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HD 210111: a new λ Bootis type SB system

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ABSTRACT

The small group of λ Bootis stars comprises late B to early F-type stars, with moderate to extreme (up to a factor 100) surface underabundances of most Fe-peak elements and solar abundances of lighter elements (C, N, O, and S). The main mechanisms responsible for this phenomenon are atmospheric diffusion, meridional mixing and accretion of material from their surroundings. Especially spectroscopic binary (SB) systems with λ Bootis type components are very important to investigate the evolutionary status and accretion process in more details. For HD 210111, also δ Scuti type pulsation was found which gives the opportunity to use the tools of asteroseismology for further investigations. The latter could result in strict constraints for the amount of diffusion for this star. Together with models for the accretion and its source this provides a unique opportunity to shed more light on these important processes. We present classification and high resolution spectra for HD 210111. A detailed investigation of the most likely combinations of single star components was performed. For this, composite spectra with different stellar astrophysical parameters were calculated and compared to the observations to find the best fitting combination. HD 210111 comprises two equal (within the estimated errors) stars with $T_{\rm eff} = 7400\,{\rm K}$, $\log g = 3.8\,{\rm dex}$, $[{\rm M/H}] = -1.0\,{\rm dex}$ and $v \sin i = 30\,{\rm km\,s^{-1}}$. This result is in line with other strict observational facts published so far for this object. It is only the third detailed investigated λ Bootis type SB system, but the first one with a known IR-excess.

Key words: Stars: chemically peculiar – stars: binaries: spectroscopic – stars: variables: delta Scuti – stars: individual: HD 210111

1 INTRODUCTION

The group of λ Bootis stars comprise of true Population I, late B to early F-type stars, with moderate to extreme (up to a factor 100) surface underabundances of most Fe-peak elements and solar abundances of lighter elements (C, N, O, and S). Only a maximum of about 2% of all objects in the relevant spectral domain are found to be λ Bootis type stars (Paunzen et al. 2002).

Michaud & Charland (1986) suggested that the peculiar chemical abundances on the stellar surfaces are due to accretion of circumstellar material that is mixed in the shallow convection zone of the star by the joint action of gravitational settling and radiative acceleration. It naturally explains why the anomalous abundance pattern is similar to that found in the gas phase of the interstellar medium (ISM), where refractory elements like iron and silicon have condensed into dust grains.

Kamp & Paunzen (2002) and Martinez-Galarza et al. (2009) developed a model which is based on the interaction of the star with its local ISM environment. Different levels of underabundance are produced by different amounts of accreted material relative to the photospheric mass. The small fraction of this star group is explained by the low probability of a star-cloud interaction and by the effects of meridional circulation, which washes out any accretion pattern a few million years after the accretion has stopped. The hot end of this model is due to strong stellar winds for stars with $T_{\rm eff} > 12\,000\,{\rm K}$ whereas the cool end at about 6500 K is defined by convection which prevents the accreted material to manifest at the stellar surface.

Up to now, there are at least eight double-lined spectroscopic binary (SB2) systems with suspected λ Bootis candidates known (Paunzen et al. 2002). A detailed abundance

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analysis was done only for HD 84948 and HD 171948 so far (Heiter 2002 and Iliev et al. 2002). Both SB2 systems consist of true λ Bootis type objects. The analysis of such SB2 systems is very important for the above described model because it shows that both components of the system are λ Bootis type stars. It is clearly in contradiction with the suggested scenario by (Faraggiana et al. 2004) who suggested that two unresolved solar abundant stars mimic a metal-weak single star spectrum. The limitations and the inconsistencies of this scenario with accurate photometric measurements was already discussed by Stütz & Paunzen (2006).

In this paper we present the detection of HD 210111 (HR 8437, HIP 109306) being a true λ Bootis type SB system. New high resolution and classification spectroscopy is analysed and discussed in the context of already published data. This object, also showing δ Scuti type pulsation, is especially interesting because an IR excess was already detected which makes it an ideal test case for the accretion model.

2 OBSERVATIONS

The high resolution spectra, used for the abundance and stellar parameter estimation (Fig. 2), were taken from the UVES Paranal Observatory Project (Bagnulo et al. 2003). In total, 24 spectra from the night of 07.07.2002 are available which were observed with a slit width of 0.5Å, resulting in a spectral resolution of about 80000. The final, averaged, spectrum was normalized using standard IRAF routines[1].

We compared the line profiles of the averaged spectrum to those of the individual spectra to exclude a misinterpretation due to an incorrect merging of the data. The line profiles due to the SB2 nature are clearly visible in all spectra.

Additional high resolution spectra were obtained at the 1.5 meter telescope (20./21.10.2009) at the Cerro Tololo Inter-American Observatory and the 2.15 meter telescope (05./06.09.2011) at the Complejo Astronómico El Leoncito (CASLEO) with the Echelle de Banco Simmons (EBASIM) Spectrograph. The integration times were set to ten minutes and one hour, respectively. The spectral resolutions are comparable to that of UVES but the signal-to-noise ratio is much lower. As supplement, a classification resolution ($R \approx 500$) spectrum (Fig. 1) was obtained at the Southern Astrophysical Research (SOAR) 4.1 meter telescope at Cerro Pachon using the Goodman Spectrograph in the night of 26./27.07.2010.

In a first step, all the spectroscopic data have been reduced using standard IRAF routines. The standard reduction includes: bias subtraction, flat-fielding, cosmic ray cleaning and wavelength calibration.

3 TARGET CHARACTERISTICS

HD 210111 (HR 8437, HIP 109306) is one of the southern bright ($V = 6.83$ mag) λ Bootis prototype stars. It is classified as kA2hA7mA2 Vas λ Boo with peculiar hydrogen lines

[1] Available from http://iraf.noao.edu/

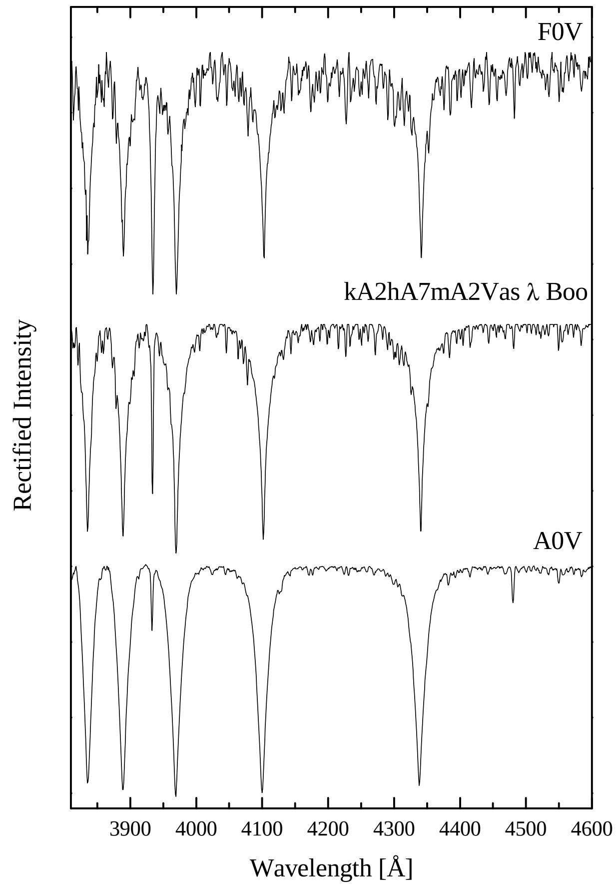

Figure 1. A new high signal-to-noise classification resolution spectrum of HD 210111 collected with Goodman Spectrograph attached to the SOAR telescope together with two corresponding MK standards (HR 3314, A0 V and HD 23585, F0 V) taken from Gray (1988)

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by Gray (1988). In Fig. 1 we present a new high signal-to-noise classification resolution spectrum of the target. Together with the appropriate MK standard stars, it shows the uniqueness of the overall spectral features.

The high resolution spectrum ($R \approx 50\,000$) presented by Holweger & Stürenburg (1991) indicate asymmetric line profiles which were not discussed in that paper. It is interesting to note that HD 183324 (HR 7400), another well established member of the λ Bootis group, shows similar line profile characteristics as HD 210111 according to their presented spectra. This star might also be an undetected SB2 system. On the other hand, Holweger & Rentzsch-Holm (1995) observed a clean, unperturbed rotationally broadened Ca II K line. This can be understood within the framework of a small radial velocity difference between the two binary components, the broadening of the Ca II K line and the spectral resolution. Even in our spectrum, this line (as well as the hydrogen lines) are not affected by the SB2 characteristics. In the catalogue of Grenier et al. (1999) this star is marked as a suspected binary system. Faraggiana et al. (2004) suspected that HD 210111 could be an undetected SB system on the basis of a cross-correlation of three spectra ($R \approx 28\,000$)

observed in 1993 and 1994. However, this material was not sufficient to draw any decisive conclusions.

The δ Scuti type pulsation of this object was detected in 1994 and a global observational campaign was reported by Breger et al. (2006). In total, they found thirteen statistically significant pulsation frequencies with very small photometric amplitudes in the visual. It is well known that diffusion and accretion affect the pulsation frequencies of stars at the upper main sequence (Turcotte 2002). In λ Bootis stars, the opacity in the metal bump will be significantly lowered. However, only little direct pulsational excitation from Fe-peak elements was found, but effects due to settling of helium along with the enhancement of hydrogen are important. Nevertheless, the structure of the star is changed and thus the frequencies of the excited modes. Since the effects are rather small, new satellite based observations with Convection, Rotation and Planetary Transits (CoRoT) or Microvariability & Oscillations of Stars (MOST) are clearly needed.

A significant IR-excess from IRAS data due to a circumstellar disk was detected for HD 210111 (Paunzen et al. 2003). Since we find that both components of this system are very similar with an equal luminosity (Sect. 4), the conclusions about the characteristic dust temperature, the fractional dust luminosity, and the radiative equilibrium distance of the above mentioned paper are still valid.

The overall characteristics of this star makes it an excellent test case for the published models explaining the λ Bootis phenomenon. With the tools of asteroseismology further insights of the stellar atmospheres should be possible whereas a detailed analysis of its environment will allow to understand the source as well as the mechanism of accretion.

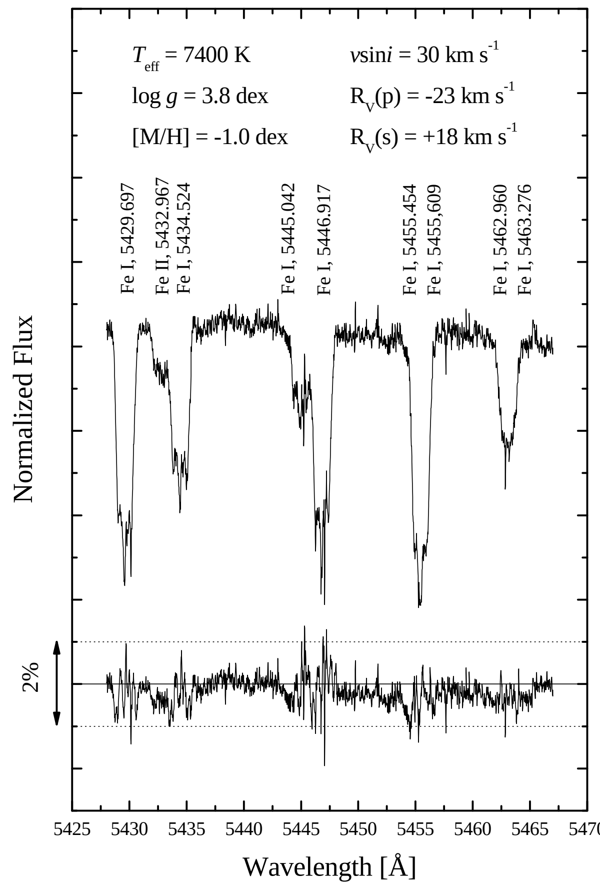

Figure 2. Upper curve: A part of the averaged UVES spectrum. Lower curve: The difference between the best fit synthetic composite spectrum from a wide variety of single star spectrum combinations and the observed spectrum.

4 ANALYSIS

The ATLAS9 model atmospheres, including the treatment of convection by Canuto et al. (1996), were calculated with scaled solar abundances using pretabulated opacity distribution functions taken from the Vienna New Model Grid of Stellar Atmospheres (NEMO) (Heiter et al. 2002). All models are scaled to the solar abundance values as listed by Grevesse & Sauval (1998), except for C, N and O for which the values of Asplund et al. (2005) were used. The microturbulent velocity ξ was set to $2.0\,\mathrm{km\,s^{-1}}$. This is a typical value used for previous abundances studies of λ Bootis and A-type stars. Changing ξ to a value of $3.5\,\mathrm{km\,s^{-1}}$ (see Heiter 2002) alters the spectral broadening by an amount which is negligible compared to the rotational broadening. The atomic transition parameters for the spectrum synthesis have been taken from the Vienna Atomic Line Database (VALD; Kupka et al. 1999).

Starting values for an effective temperature, surface gravity and [M/H] were based on the results by Stürenburg (1993). The continuum flux was calculated with the program SYNTH (Piskunov 1992). In order to derive a "composite" spectrum, the individual spectrum of each component was shifted by an arbitrary relative radial velocity, weighted by the continuum flux ratios and added.

First of all, we estimated the rotational velocity $v \sin i$ by inspecting a composite spectrum with several different values for both components. A value of $v \sin i \approx 30\,\mathrm{km\,s^{-1}}$ for both components fitted the observations best and was set, accordingly, for the further analysis. The heuristic error of the rotational velocity is $\approx 5\,\mathrm{km\,s^{-1}}$. Prior published values of the rotational velocity for HD 210111 range from 50 to $60\,\mathrm{km\,s^{-1}}$ on the basis of classification to high resolution spectroscopy (Solano et al. 2001). Besides the broadening due to the instrumental profile, a radial velocity difference of $50\,\mathrm{km\,s^{-1}}$ at 4200 Å is needed to convolve two single line profiles with a $v \sin i$ of $30\,\mathrm{km\,s^{-1}}$ to a "composite" one with $60\,\mathrm{km\,s^{-1}}$. This value can be set as upper limit of the orbital total radial velocity amplitude for all published data.

As next step, the radial velocities were manually determined and set to -23 and $+18\,\mathrm{km\,s^{-1}}$, respectively. Due to the high resolution of the spectrum and the wide separation of the components, these values are unambiguous with an accuracy better than $1\,\mathrm{km\,s^{-1}}$. The averaged mean radial velocity of $-5\,\mathrm{km\,s^{-1}}$ is in the same range as the three measurements ($-5.13\pm0.59\,\mathrm{km\,s^{-1}}$) published by Grenier et al. (1999). These observations were made in a time interval of 434 days. Such a rather constant mean radial velocity could point towards a very long orbital period of this spectroscopic binary system.

The published values for the effective temperature range from 7400 to 7900 K whereas the $\log g$ ones are between 3.75 and 3.90 dex (Paunzen et al. 2002). We calculated all combinations of stellar atmospheres with $7000 < T_{\rm eff} < 8000$ K, $3.7 < \log g < 4.0$ dex and [M/H] = [+0.0,−0.5,−1.0,−1.5]. A possible much cooler component would have been detected by enhanced X-ray fluxes from the ROSAT measurements (Hünsch et al. 1998). The composite spectra were semi-automatically compared to the observed spectrum in the wavelength region between 4500 and 5500 Å including the most prominent unblended metallic lines. In addition, the Ca II K, Na D, and the Ca II lines in the red spectral region were used. The ten best fitting composite spectra deduced via a SIMPLEX method described by Gray et al. (2003) were manually inspected and re-fitted.

Bohlender et al. (1999) presented time series spectroscopy of HD 210111 finding non-radial pulsation (NRP) of this object with a period of 49 minutes and a peak-to-peak amplitude of 2.5% of the continuum in the mean-absolute-deviation. The corresponding radial velocity amplitude of such kind of variation is below 3 km s^{-1} depending on the detected pulsation mode (Kiss et al. 2002). Our reported absolute radial velocity difference of 41 km s^{-1} is more than one order of magnitude larger than that and can not be explained by NRP.

Finally, we found that a composite spectrum with equal components fitted the observed spectrum best. In Fig. 2 the observed spectrum in the wavelength region from 5425 to 5470Å together with the difference to the synthetic one is shown. The fit of the line profiles and depths is better than 1% which is very satisfactory. Changing the effective temperatures by ±100 K and the surface gravities by ±0.05 dex already significantly (3σ of the estimated error due to the signal-to-noise ratio) decreases the quality of the fit. For the metallicity we can only state that the best fifteen composite spectra always comprise two components with [M/H] = −1.0 dex. No combination with at least one solar abundant component is able to fit the observed line profiles in a satisfactory way.

Finally we conclude that HD 210111 consists of two similar (within the estimated errors) stars with $T_{\rm eff} = 7400$ K, $\log g = 3.8$ dex, [M/H] = −1.0 dex and $v \sin i = 30$ km s^{-1}. This result perfectly matches the strict limitations of the photometric 7-color Geneva, Strömgren *uvby* and Δa measurements presented in Stütz & Paunzen (2006).

Within the usable wavelength range, we mainly find Fe and Si lines as well as a few Mg, Si, Cr and Ni lines. For these elements, the best-fit spectra with an abundance of −1.0 dex compared to the Sun in each of the components agree with the observed line profiles which is in line with the result by Stürenburg (1993).

For a more detailed abundance analysis, additional data, especially with a large separation of the two components are needed.

We fitted a composite synthetic spectrum with the above listed parameters to the Hβ line profiles of the available high resolution observations. Besides the known inadequateness of fitting the hydrogen line core correctly, the normalization of the echelle spectra is quite problematic because the line spreads over two consecutive orders. The classification resolution spectrum, on the other hand, allows only a rough determination and check of the parameter space. The fits themselves result in a good agreement. However, we are not able to use the Hβ line profiles for further improvements via an iterative method.

From the parallax measurement of the final release of the Hipparcos catalogue (van Leeuwen 2007), we derived a distance of 78±4 pc for HD 210111. With the absolute bolometric magnitude of the Sun $(M_{\rm Bol})_\odot = 4.75$ mag (Cayrel de Strobel 1996) and the bolometric correction taken from Drilling & Landolt (2000), the luminosity ($\log {\rm L}_*/{\rm L}_\odot$) was calculated. As the next step, we used the post-MS evolutionary tracks and isochrones from Claret (1995) to estimate the mass and age. The models were calculated with solar abundances. That is justified because the stellar abundance is restricted to the surface only.

Using the derived astrophysical parameters, an age of almost 1 Gyr for this system and a mass of 1.9 M$_\odot$ for both components is deduced. The errors are about 10 %. This is in line with the ages published by Iliev & Barzova (1995) and Paunzen et al. (2002).

Its brightness and close distance to the Sun makes HD 210111 to an excellent candidate for follow-up observations in the NIR and IR not only to study its surrounding environment, i.e. the circumstellar disk characteristics, but also to understand the accretion process at such evolved ages.

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