PROCEEDINGS OF SCIENCE

Niobium in the spectra of metal-poor stars

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Abundances of neutron-capture elements are calculated in the atmospheres of three metal-poor stars and the standard star Arcturus with a special emphasis to niobium. The method of spectral synthesis, carefully compiled line lists and recent data of hyperfine splitting for Nb I lines are used. The results and possible origin of niobium in the analyzed metal-poor stars are discussed.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

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PoS(NIC XI)287

1. INTRODUCTION

The chemical elements heavier than iron are created by a combination of slow (s) and rapid (r) neutron-capture nucleosynthesis processes [1]. The theory of nucleosynthesis identifies different astrophysical sites for s- and r-processes. The r-process nuclei are the products formed primarily during the evolution of massive stars and supernova explosions. The s-process nuclei are generally thought to have been synthesized during late stages of stellar evolution of low-mass stars. Recents studies that argue two separate r-processes are responsible for the production of the heavier and lighter neutron capture elements ([2], and references therein). The detection of lighter neutron capture elements ($38 \leq Z \leq 48$) in the spectra of metal-poor stars is crucial for determining whether two different r-processes indeed exist. To date the niobium abundance was calculated only in the atmospheres of a few stars using a couple of identified lines in high-resolution absorption spectra [3,4,5,6]. Future studies of abundance patterns of neutron-capture elements including niobium are encouraged to create a statistically significant sample of metal poor stars. The recent measurements of transition probabilities and hyperfine splitting reported for some elements (see, for example, [7,8]) should be incorporated.

A reliable abundance of niobium in the solar photosphere was determined in [9] using original radiative lifetimes of Nb II lines. Equivalent widths of eleven Nb II lines were measured in the solar spectrum to calculate the niobium abundance, $\log\varepsilon(\mathrm{Nb}) = \log(N_{Nb}/N_H) + 12.00 = 1.42 \pm 0.06$. The hyperfine structure splitting was neglected in these estimates. The latest review of the standard solar composition (SAD) recommends the value $\log\varepsilon(\mathrm{Nb}) = 1.42 \pm 0.06$, which is in good agreement with the meteoritic abundance, $\log\varepsilon(\mathrm{Nb}) = 1.39 \pm 0.03$ [10]. Kwiatkowski et al. [11] obtained a much higher solar niobium Abundance, $\log\varepsilon(\mathrm{Nb}) = 2.10 \pm 0.10$, using Nb I lines. The most plausible explanation of such a discrepancy seems to be the uncertainty in measurements of equivalent widths for weak and broad Nb I lines disturbed by hyperfine splitting. Thus, the hyperfine structure can have a significant effect on stellar absorption line profiles and the corresponding abundances can be substantially overestimated if such effects are not taken into account in the calculations [12].

2. OBSERVATIONS AND ANALYSIS

High resolution spectra of three metal-poor stars (see Table 1) were obtained on August 24th 2008 with the optical echelle spectrograph FIES installed at the 2.5 m Nordic Optical Telescope (NOT) on La Palma with a resolving power of R = 67 000 and S/N $>$ 100. The spectra cover a wavelength range from about 3700 to 7300 Å. The Visible and Near Infrared Atlas of the Arcturus spectrum [13] was used for the comparison Star Arcturus. For the data reduction, the Python- and PyRAF-based data reduction software package FIEStool was used. The LTE analysis program ABUNDANCE available together with the spectral synthesis program SPECTRUM written by Corbally & Gray [14] was used to calculate abundances. Atmospheric models were taken from the ATLAS9 model atmosphere grid [15]. For spectral synthesis the SPECTRUM and STARSP code and atomic line data from VALD [16] and DREAM [17] databases were used.

The ratio of light to heavy neutron capture elements was calculated: [hs/ls] = [hs/Fe] - [ls/Fe]; [ls/Fe] = 1/4 ([Sr/Fe] + [Y/Fe] + [Zr/Fe] + [Nb/Fe]); [hs/Fe] = 1/5 ([Ba/Fe] + [La/Fe] + [Ce/Fe] +

Table 1: Basic data for observed stars and the comparison star Arcturus.

Star	Sp.type	M_V	$T_{\rm eff}$ (K)	$\log g$ (cgs)	ξ_t (km s^{-1})	[Fe/H]	[hs/ls]	$\log\varepsilon$(Nb)
HD209621	C1,2 CH	$-1.9M_{bol}$	4500	1.5	1.9	-1.8	+0.5	
HD218732	G6/G8 Ib	-2.8	4200	0.5	2.4	-1.5	-0.1	0.30
HD232078	K3 IIp	-2.2	4000	0.5	2.0	-1.5	-0.2	0.35
Arcturus	K1.5 III	-0.3	4300	1.5	1.4	-0.5		0.74

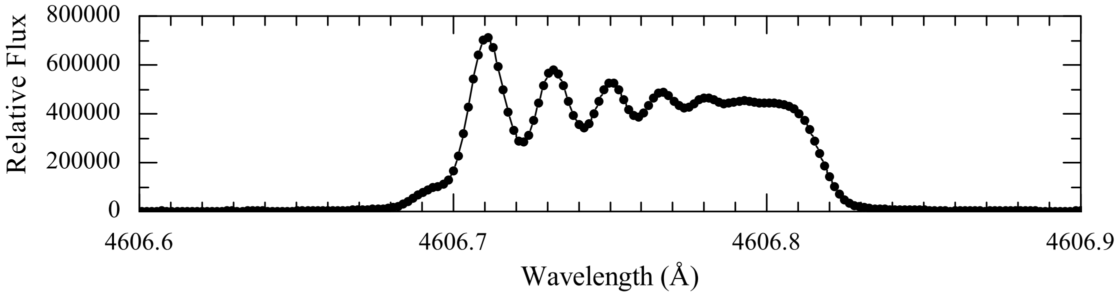

Figure 1: Fourier transform spectrum of Nb I line at 4606.756 Å according [8], showing its hyperfine structure.

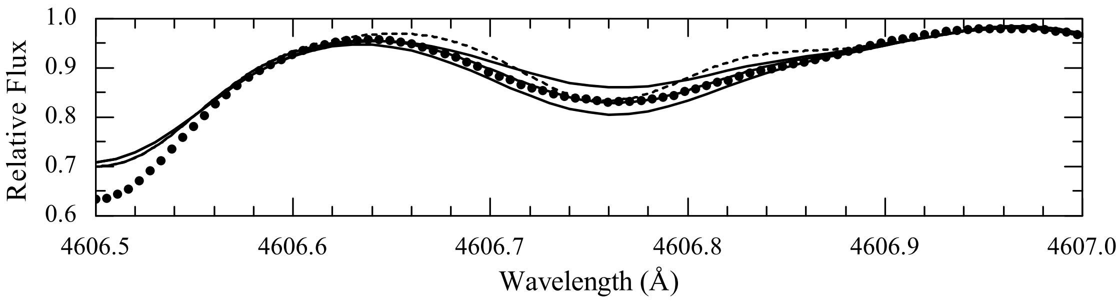

Figure 2: Observed spectrum (filled circles) of Arcturus around the Nb I line at 4606.756 Å along with the synthesized profile without (dashed line) and with HFS correction (solid lines) calculated for the final niobium abundance: $\log\varepsilon(\mathrm{Nb})$ = 0.65 and 0.74 $\pm$ 0.1 dex.

[Nd/Fe] + [Sm/Fe]).

3. RESULTS AND CONCLUSIONS

Abundance of niobium in the atmosphere of Arcturus was calculated using four relatively unblended Nb I lines including HFS correction (see Figure 1 and 2). Abundance ratio [Nb/Fe] = -0.06 is close to the solar and meteoritic abundance [10].

Abundance of niobium is slightly enhanced in the atmospheres of HD218732 and HD232078 relative to the Sun, [Nb/Fe] $\approx$ +0.4 (see Figure 3). The abundance ratio of the heavy s-process peak elements to the light s-process peak elements, [hs/ls] was found to be in the range -0.1 to -0.2 dex (see Table 1). The distribution of neutron-capture elements are well described by the solar r-process abundance curve, suggesting a large r-process contribution.

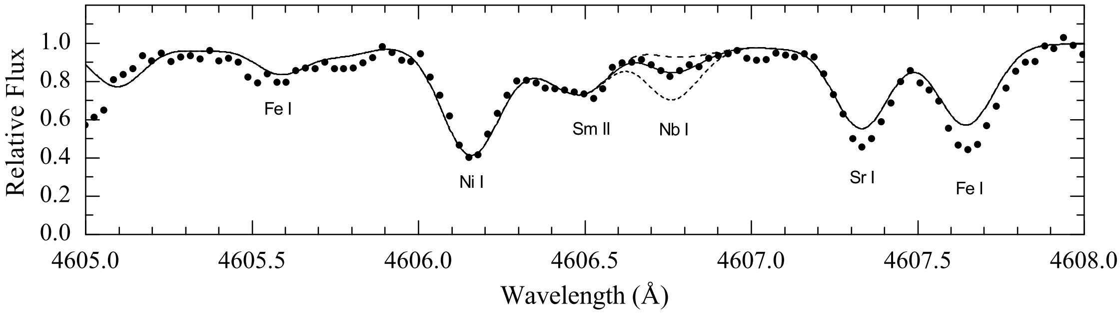

Figure 3: The observed spectrum (filled circles) of HD232078 around Nb I line at 4606.756 Å along with synthesized spectra for three different niobium abundances: $\log\varepsilon(\mathrm{Nb})$ = +0.35 ± 0.5.

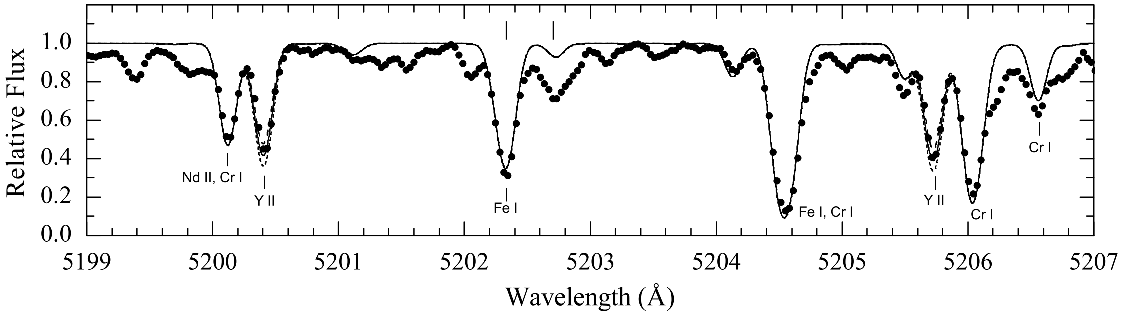

Figure 4: Observed spectrum (filled circles) of HD209621 along with synthesized profiles of important atomic lines calculated using the final atmospheric parameters and abundances for three Y abundances: $\log\varepsilon(\mathrm{Y})$ = 1.26 ± 0.3 dex. The positions of CN Red system lines are marked by vertical ticks.

The mean abundances for 28 elements are calculated in the atmosphere of HD209621 and neutron-capture elements are found to be significantly enhanced. Calculations of abundances for Y, Ce, and Nd are illustrated in Figures 4 and 5. Unfortunately, the synthesis of weak niobium lines was plagued because of blending with strong lines of carbon bearing molecules (CN, C_2, etc.) and therefore it was not possible to determine a reliable Nb abundance. The abundance ratio of the heavy s-process peak elements to the light s-process peak elements was found to be higher for HD209621, [hs/ls] = +0.5, close to the mean value found for CH-stars. Long-period radial velocity variations are confirmed for HD209621 by McClure [18]. Thus, enhanced neutron-capture elements in the atmosphere of HD209621 seems to be the result of mass transfer in the past from the companion star of higher initial mass (which is now a white dwarf).

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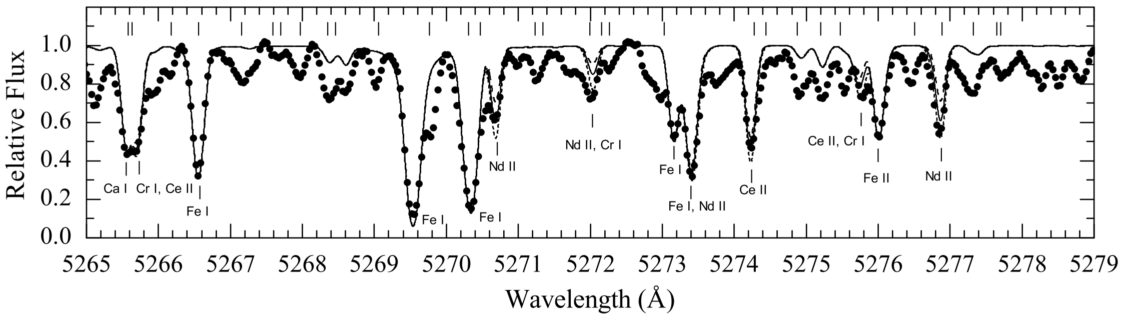

Figure 5: Observed spectrum (filled circles) of HD209621 along with synthesized profiles of important atomic lines calculated using the final atmospheric parameters and abundances for three different Ce and Nd abundances: $\log \varepsilon(\mathrm{Ce}) = 1.48 \pm 0.3$ dex and $\log \varepsilon(\mathrm{Nd}) = 1.18 \pm 0.3$ dex. Positions of CN Red system lines are marked by vertical ticks.

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