D model, precisely in the layers where OH molecular lines are formed, and translates into negative 3D-1D$_{\mathrm{LHD}}$ abundance corrections.

FIGURE 4

NOTES.- Temperature structure of the 3D CO^{5}BOLD photospheres of the primary (left panel) and secondary stars (right panel) in comparison with the ⟨3D⟩ atmospheric model (solid lines) and 1D$_{\mathrm{LHD}}$ model (dashed lines).



CHEMICAL ABUNDANCES

Most of the element abundances were determined from equivalent width measurements of selected, unblended lines. The equivalent widths were then corrected for the appropriate veiling that the flux of each star causes on the line strength of the other star's lines and given as input to TURBOSPECTRUM to determine the abundances of Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Fe, Co and Ni. We find 1D Fe abundances of [FeI/H]=-3.66 and -3.57 for the primary and secondary, respectively. For all these elements, we also determined 3D abundances using the ⟨3D⟩ models. We found ⟨3D⟩ -1D corrections of ~ -0.1 dex for Fe. We computed 1D synthetic spectra to determine the Li and O abundances from the Li 6708 Å doublet and the near-UV OH bands, respectively. In Fig. 5 and 6, we displayed some of the spectral regions which have been analysed. We found 1D oxygen abundances which provide [O/FeI]~2.1 and ~1.8 for the primary and secondary stars. For these two elements we also performed a full 3D synthesis using the Linfor3D code. We found 3D-1D$_{\mathrm{LHD}}$ corrections of roughly -1.5 and -1 dex for the primary and secondary. 1D NLTE Li abundances were estimated at 2.18 and 1.84dex with LTE 3D-1D$_{\mathrm{LHD}}$ corrections of -0.19 and -0.29 dex for the primary and secondary respectively. Preliminary results on NLTE 3D corrections appear to compensate these 3D LTE effects (Cayrel et al., in preparation).

FIGURE 5

NOTES.-Synthetic spectral fits to the Li line in the UVES spectrum of the primary star (top panel) and secondary star (bottom panel) of CS 22876- 032 . Observed spectra have been corrected for a veiling factor of 1.36 and 3.74 for primary and secondary stars, respectively

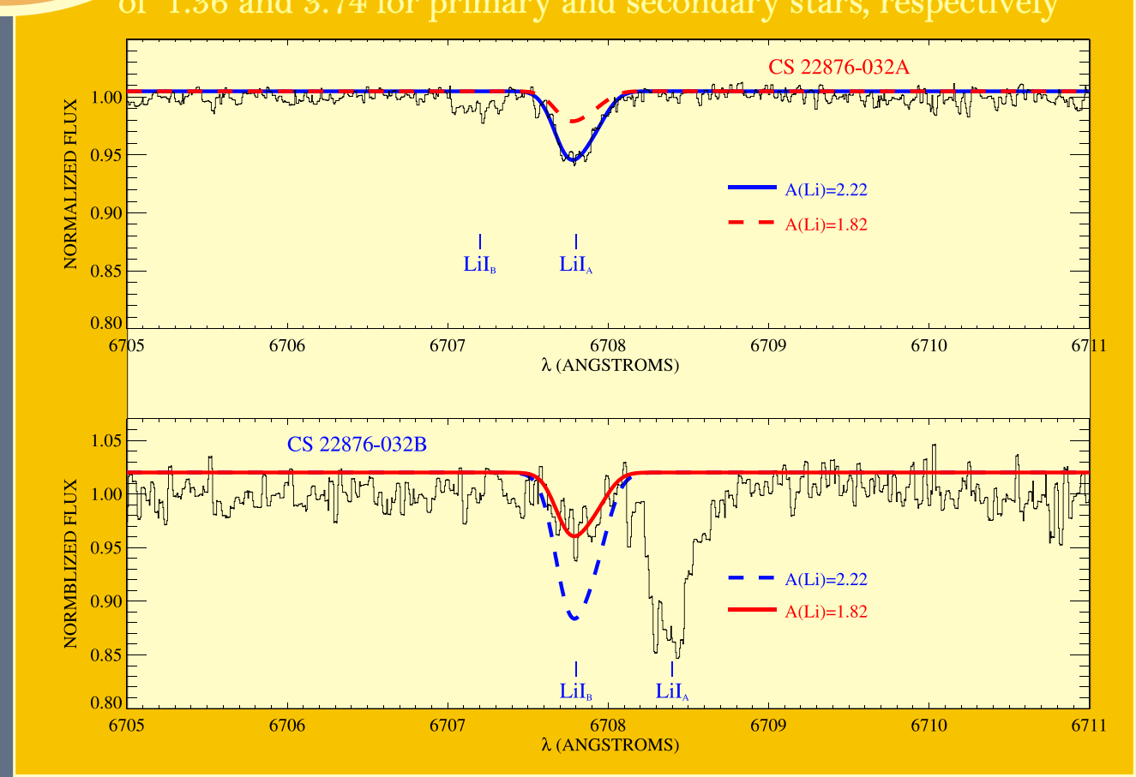
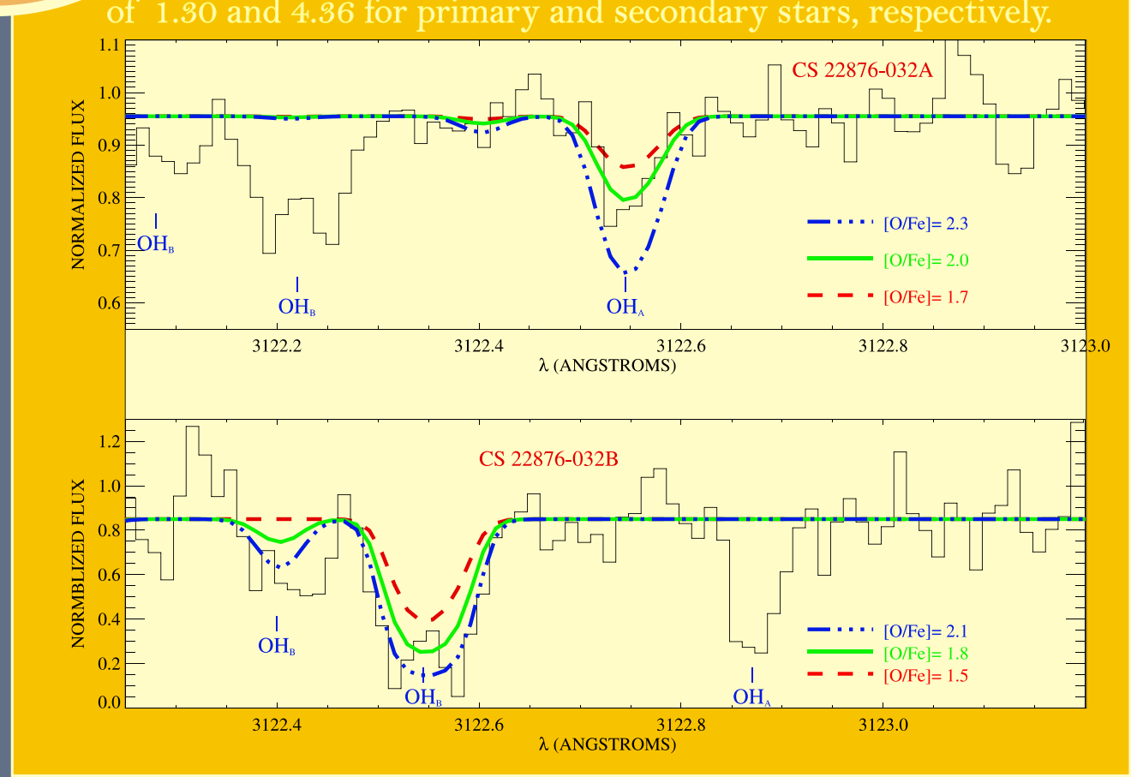


FIGURE 6

NOTES.-Synthetic spectral fits to OH lines in the UVES spectrum of the primary star (top panel) and secondary star (bottom panel) of Cs22876 –032. Observed spectra have been corrected for a veiling factor of 1.30 and 4.36 for primary and secondary stars, respectively.

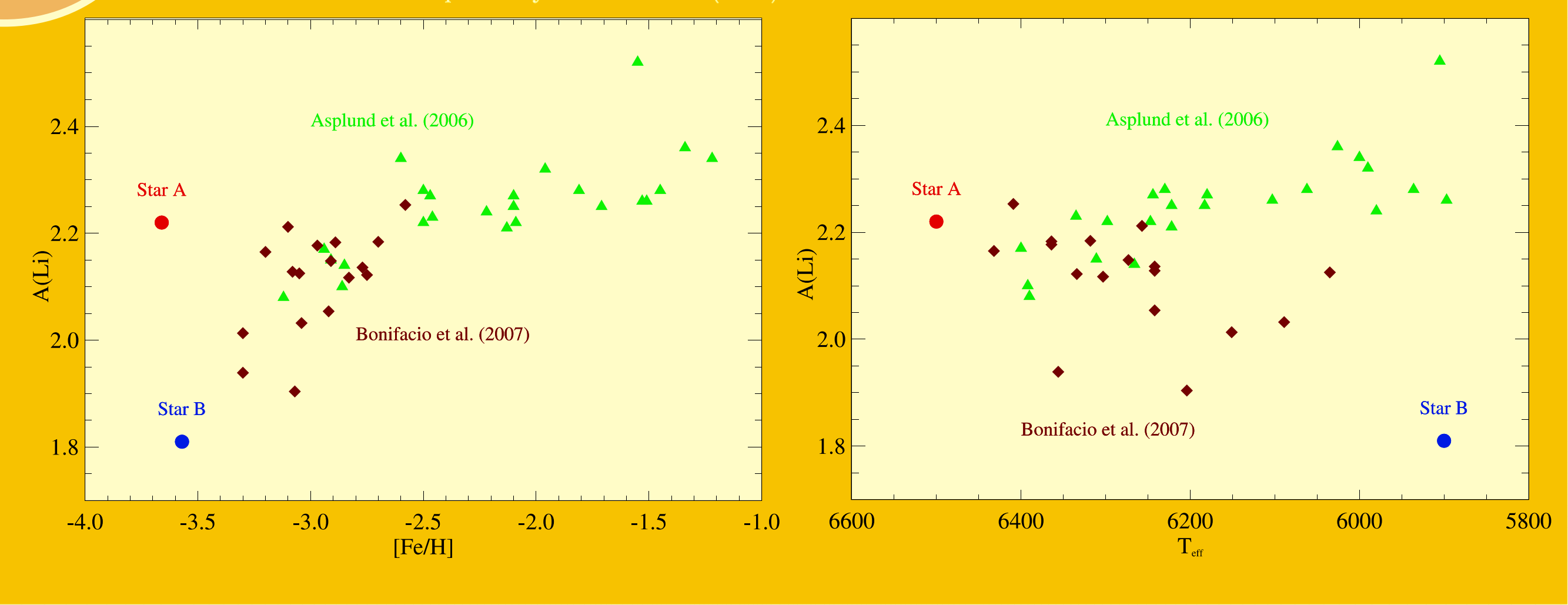


DISCUSSION AND CONCLUSIONS

We find a metallicity of [Fe/H]~-3.7 in both stars using ⟨3D⟩models. We find α-elements consistent with those found for metal-poor giants with similar iron content (Cayrel et al. 2004), although Ca and Si show rather low values [X/Fe] ≃0. The primary star A appears to have a Li at the level of the Li plateau as the majority of stars with metallicity below -2.5 (see Fig. 7). The secondary appears to be far below any of other measured stars reported in Bonifacio et al. (2007). These data suggest an increased scatter in A(Li) at the lowest metallicities with no clear slope of A(Li) with [Fe/H].

FIGURE 7

NOTES.-Li abundances of the dwarfs in the CS 22876–032 system (circles) in comparison with Li abundances in other metal-poor dwarfs reported by Asplund et al. (2006, triangles) and Bonifacio et al (2007, rhombus) in the Li-[Fe/H] plane (left panel) and in the Li-T_{eff} plane (right panel). Li abundances of Asplund et al. (2006) were recomputed using TURBOSPECTRUM as reported by Bonifacio et al. (2007)



The 1D oxygen abundances measured in these stars together with the O abundances in the literature also derived from the OH UV lines show an increasing trend towards lower metallicities (see Fig.8). The 3D-1D$_{\mathrm{LHD}}$ corrections bring closer the O abundances from near-UV OH bands in these two dwarfs to other high quality measurements obtained from [OI] line in giants, subgiants and dwarfs (see Fig.9). 3D corrections for the [OI] lines are estimated at -0.2 dex (Nissen et al. 2002) and are expected to be certainly smaller in giants. The 3D corrections make clearly the slope less steep, but they do not cancel it out. However, the effects of deviations from LTE in 3D atmospheres should be studied in detail to finally confirm the existence of this trend of [O/Fe] with metallicity.

FIGURE 8

NOTES.-1D oxygen to iron abundance ratios of the CS 22876-032 dwarfs (circles) in comparison with ratios in other metal-poor dwarfs as reported by Israelian et al. (1998, 2001, rhombus) and Boesgaard et al. (1999, triangles), and subgiants from García Pérez et al. (2006, squares). O abundances were determined from near-UV OH bands. The [O/Fe] ratios and [Fe/H] are calculated using the Fe I abundances.

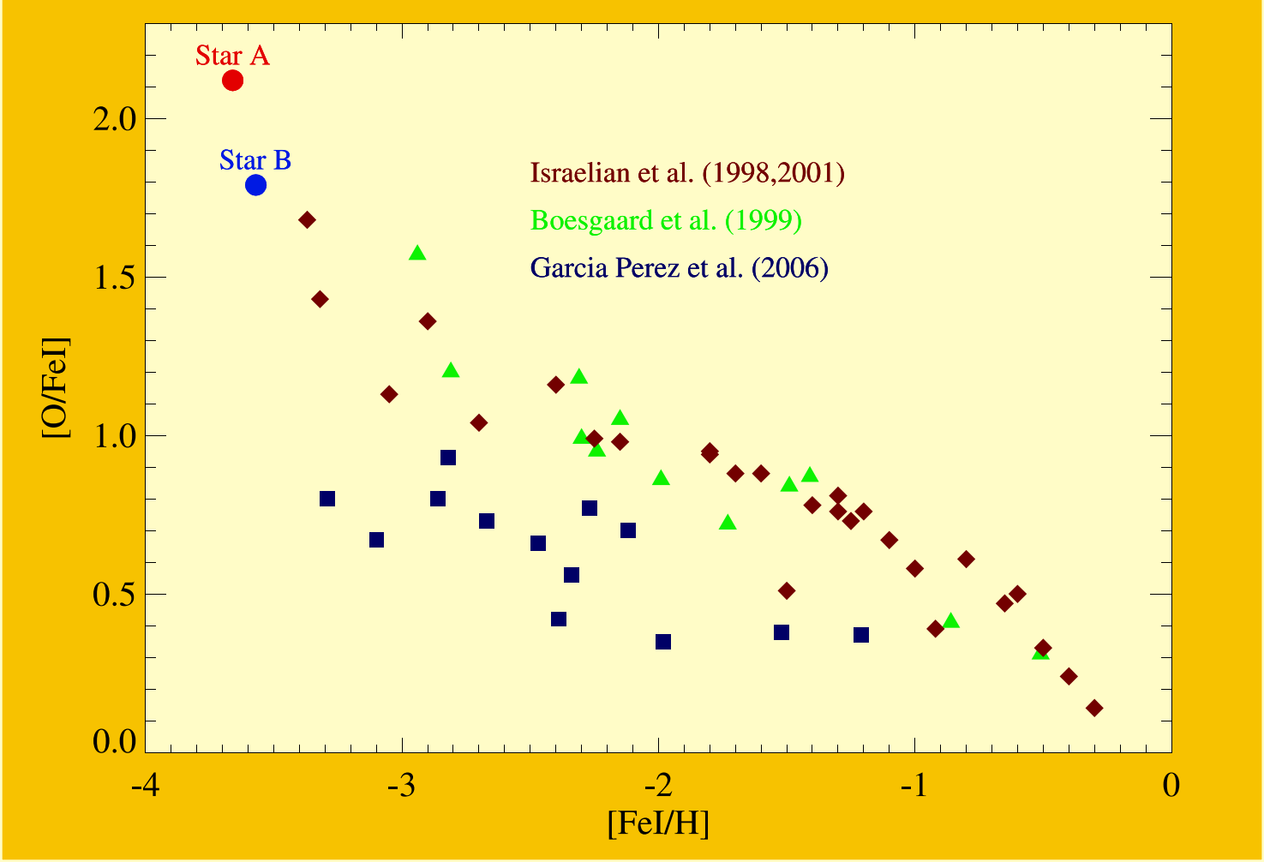
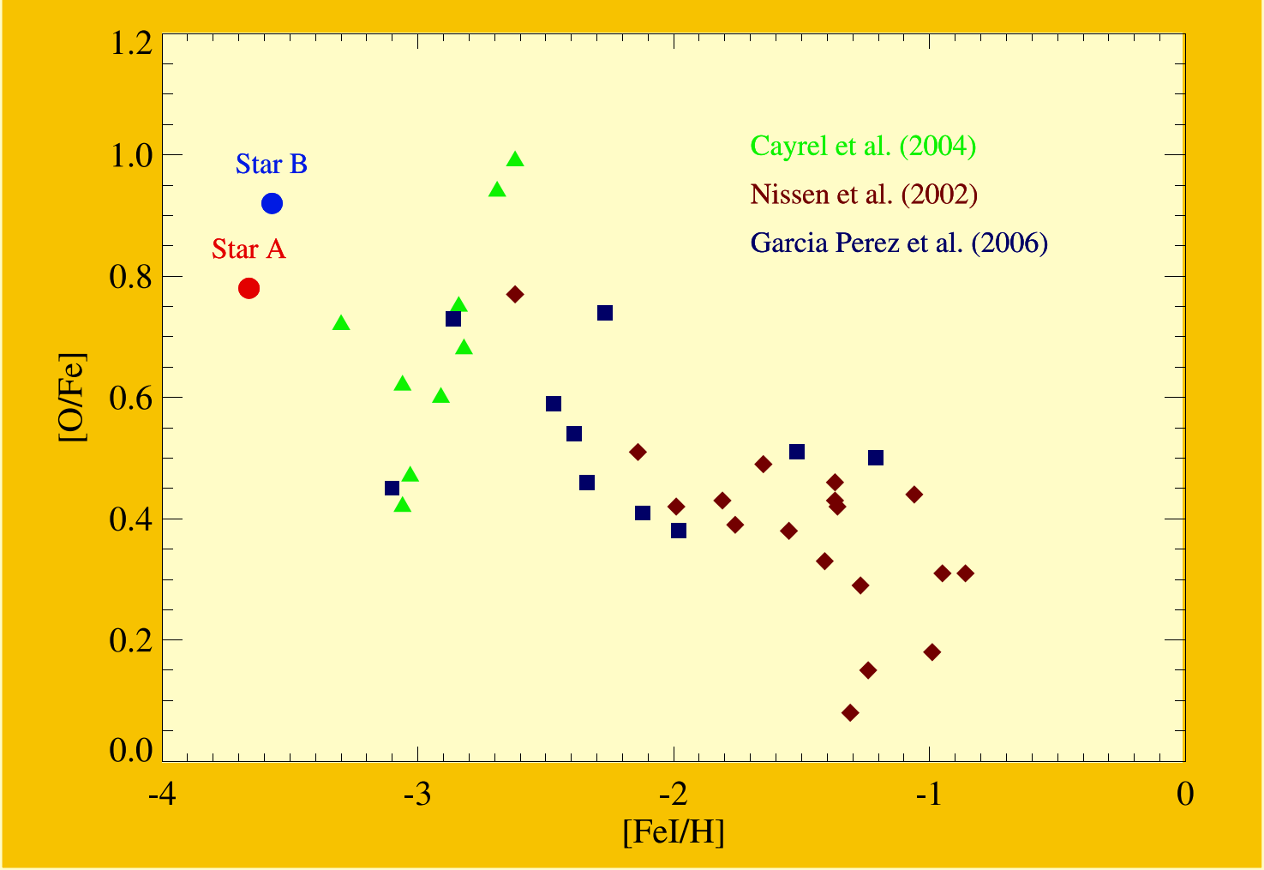


FIGURE 9

NOTES.-3D oxygen to iron abundance ratios of the CS 22876-032 dwarfs (circles) in comparison with ratios in metal-poor giants as reported by Cayrel et al. (2004, triangles), in subgiants from García Pérez et al. (2006, squares) and in dwarfs from Nissen et al. (2002, rhombus). Except for the stars in this work, O abundances were determined from the [OI] line, and the [O/Fe] ratios were estimated using FeII abundances, whereas [Fe/H] was calculated using Fe I lines. The [Fe/H] values of Nissen et al. (2002), which were measured with Fe II lines, have been shifted by -0.2 dex, in order to be on the Fe I scale.



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