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A SPECTRAL ATLAS OF λ BOOTIS STARS

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SUMMARY: Since the discovery of λ Bootis stars, a permanent confusion about their classification can be found in literature. This group of non-magnetic, Population I, metal-poor A to F-type stars, has often been used as some sort of trash can for "exotic" and spectroscopically dubious objects. Some attempts have been made to establish a homogeneous group of stars which share the same common properties. Unfortunately, the flood of "new" information (e.g. UV and IR data) led again to a whole zoo of objects classified as λ Bootis stars, which, however, are apparent non-members.

To overcome this unsatisfying situation, a spectral atlas of well established λ Bootis stars for the classical optical domain was compiled. It includes intermediate dispersion (40 and 120 Å mm^{-1}) spectra of three λ Bootis , as well as appropriate MK standard stars. Furthermore, "suspicious" objects, such as shell and Field Horizontal Branch stars, have been considered in order to provide to classifiers a homogeneous reference.

As a further step, a high resolution (8 Å mm^{-1}) spectrum of one "classical" λ Bootis star in the same wavelength region (3800 − 4600 Å) is presented. In total, 55 lines can be used for this particular star to derive detailed abundances for nine heavy elements (Mg, Ca, Sc, Ti, Cr, Mn, Fe, Sr and Ba).

Key words. atlases – stars: chemically peculiar – stars: fundamental parameters

1. INTRODUCTION

The classification of stars in the blue-violet optical domain is highly successful since the MK system was introduced in 1943 (Morgan et al. 1943). Using moderate dispersion (40 to 120 Å mm^{-1}) allows to determine basic astrophysical quantities such as the effective temperature (or spectral type) and surface gravity (or luminosity type). As an additional parameter, the metallicity plays an important role. The latter exhibits many peculiarities among various type of stars. One example is the group of λ Bootis stars. These nonmagnetic, Population I, A to F-type stars are characterized by a prominent metal-weakness of the Fe-peak elements (the light elements C, N, O and S are solar abundant). Since most of the heavy elements (e.g. Fe, Si, Ti and Ca) are main contributors of the metallic line spectrum, at least a dispersion of 120 Å mm^{-1} is needed to identify true

λ Bootis stars. For spectra with a lower dispersion, the metal-weakness can not be clearly identified. As Gray (1988) pointed out, other stars (e.g. Population II, shell, some Ap and high $v \sin i$ stars) can be identified as bona fide λ Bootis candidates. In this paper, spectra with a dispersion of 40 and 120 Å mm^{-1} of three well established λ Bootis stars (HD 74873, HD 125162 and HD 142703), together with standard, as well as "suspicious", stars are presented in order to provide a reference to classifiers for identifying true λ Bootis stars (Figs. 1 to 4). In addition, a high dispersion (8 Å mm^{-1}) spectrum of HD 192640 (Fig. 5) shows the lines useful for a detailed abundance analysis in the same wavelength region (3800 – 4600 Å). Finally, a discussion of the main spectral characteristics for λ Bootis stars is given.

2. OBSERVATIONS AND REDUCTIONS

The presented spectra were obtained at three different sites. Most of the observations were made at the Dark Sky Observatory 0.8m reflector (Appalachian State University) using the Gray/Miller spectrograph with the 1200 lines/mm grating (blazed at 4200 Å), giving a dispersion of 0.85 Å pixel^{-1} ($\lambda/\Delta\lambda$ = 4950 at 4200Å) and a spectral coverage of about 800 Å. These spectra were kindly provided by R.O. Gray. Additional observations were made with the 1.6m telescope at Itajuba, Brazil (observer: E. Paunzen). A coverage of 1000 Å with the 1200 lines/mm grating and dispersion of 0.89 Å pixel^{-1} ($\lambda/\Delta\lambda = 4700$ at 4200Å) was achieved. The high resolution spectrum ($\lambda/\Delta\lambda = 20000$) of HD 192640 was taken at the Observatoire de Haute-Provence 1.52m telescope using the AURELIE spectrograph (a detailed observations log can be found in Heiter et al. 1998).

All spectra were reduced using standard IRAF routines. The 40 Å mm^{-1} spectra were smoothed to a dispersion of 120 Å mm^{-1} using cubic splines. The observed flux was normalized to the continuum.

Table 1. Line identifications for the high resolution spectrum of HD 192640 (Fig. 5).

#	λ [Å]	El.	#	λ [Å]	El.
1	3933.663	Ca II	29	4307.902	Fe I
2	4005.241	Fe I	30	4320.732	Sc II
3	4012.385	Ti II	31	4325.762	Fe I
4	4030.753	Mn I	32	4383.544	Fe I
5	4033.062	Mn I	33	4395.033	Ti II
6	4034.483	Mn I	34	4399.772	Ti II
7	4045.813	Fe I	35	4404.750	Fe I
8	4063.594	Fe I	36	4415.122	Fe I
9	4071.737	Fe I	37	4434.957	Ca I
10	4077.709	Sr II	38	4443.794	Ti II
11	4178.862	Fe II	39	4450.482	Ti II
12	4181.754	Fe I	40	4454.779	Ca I
13	4187.038	Fe I	41	4468.507	Ti II
14	4187.795	Fe I	42	4481.126	Mg II
15	4199.095	Fe I	43	4481.325	Mg II
16	4202.028	Fe I	44	4501.273	Ti II
17	4215.519	Sr II	45	4508.288	Fe II
18	4219.360	Fe I	46	4515.339	Fe II
19	4226.728	Ca I	47	4520.224	Fe II
20	4233.172	Fe II	48	4522.634	Fe II
21	4238.809	Fe I	49	4533.969	Ti II
22	4246.822	Sc II	50	4554.029	Ba II
23	4250.787	Fe I	51	4555.893	Fe II
24	4254.332	Cr I	52	4558.650	Cr II
25	4260.473	Fe I	53	4563.761	Ti II
26	4271.759	Fe I	54	4571.968	Ti II
27	4274.796	Cr I	55	4583.837	Fe II
28	4283.011	Ca I			

Table 2. Stars used for the spectral atlas.

HD	HR	Durchm.	V [mag]	$b-y$ [mag]	m_1 [mag]	c_1 [mag]	β [mag]	$v \sin i$ [km s^{-1}]	Spectral type
23585		BD+23 528	8.38	0.190	0.178	0.717	2.780	100	F0 V (MK)
74873	3481	BD+12 1904	5.87	0.064	0.188	0.934	2.890	89	kA0.5hA5mA0.5 V λ Boo
102647	4534	BD+15 2383	2.14	0.043	0.211	0.973	2.811	123	A3 Va (MK)
125162	5351	BD+46 1949	4.18	0.051	0.182	1.000	2.894	113	A0 Va λ Boo
130095		BD–26 10505	8.13	0.066	0.106	1.261	2.814	9	FHB
142703	5930	BD–14 4314	6.13	0.180	0.118	0.725	2.743	105	kA1hF0mA1 Va λ Boo
172167	7001	BD+38 3238	0.03	0.003	0.157	1.088	2.903	23	A0 Va (MK)
192640	7736	BD+36 3955	4.92	0.099	0.158	0.928	2.832	73	A0.5 Va^{-} λ Boo
195325	7836	BD+10 4303	6.08	0.025	0.092	1.071	2.766	200	A1 shell

3. WORKING DEFINITION

The following definition was established by Gray (1988) and Paunzen (2001). It summarizes the basic features of moderate dispersion spectra which seem to be shared by all well established λ Bootis stars:

(1) The λ Bootis stars are early-A to early-F type stars, with approximate spectral type range (based on the hydrogen lines) of B9.5 to F0 with possible members as late as F3.

(2) The λ Bootis stars seem to be always characterized by weak Mg II 4481 lines, such that the ratio Mg II 4481/Fe I 4383 is significantly smaller than in normal stars. For a standard A0 star, this ratio is normally 0.9, but it can reach 0.2 for λ Bootis group members. In addition, the spectra exhibit a general metal-weakness. The typical shell lines (Ca II 3968, Fe II 4233, Ti II 3759/61, etc.) tend to be weak as well, but the λ Bootis stars do not show the typical shell spectral characteristics.

(3) The following classes of stars should be excluded from the λ Bootis even if they show weak λ 4481 lines: shell stars, protoshell stars, He-weak stars (easily distinguished on the basis of their hydrogen-line temperature types), and other chemically peculiar (CP) stars. Field Horizontal Branch (FHB) and intermediate Population II stars may be distinguished from the λ Bootis stars on the basis of their hydrogen-line profiles. High-$v \sin i$ stars should be considered as λ Bootis candidates only if the weakening of λ 4481 is obvious with respect to standards with high values of $v \sin i$.

(4) λ Bootis stars are also characterized by broad hydrogen lines, and in many cases these hydrogen lines are exceptionally broad. In the late-A and early-F λ Bootis stars the hydrogen line profiles are often peculiar, and are characterized by broad wings but shallow cores.

(5) The distribution of rotational velocities of the λ Bootis stars cannot be distinguished from that of normal Population I, A-type stars.

This definition already includes the basic criteria for a successful classification of a true λ Bootis star. Unfortunately, many other types of stars were confused with this group (Paunzen et al. 1997). A good example is the work of Abt and Morrell (1995) who found many "4481-weak" stars.

4. HIGH RESOLUTION SPECTROSCOPY

Although the membership criteria for the λ Bootis group are based on intermediate dispersion spectroscopy, a final conclusion about membership can only be drawn by using abundances derived from high dispersion spectra.

The blue-violet region up to 4600 Å is most suitable to derive abundances for most of the Fe-peak elements (Table 1). Since the definition of a λ Bootis star also includes the (solar) abundance of the light elements (C, N, O and S), a determination of these elements is crucial. However, useful lines can only be found in the red region (e.g. O I triplet at 7775 Å) and the abundance can therefore *not* be determined in the given spectral range (Kamp et al. 2001).

The needed spectral dispersion for a detailed abundance analysis is dependent on the effective temperature (cooler stars exhibit more detectable lines) and the projected rotational velocity ("smearing" of blends) for a particular star. Furthermore, one has to consider the signal-to-noise ratio in order to detect very weak lines (most of the "strong" metallic lines are very much underabundant). The signal-to-noise ratio should be at least 150 to unambiguously identify a true λ Bootis star.

The choice of presenting a high dispersion spectrum of HD 192640 is a compromise between all important parameters. Its effective temperature (7800 K), surface gravity (4.0) and projected rotational velocity (73 $\mathrm{kms^{-1}}$), as well as the very low overall abundance ([Z] ≈ -2 dex), makes HD 192640 a very good example of what needs to be achieved to do a reliable abundance analysis.

Fig. 5 shows the observed, as well as the synthetic spectrum for this star. The synthetic spectrum was calculated using an ATLAS9 model atmosphere (Kurucz 1993) and [Z] $= -2$ dex, while a detailed description of the procedure and individual abundances are given in Heiter et al. (1998).

In the range from 3800 to 4600 Å, 55 useful lines for an abundance determination can be found. These lines are sufficiently unblended (no line with a central depth greater than 30 percent relative to the depth of the examined line within 3 Å of the latter) and the individual line depths are greater than 1 percent of the continuum. The following nine elements can be determined: Mg, Ca, Sc, Ti, Cr, Mn, Fe, Sr and Ba (Table 1).

5. SPECTRAL ATLAS

In total nine stars were chosen for our spectral atlas listed in Table 2. The MK standards are from the list of Gray and Garrison (1987, 1989a,b), whereas the well established λ Bootis stars have been taken from Gray (1988) and Paunzen (2001). The Strömgren colors, V-magnitudes and the $v \sin i$ values are from literature.

Figs. 1 and 2 show three well established λ Bootis stars in comparison with MK standards. Even at a dispersion of 120 Å $\mathrm{mm^{-1}}$ the λ Bootis stars are clearly distinguished using the "classical" classification criteria (Gray and Garrison 1987, 1989a,b).

Since λ Bootis stars do not exhibit prominent shell features they are well separated from "classical" shell stars (Figs. 3 and 4).

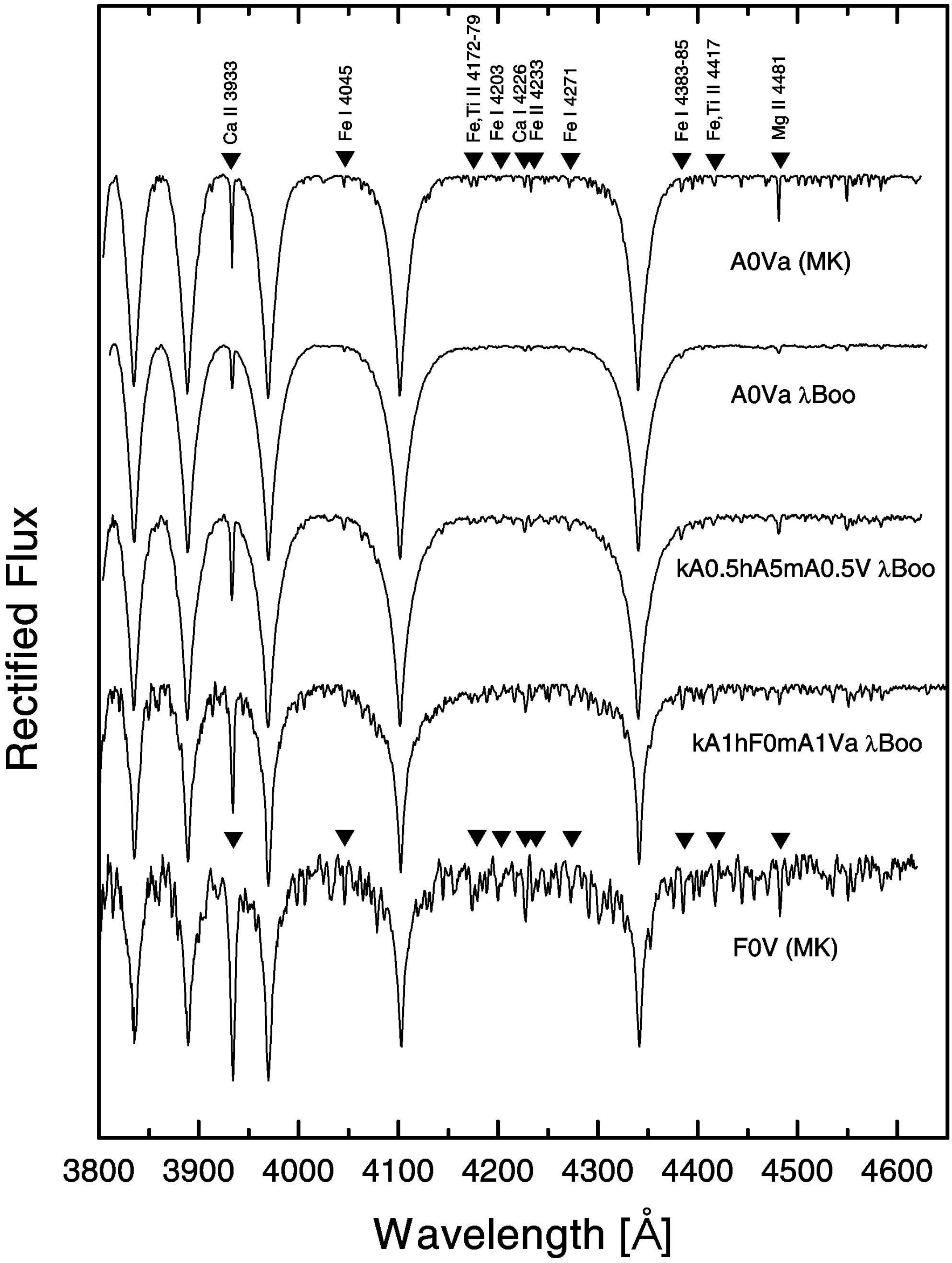

Fig. 1. *40 Å mm^{-1} spectra of three well established λ Bootis stars together with MK standards.*

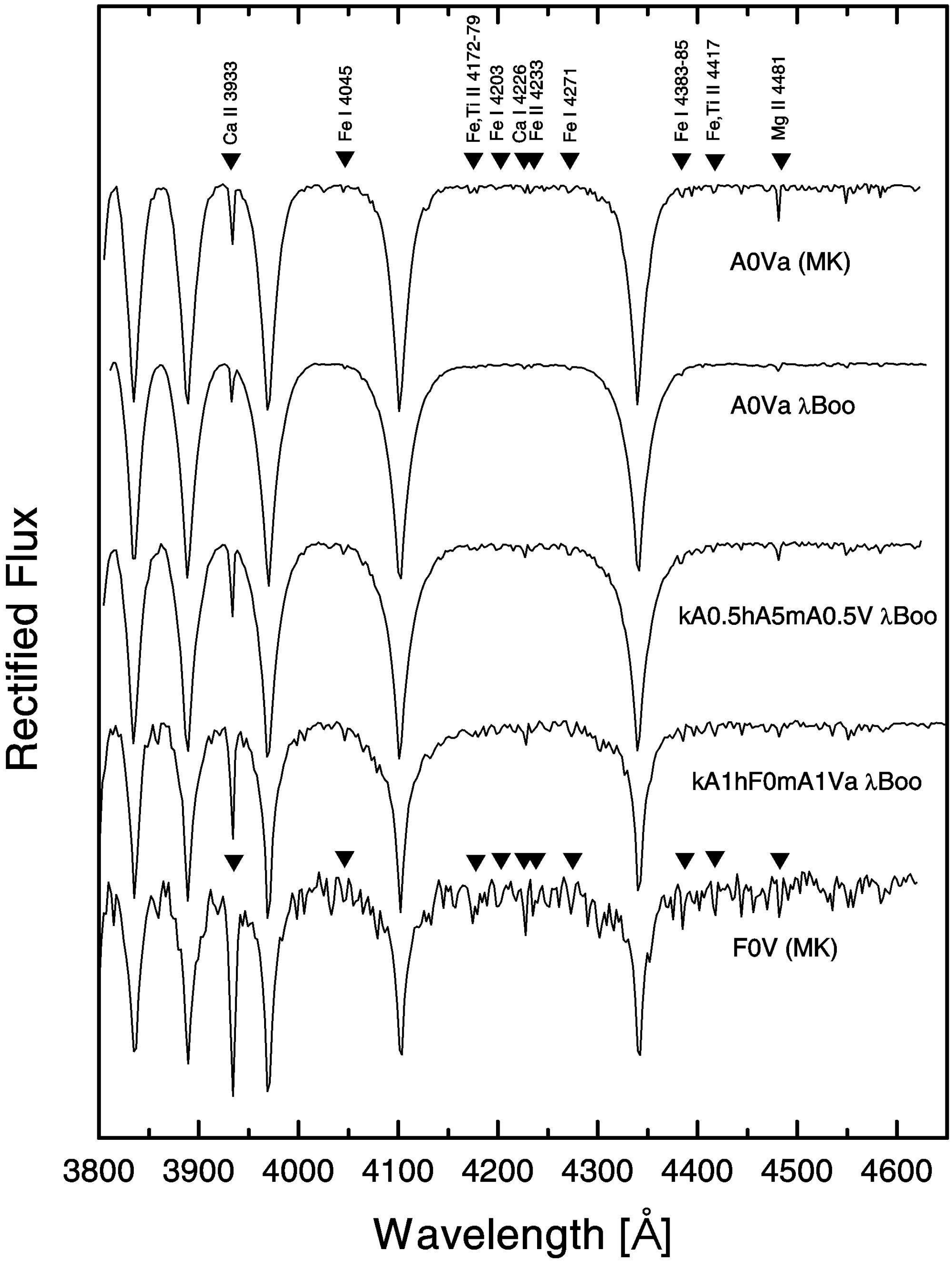

Fig. 2. *Same as Fig. 1 but but for a dispersion of 120 Å mm^{-1}.*

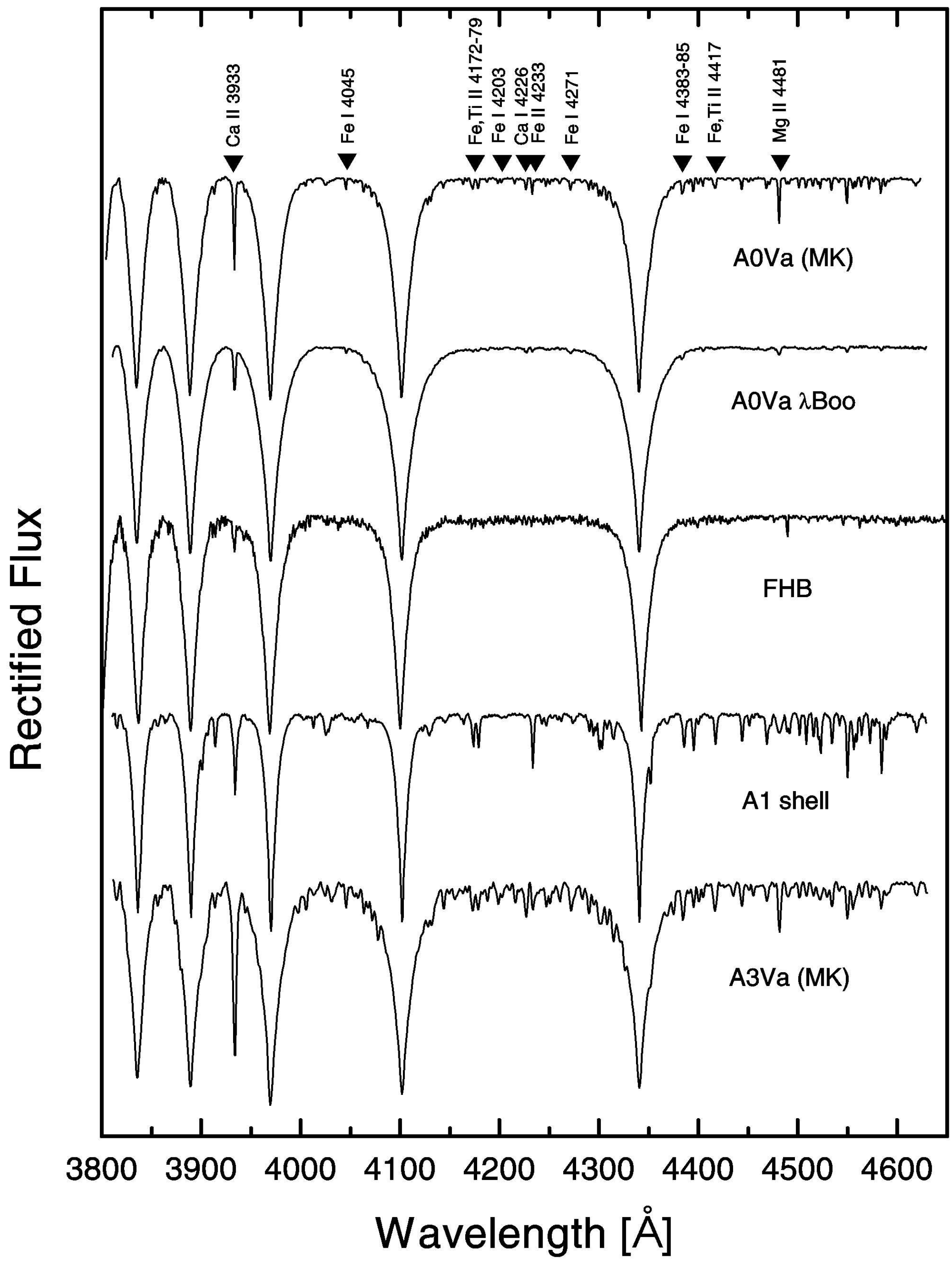

Fig. 3. *40 Å mm^{-1} spectra of a λ Bootis, A1 shell and FHB star together with MK standards.*

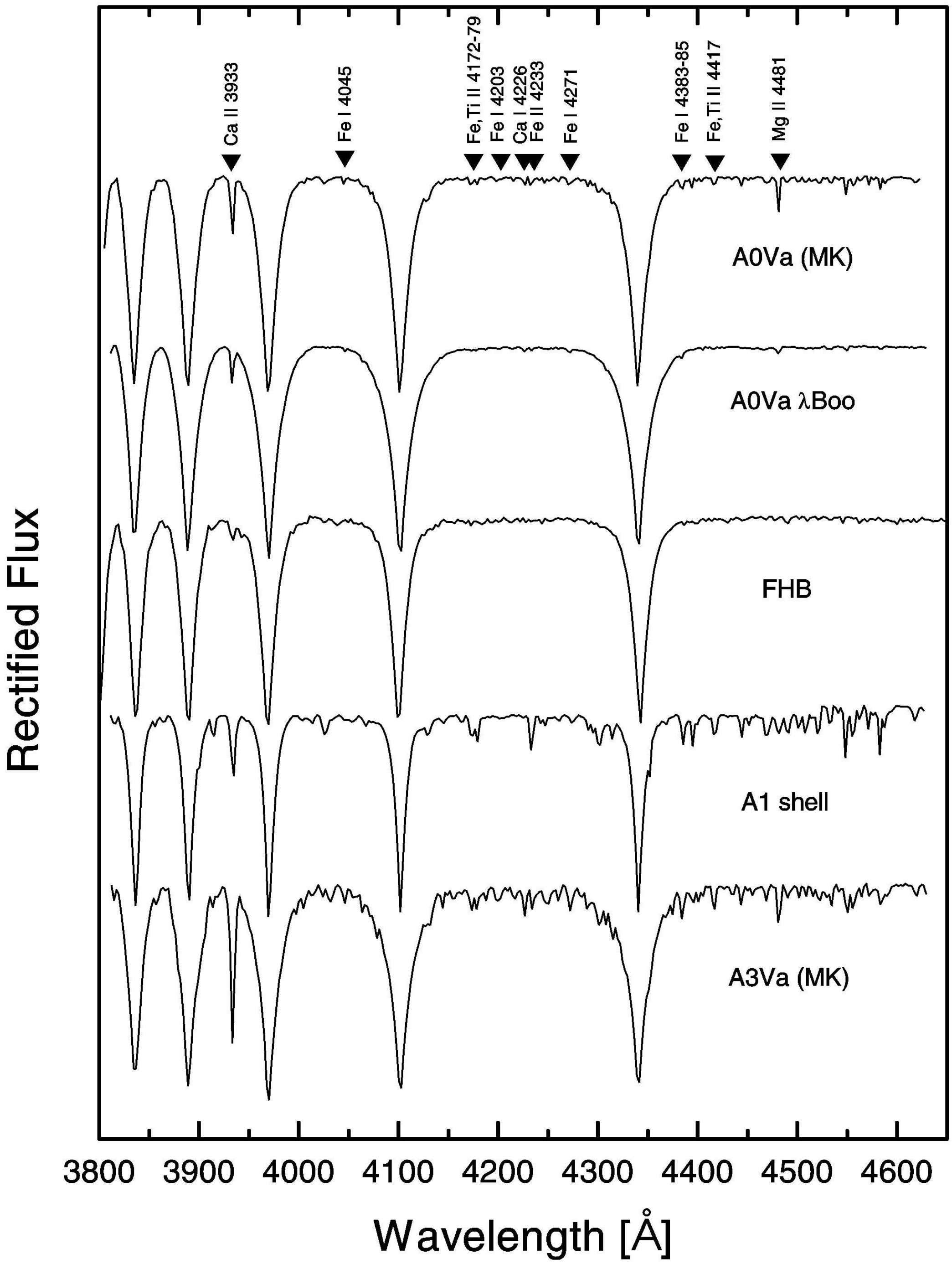

Fig. 4. *Same as Fig. 3 but but for a dispersion of 120 Å mm^{-1}.*

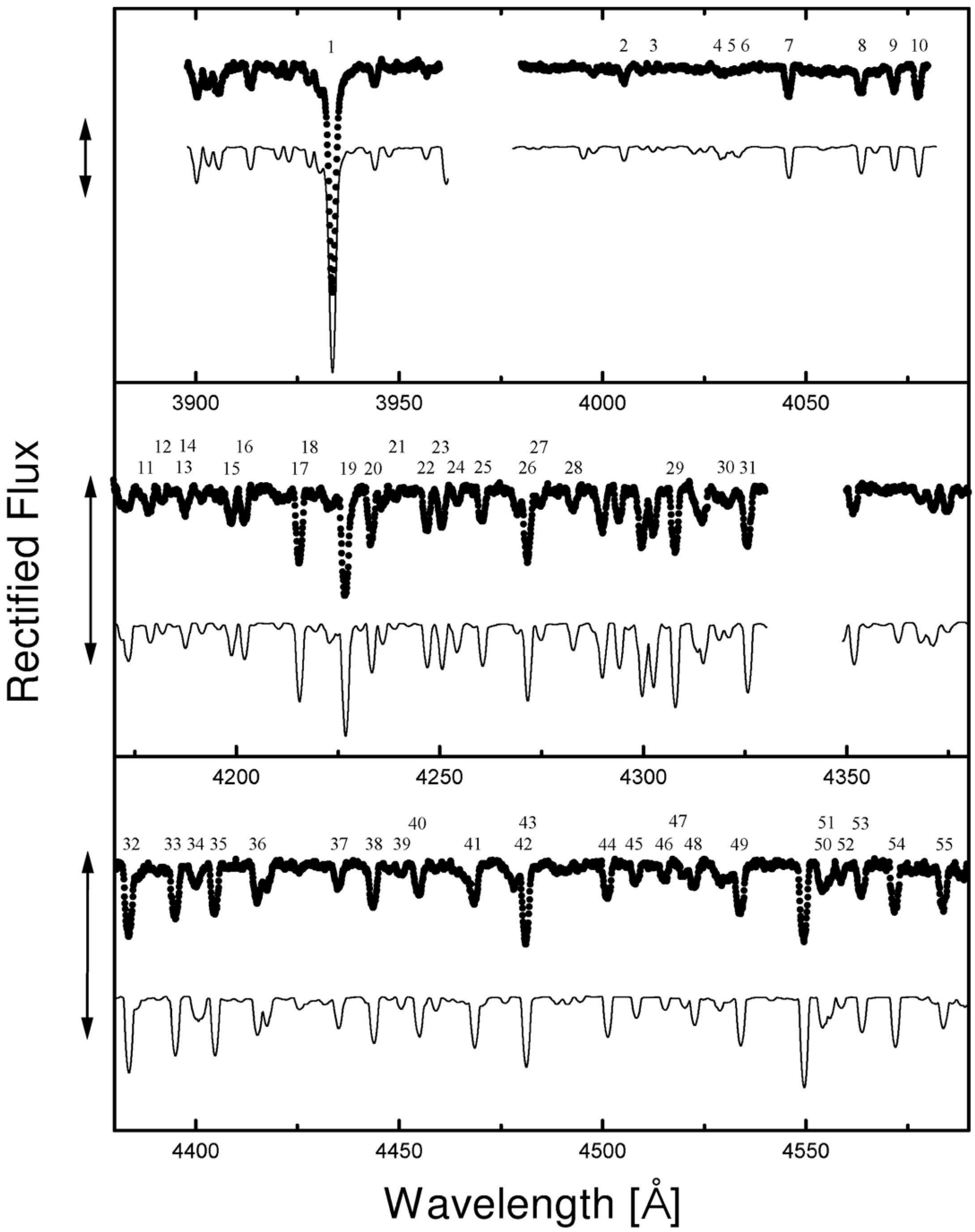

Fig. 5. *Observed (dots) and synthetic high resolution spectrum of HD 192640. Indicated are the lines useful to derive abundances as listed in Table 1. Note the different scaling of the three panels. The arrows on the side of each panel denote the same absolute rectified flux (20% of the continuum).*

The hydrogen line profiles are the most important criteria to distinguish λ Bootis from FHB stars. Fig. 4 shows that a dispersion of 120 Åmm^{-1} may be taken as the upper limit to clearly identify the "true" λ Bootis stars. To avoid confusion about the classification of a star being either a true λ Bootis or a FHB type, it is helpful to use Strömgren (Geneva) colors and/or IUE spectra (Solano and Paunzen 1999).

As a summary, a "check list" for identifying true λ Bootis stars was made. For a successful identification, (low and high $v \sin i$) MK standards, shell and FHB stars need to be observed with a dispersion between 40 and 120 Åmm^{-1}. If the following five conditions are fulfilled, a star can be addressed as bona-fide λ Bootis candidate:

(1) Spectral type deduced from the Ca II K line is the same as from the overall metallic lines but the hydrogen lines indicate a later one, or in the Yerkes notation: Sp(k)=Sp(m)<Sp(h),
(2) Luminosity class V,
(3) Hydrogen lines typical for Population I,
(4) No strong shell features,
(5) Strömgren and Geneva colors typical for Population I.

The most crucial point is the estimation of the strength for the metallic line spectrum because of its dependency on the projected rotational velocity. It is absolutely necessary to include MK standards (or suitable "normal" type stars) with $v \sin i$ values up to 250 $\mathrm{km\,s^{-1}}$. The same statement holds for the estimation of the calcium strength. The further procedure is then straightforward.

Beside the classical spectroscopic way of classification, it is very helpful (and sometimes necessary) to include additional information such as photometric indices or UV-data.

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СПЕКТРАЛНИ АТЛАС ЗВЕЗДА ТИПА λ BOOTIS

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Стручни чланак

Још од открића звезда типа λ Bootis присутна је конфузија у литератури везана за њихову класификацију. Ова група немагнетних звезда ниске металичности популације I, спектралних класа од A до F, често је служила као нека врста "канте за отпатке" за све "егзотичне" и спектроскопски "сумњиве" објекте. Било је покушаја да се дефинише једна хомогена група звезда које ће имати исте особине, међутим, права "поплава" информација (попут податак из UV или IC дела спектра) довела је до тога да се велики број објеката прелиминарно класификује као звезде типа λ Bootis, иако је очигледно да не припадају тој класи.

Да бисмо превезишли ову ситуацију начинили смо спектрални атлас користећи сигурне, класичне звезда типа λ Bootis, у оптичком домену. Атлас садржи спектре средње резолуције (40 и 120 Å mm^{-1}) за три звезде типа λ Bootis као и одговарајуће MK стандардне звезде. Осим тога, разматрани су "сумњиви" објекти попут прстенастих или звезда у пољу на хоризонталној грани, како би истраживачима који се баве класификацијом пружили поуздане, хомогене референтне податке.

Као корак више, приказан је спектар високе резолуције (8 Å mm^{-1}) једне "класичне" звезде типа λ Bootis у истом опсегу таласних дужина (3800 − 4600 Å). У случају ове звезде, може се искористити укупно 55 спектралних линија како би се извеле поуздане заступљености девет тежих елемената (Mg, Ca, Sc, Ti, Cr, Mn, Fe, Sr и Ba).