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Library of high-resolution UES echelle spectra of F, G, K and M field dwarf stars*,**,***

D. Montes[1,2] and E.L. Martín[3,4]

[1] Departamento de Astrofísica, Facultad de Físicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain
[2] Pennsylvania State University, Department of Astronomy & Astrophisics, 525 Davey Lab., University Park, PA 16802, U.S.A.
[3] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
[4] University of California at Berkeley, Department of Astronomy, Berkeley, CA 94720, U.S.A.

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Abstract. We present a library of Utrecht echelle spectrograph (UES) observations of a sample of F, G, K and M field dwarf stars covering the spectral range from 4800 Å to 10600 Å with a resolution of 55000. These spectra include some of the spectral lines most widely used as optical and near-infrared indicators of chromospheric activity such as Hβ, Mg I b triplet, Na I D_1, D_2, He I D_3, Hα, and Ca II IRT lines, as well as a large number of photospheric lines which can also be affected by chromospheric activity. The spectra have been compiled with the aim of providing a set of standards observed at high-resolution to be used in the application of the spectral subtraction technique to obtain the active-chromosphere contribution to these lines in chromospherically active single and binary stars. This library can also be used for spectral classification purposes. A digital version with all the spectra is available via ftp and the World Wide Web (WWW) in both ASCII and FITS formats.

Key words: Atlases — stars: activity — stars: chromospheres — stars: late-type — stars: fundamental parameters — stars: general

1. Introduction

Spectral libraries of late-type stars are a very powerful tool for the study of the chromospheric activity by application of the spectral subtraction technique (see Montes et al. 1995a,b,c; and references therein). Furthermore, these libraries are also very useful in many areas of astrophysics such as the stellar spectral classification, modelling stellar atmospheres, stellar abundances, calibration of temperatures, spectral synthesis applied to composite systems, and spectral synthesis of the stellar population of galaxies.

While for many of this purposes, obtaining as large a spectral range as possible was the main priority, for the chromospheric activity studies, which are centered in specific spectral features, it is much more important to increase the spectral resolution. However, previously published stellar libraries are of poor spectral resolution (between 45 and 1.25 Å) and the only attempt to improve the spectral resolution is our library of high and mid-resolution spectra in the Ca II H & K, Hα, Hβ, Na I D_1, D_2, and He I D_3 line regions of F, G, K and M field stars (Montes et al. 1997a, hereafter Paper I) with resolutions that range between 3 and 0.2 Å.

However, even more higher resolutions are needed when we are interested in very detailed studies of chromospheric activity such as the analysis of the difference features present in the chromospheric emission line profiles, the study of chromospherically active binaries aimed to determine from which component of the binary belong the emission lines (see Montes et al. 1997b), or the analysis of the time variations and line asymmetries that occur during a stellar flare (see Montes et al. 1998b).

On the other hand, the simultaneous observations of different lines, that are formed at different height in the chromosphere (from the region of temperature minimum to the higher chromosphere), are of special interest for stellar activity studies since they provide very useful information about this stellar region. Ideally, simultaneous

Send offprint requests to: D. Montes (dmg@astrax.fis.ucm.es)
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** Figure 1 and Tables 1 to 5 are only available in electronic form, and Table 6 is also available in electronic form.
*** The spectra of the stars listed in Table 6 are also available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

observations should be performed at all wavelengths in order to develop a coherent 3-D atmosphere model (see the multiwavelength optical observations of chromospherically active binary systems by Montes et al. 1997b, 1998a). So, to carry out these purposes applying the spectral subtraction technique, to as many lines as possible, a spectral library with a good spectral resolution and a good spectral coverage is needed.

The spectral library that we present in this paper is an extension of our previous one (Paper I) to higher spectral resolution covering a large spectral range. The library consist of echelle spectra of a sample of F, G, K and M field dwarf stars covering the spectral range from 4800 Å to 10600 Å and with spectral resolution ranging from 0.19 to 0.09 Å. These spectra include some of the spectral lines most widely used as optical and near-infrared indicators of chromospheric activity such as: Na I D_1, D_2, and Mg I b triplet (formed in the upper photosphere and lower chromosphere), Ca II IRT lines (lower chromosphere), Hα, Hβ (middle chromosphere), and He I D_3 (upper chromosphere), as well as a large number of photospheric lines which can also be affected by chromospheric activity. Furthermore, the spectra also include a lot of lines of interest to spectral classification and calibration of temperatures purposes, as well as other lines normally used for the application of the Doppler imaging technique.

In Sect. 2 we report the details of our observations and data reduction. The library is presented in Sect. 3 with comments on the behaviour of some interesting spectral lines.

2. Observations and data reduction

The high-resolution echelle spectra presented here were obtained by us during several observing runs with the 4.2 m William Herschel Telescope (WHT) at La Palma Observatory, using the Utrecht Echelle Spectrograph (UES) mounted on a Nasmith focal station. A description of the WHT/UES is given by Unger (1992). In addition, we analysed also different WHT/UES observational campaigns retrieved from La Palma Data Archive (Zuiderwijk et al. 1994).

In Table 1 we give a summary of WHT/UES observations, for each observing run we list the date, the observer, the CCD detector, the number of echelle orders included, the central wavelength ($\lambda_{\rm c}$), the wavelength range covered ($\lambda_{\rm i} - \lambda_{\rm f}$) and the range of reciprocal dispersion achieved (Å/pixel) from the first to the last echelle orders. The echelle grating used in all these runs was the E31. The interorder spacing was too small to perform a good sky subtraction. Sky contamination is only significant for the few faint very-late M-type stars of this library (VB 8 and VB 10). As can be seen in Table 1, the spectra cover the spectral range from 4800 Å to 10600 Å with spectral resolution (FWHM = 2 pixels) ranging from 0.19 to 0.09 Å, corresponding to $R \sim 55000$. However, as the CCD chips we have used were smaller than the echelle orders, we did not get a full recording of the different orders. The gaps between the adjacent recorded orders got larger towards longer wavelengths, as can be seen in Tables 2 to 5, where we give for each observing run the wavelength range and the spectral lines of interest in each echelle order.

The spectra have been extracted using the standard reduction procedures in the IRAF[1] package (bias subtraction, flat-field division, and optimal extraction of the spectra). The wavelength calibration was obtained by taking spectra of a Th-Ar. Finally, the spectra have been normalized by a polynomial fit to the observed continuum.

3. The library

As in Paper I, the stars included in the library have been selected as stars with low levels of chromospheric activity, that is to say, stars that do not present any evidence of emission in the core of Ca II H & K lines in our spectra (Montes et al. 1995c, 1996a), stars with the lower Ca II H & K spectrophometric index S (Baliunas et al. 1995), or stars known to be inactive and slowly rotating stars from other sources (see Strassmeier et al. 1990; Strassmeier & Fekel 1990; Hall & Ramsey 1992). In addition, we provide spectra of some active stars of late and very-late spectral types.

Table 6 presents information about the observed stars. In this table we give the HD, HR and GJ numbers, name, spectral type and luminosity class ($T_{\rm sp}$), from the Bright Star Catalogue (Hoffleit & Jaschek 1982; Hoffleit & Warren 1991) and the Catalogue of Nearby Stars (Gliese & Jahreiss 1991), except for some M dwarfs for which we list the more recent spectral type determination given by Henry et al. (1994) and Kirkpatrick et al. (1995). In Col. (6) MK indicates if the star is included in the list of Morgan and Keenan (MK) Standard Stars compiled by García (1989). Column (7) give the metallicity [Fe/H] from Taylor (1994; 1995) or Cayrel de Strobel (1992; 1997) and Col. (8) rotational period ($P_{\rm rot}$) and $v\sin i$ from Donahue (1993); Baliunas et al. (1995); Strassmeier & Fekel (1990); Fekel (1997); Stauffer & Hartmann (1986); Martín et al. (1996), and Basri & Marcy (1995; 1996). We also give, in Col. (9), the Ca II H & K spectrophometric index S from Baliunas et al. (1995) and Duncan et al. (1991). In Col. (10) we list information about the observing run in which each star have been observed, using a code given in the first column of Table 1, and the last column indicate if the star was also included in Paper I.

In Fig. 1 we have plotted for a K1V star representative spectral orders, with the line identification marked. The two first orders (Hβ and Mg I b lines) correspond to the

[1] IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

K1V star HD 10476 from the Dec-93 observing run and the following orders correspond to K1V star HD 9546 from the the Nov.-94 run.

Representative spectra (from F to M stars) in different spectral regions are plotted in Figs. 2 to 6 in order to show the behaviour of the more remarkable spectroscopic features with the spectral type. In order of increasing wavelength we have plotted the following line regions: Hβ (Fig. 2), Mg I b triplet (Fig. 3) Na I D_1, D_2 (Fig. 4) and He I D_3) (Fig. 4), Hα (Fig. 5),and Ca II IRT λ8498, 8542, 8662 (Fig. 6).

In the following, we describe the behaviour of some interesting spectral lines and molecular bands present in the spectral range covered by the spectra (from 4800 to 10600 Å). We list the spectroscopic features in order of increasing wavelength, and the echelle order in which they appear in each observing run can be found in Tables 2 to 5.

- The Hβ λ4861.3 line (Fig. 2) is a well know chromospherically activity indicator (emission or filled-in).
- The Mg I b triplet $\lambda\lambda$5167, 5172, 5183 (Fig. 3) is luminosity sensitive in the range G8-K5. These strong neutral metal lines are formed in the lower chromosphere and the region of temperature minimum and they are good diagnostics of activity (Basri et al. 1989; Gunn & Doyle 1997; Gunn et al. 1997; Montes et al. 1998b).
- The He I D_3 λ5876 absorption line is another important indicator of stellar activity in the upper chromosphere (García López et al. 1993; Montes et al. 1997b, 1998a; Saar et al. 1997) and also could be in emission during stellar flares (Huenemoerder & Ramsey 1987; Montes et al. 1996b, 1997b, 1998b).
- The Na I D_1 λ5895.92 and D_2 λ5889.95 lines (Fig. 4) are well known temperature and luminosity discriminant. These resonance lines are collisionally-controlled in the atmospheres of late-type stars and then provide information about chromospheric activity see Montes et al. (1996b, 1997b, 1998a) and the recent models of these lines for M dwarfs stars by Andretta et al. (1997).
- The wings of the Ca I triplet $\lambda\lambda$6102, 6122, 6162 lines can be used as luminosity indicators (Cayrel et al. 1996). These lines are very weak at spectral type F and increase in strength with decreasing temperature.
- The V I λ6251.83 and Fe I λ6252.57 line-depth ratio can be used to determine stellar temperatures (Gray & Johanson 1991; Gray 1994).
- The line ratio Fe II λ6432.65/Fe I λ6430.85 is useful for spectral-class/temperature classification for F to M stars. Other spectral class indicators are the ratios of V I λ6452/Ca I λ6456 (for F, and G stars), Co I λ6455/Ca I λ6456 and Fe II λ6457/Ca I λ6456 (for F to K stars) (Strassmeier & Fekel 1990).
- The Fe I 6411.66 Å, Fe I 6430.85 Å, and Ca I 6439.08 Å lines normally used for the application of the Doppler imaging technique.
- The emission or filled-in of the Hα (6562.8 Å) (Fig. 5) line is one the primary optical indicators of chromospheric activity in late-type stars, together with the Ca II H & K emission lines.
- The Li I resonance line at λ6707.8 Å and the subordinate lines at λ6103 Å and λ8126 Å (Pavlenko et al. 1995; Carlsson et al. 1994).
- The K I λ7664.91, 7698.98 doublet is a resonance transition and thus will be influenced by chromospheric activity, particularly in M dwarf stars (see Basri & Marcy 1995; Schweitzer et al. 1996).
- The Rb I resonance line at 7947.63 Å is strong in very late-type stars, and it seems to be a good temperature diagnostic (Basri & Marcy 1995).
- The Na I doublet $\lambda\lambda$8183.26, 8194.8 lines are subordinate transitions and therefore, form mainly in the photosphere and should not be significantly affected by the chromosphere. These lines can be used as a dwarf/giant indicator (Schiavon et al. 1997).
- The Ti I lines for multiplet 33 (specially the λ8382.54, 8382.82 lines) and other Ti I lines. can be used as a luminosity classification criterium because they present a positive luminosity effect (Keenan & Hynek 1945; Ginestet et al. 1994; Jashek & Jashek 1995; Montes et al. 1998a).
- The Ca II infrared triplet (IRT) $\lambda\lambda$8498, 8542, and 8662 lines (Fig. 6) formed in the lower chromosphere and are also important activity indicators (Linsky et al. 1979; Foing et al. 1989; Dempsey et al. 1993; Montes et al. 1998a). These lines have been also used by several authors as a gravity sensitive index. In this spectral region the Paschen lines P12 (λ8750) and P14 (λ8598) are also visible in F stars (Carquillat et al. 1997).
- From mid K through M stars we can also see a number of titanium oxide (TiO) molecular bands such as (5847−6058), (6080−6390), (6322−6512), (6569−6649), (6651−6852), (7053−7270), (7666−7861), (8206−8569), (8432−8452), and (8859−8937), useful in classifying early M dwarfs, and a number of vanadium oxide (VO) bands such as (7400−7510), (7851−7973), and (8521−8668), useful in classifying late M dwarfs. CaH bands at (6346, 6382, 6389) and (6750−7050) are also present in these stars.
- Other strong features that appear in the spectra are the telluric O_2 A and B bands at 6867 Å 7600 Å and several telluric H_2O bands at (7186−7273), (8164−8177), 8227, 8282, (8952−8972), and (8980−8992).

A more detailed description of the Hα, Hβ, Na I D_1, D_2 and He I D_3 lines and the corresponding photospheric features included in these spectral regions, can be found in Paper I. An extensive list of features identifiable in late-K to late-M spectra from 6300 to 9000 Å can be found in Kirkpatrick et al. (1991). A description of the spectroscopic characteristics of very cool dwarfs and substellar candidates is given by Martín et al. (1996). For more information about spectral classification of stars and the behaviour of chemical elements in stars the reader is referred to Jaschek & Jaschek (1990; 1995).

In order to enable other investigators to make use of the spectra of this library, all the multidimensional spectra containing all the echelle orders of the stars listed in Table 6 are available as FITS format files at the CDS in Strasbourg, France, via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5). They are also available via the World Wide Web at:
http://www.ucm.es/OTROS/Astrof/fgkmsl/UESfgkmsl.html.

In order to facilitate the use of this library the onedimensional normalized and wavelength-shifted spectra, resulting for the extraction of the orders containing the more remarkable spectroscopic features (the spectral regions plotted in Figs. 2 to 6), are also available as separate FITS format files.

The extension of this library including stars of higher luminosity class, as well as the use of these spectra to analyse temperature sensitive lines in order to improve the actual line-depth ratio temperature calibrations (Gray & Johanson 1991; Gray 1994) and spectral-class/temperature classifications (Strassmeier & Fekel 1990), will be the subject of forthcoming papers.

Table 1. Summary of WHT/UES observations (published only electronically at CDS)

Table 2. UES spectral orders (Jul.-93) (published only electronically at CDS)

Table 3. UES spectral orders (Dec.-93) (published only electronically at CDS)

Table 4. UES spectral orders (Apr.-94, Mar.-95, Jun.-95) (published only electronically at CDS)

Table 5. UES spectral orders (Nov.-94) (published only electronically at CDS)

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Fig. 1. Representative spectral orders for the Dec.-93 and Nov.-94 observing runs of a K1V star, with the line identification marked (published only electronically at CDS)

Table 6. Stars

HD	HR	GJ	Name	T_{sp}	MK	[Fe/H] (dex)	P_{rot} (days)	$v \sin i$ (km s^{-1})	S	Obs.	Pap. I
F stars											
33256	1673	189.2	68 Eri	F2V		−0.49	-	0	-	3	
6406				F3/F5IV/V		-	-	-	-	3	
84937			BD+14 2151	F5VI		−1.86	-	-	-	2	
			BD+18 3423	F6V		-	-	-	-	1	
78154	3616		σ^2 UMa	F6IV		-	-	0	0.142	6	
9826	458	61	50 And	F8V	MK	−0.14	-	8	0.154	1	
142373	5914	602	χ Her	F8V		−0.431	-	10.0	0.147	5	*
144284	5986	609.1	θ Dra	F8IV (SB1)		0.23	-	27.7	0.203	6	
98230	4374	423B	ξ UMa B	F8.5V	MK	−0.12	-	3	-	5	
114762			BD+18 2700	F9V		−0.87	-	-	-	3	
79028	3648	337.1	16 UMa	F9V (SB1)		-	-	0	-	5, 6	
114710	4983	502	β Com	F9.5V	MK	0.135	12.35	4.3F	0.201	3	*
G stars											
160269	6573		26 Dra	G0IV-V (MK) (SB1)	MK	-	-	41	-	1	
15335	720	99.1	13 Tri	G0V		-	-	< 6	-	4	
39587	2047	222B	χ^1 Ori	G0V (SB1)	MK	−0.084	5.36	8.6F	0.325	3	*
98231 A	4375	423A	ξ UMa A	G0V (SB1)		−0.352	-	< 15	-	5	*
84737	3881		15 LMi	G0.5V	MK	−0.04	-	3	0.145	5	
10307	483	67	BD+41 328	G1.5V (SB1)	MK	0.14	-	2.1	0.152	2	
42807	2208	230	BD+10 1050	G2V		-	-	-	0.352	4	
153631		650	BD-13 4528	G2V (SB1)		-	-	-	-	3	
186427	7504	765.1B	16 Cyg B	G3V	MK	−0.002	-	0.4	0.145	1	*
86728	3951	376	20 LMi	G3V	MK	−0.11	-	3	0.156	6	
115617	5019	506	61 Vir	G5V		0.032	-	0.4	0.162	3	*
178428	7260	746	BD+16 3752	G5V (SB1)		-	-	-	0.154	3, 6	
33802 B			BD-12 1095B	G5Ve		-	-	-	-	3	
149414		629.2A	BD-03 3968	G5V (SB1)		−1.14	-	-	-	3, 5, 6	
20630	996	137	κ^1 Cet	G5V	MK	0.133	9.24	3.9	0.366	2	*
31966		182.1	BD+14 804	G5V		-	-	-	-	4	
108754		469.1	BD-02 3528	G7V (SB1)		-	-	-	-	3, 5	
131156 A	5544 A	566A	ξ Boo A	G8V	MK	−0.151	6.31	3.2	0.461	5	*
44867	2302		BD+16 1135	G8IV (G9III)		-	-	-	-	4	
195987		793.1	BD+41 3799	G9V (SB1)		-	-	-	-	3	
K stars											
10780	511	75	BD+63 238	K0V		0.36	-	0.6	0.280	4	
185144	7462	764	σ Dra	K0V	MK	−0.045	-	0.6	0.215	1	*
18972			BD+13 494	K0IV		-	-	-	-	4	
48432	2477		13 Lyn	K0III		-	-	< 19	0.120	2	
9546		59.3	ADS 1233 A	K1V		-	-	-	-	4	
10476	493	68	107 Psc	K1V	MK	−0.123	35.2	0.	0.198	2	*
76291	3545		BD+46 1459	K1IV		-	-	-	-	2	
6027		50.1	BD+58 155	K2V (K3III)		-	-	-	-	4	
101177 B	4486 B	433.2 B	ADS 8250 A	K2V (SB)		-	-	-	0.144	3, 6	
38392	1982	216B	γ Lep B	K2V		0.02	-	-	-	3	
136713		1191	BD-10 4088	K2V		-	-	-	-	3	
223778	9038	909 A	BD+74 1047	K3V		-	-	-	-	1	
219134	8832	892	BD+56 2966	K3V	MK	−9.000	-	-	0.230	2	*
16160 A	753	105A	BD+06 398	K3V	MK	−0.297	48.0	-	0.226	4	*
98800		2084A	ADS 8141 A	K4V		-	-	-	-	3, 5	
131156 B	5544 B	566B	ξ Boo B	K4V		0.19	12.28	20	1.381	5	*
12208		83.3	V598 Cas	K5V		-	-	-	-	4	
154363		653	BD-04 4225	K5V		-	-	-	-	3	
201091	8085	820 A	61 Cyg A	K5V	MK	−0.06	35.37	0.6	0.658	2, 6	*
201092	8086	820 B	61 Cyg B	K7V	MK	−0.10	37.84	1.4	0.986	2, 6	*
		52	BD +63 137	K7V		-	-	-	-	4	
157881		673	BD+02 3312	K7V		0.40	-	3.9	1.464	1	
88230		380	BD+50 1725	K7V(1) (K6V MK)	MK	0.28	-	3.1	1.617	3	
151877		639	BD+37 2804	K7V		-	-	-	0.197	3	
151288		638	BD+33 2777	K7.5Ve	MK	-	-	-	1.380	3, 6	

Table 6. continued

HD	HR	GJ	Name	T_{sp}	MK	[Fe/H] (dex)	P_{rot} (days)	$v \sin i$ (km s^{-1})	S	Obs.	Pap. I
M stars											
		16		M0V		-	-	-	-	1	
79210		338A	ADS 7251 A	M0Ve (1)		-	-	-	2.113	3	*
		572	BD+45 2247	M0V		-	-	-	-	3, 5	
232979		172	BD+52 857	M0.5V	MK	-	-	-	1.909	4	
1326 A		15A	GX And	M1.5V (1) (M2V MK)	MK	-	-	-	-	4	
36395		205	BD-03 1123	M1.5V (1)	MK	0.60	-	-	-	4	
95735		411	BD+36 2147	M2V	MK	−0.20	-	-	0.424	3	
		623AB	LHS 417	M2.5V (1)		-	-	-	-	3, 5, 6	
		813	LHS 3605	M3V		-	-	-	-	1	
173739 A		725A	ADS 11632 A	M3V (1)		-	-	-	0.534	3, 5	
180617		752A	LHS 473	M3 V (1)	MK	-	-	-	1.252	6	
		273	BD+05 1668	M3.5V (1)		-	-	-	-	3	
16160 B		105B	BD+06 398 B	M3.5V (1) (3)		-	-	-	-	1	
		699	Barnard's star	M4V (1)		-	-	-	-	3	
13124		748	Wolf 1062	M4V (M3.5V (4))		-	-	-	-	3, 5, 6	
		447	FI Vir, LHS 315	M4V (1) (3)		-	-	-	-	6	
12025			U Per	M4III (M6e)		-	-	-	-	4	
		234AB	LHS 1849/50	M4.5V (1) e		-	-	< 10	-	3, 5	
		831AB	LHS 511	M4.5V (1) e		-	-	< 10	-	6	
		473AB	FL Vir, LHS 333	M5.5V (1) e		-	-	-	-	3, 5, 6	
		1245A	V1581 Cyg	M5.5V e		-	-	-	-	6	
		1245B	LHS 3495	M5.5V e		-	-	-	-	6	
		406	LHS 36	M6V (1) e		-	-	< 3	-	3	*
		1111	DX Cnc, LHS 248	M6.5V		-	-	11	-	3, 5	*
		644C	VB 8, LHS 429	M7V (2)		-	0.14	8	-	3, 5, 6	
		752B	VB 10, V1298 Aql	M8V (1) e		-	-	< 5	-	6	

(1): Henry et al. (1994)
(2): Kirkpatrick et al. (1995)
(3): "Zero Hα star", Byrne (1993)
(4): Kirkpatrick et al. (1991)
MK: "A List of MK Standard Stars", García (1989)
SB: Spectroscopic Binary (Duquennoy & Mayor 1991; Mazeh et al. 1997).

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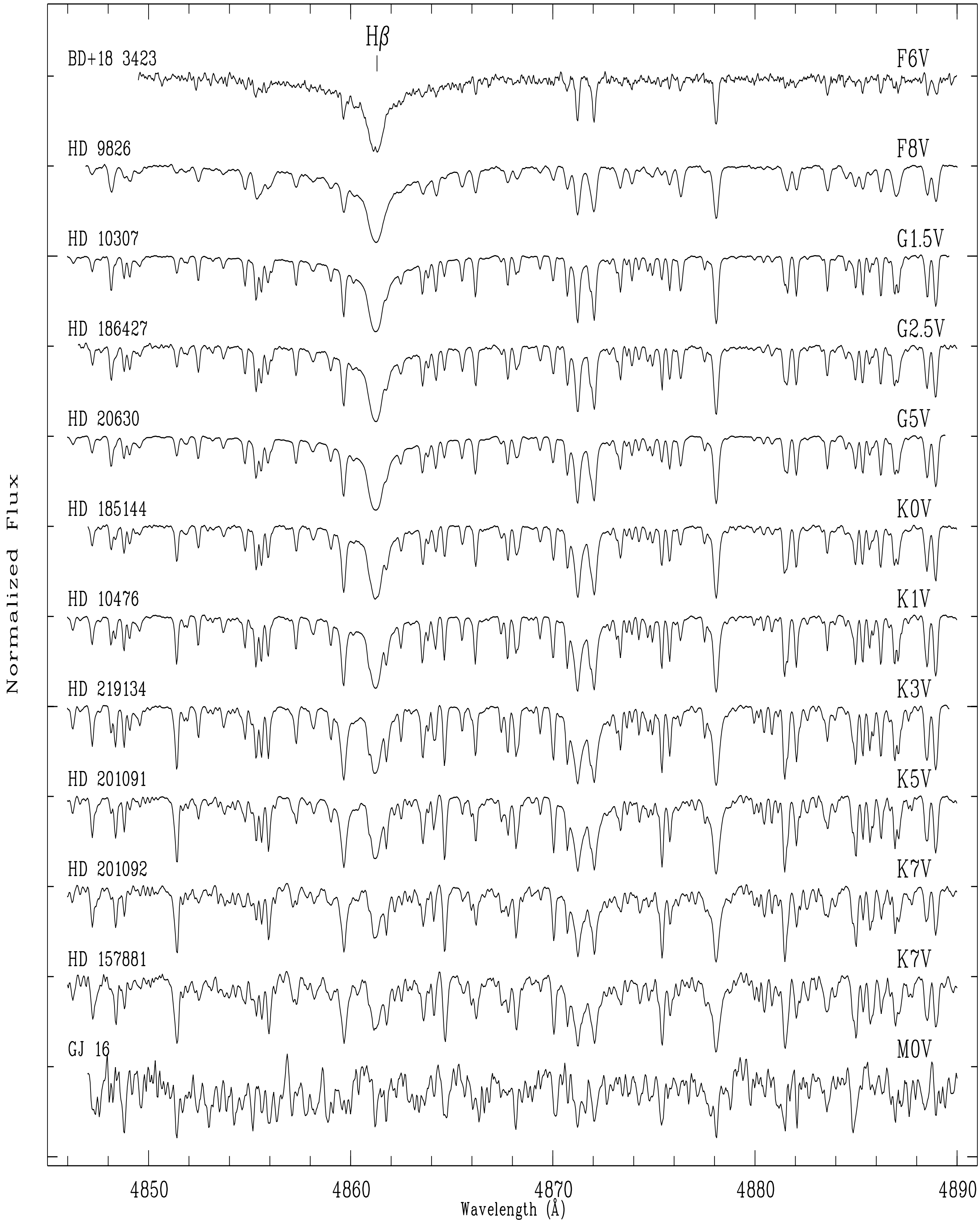

Fig. 2. Spectra in the Hβ line region

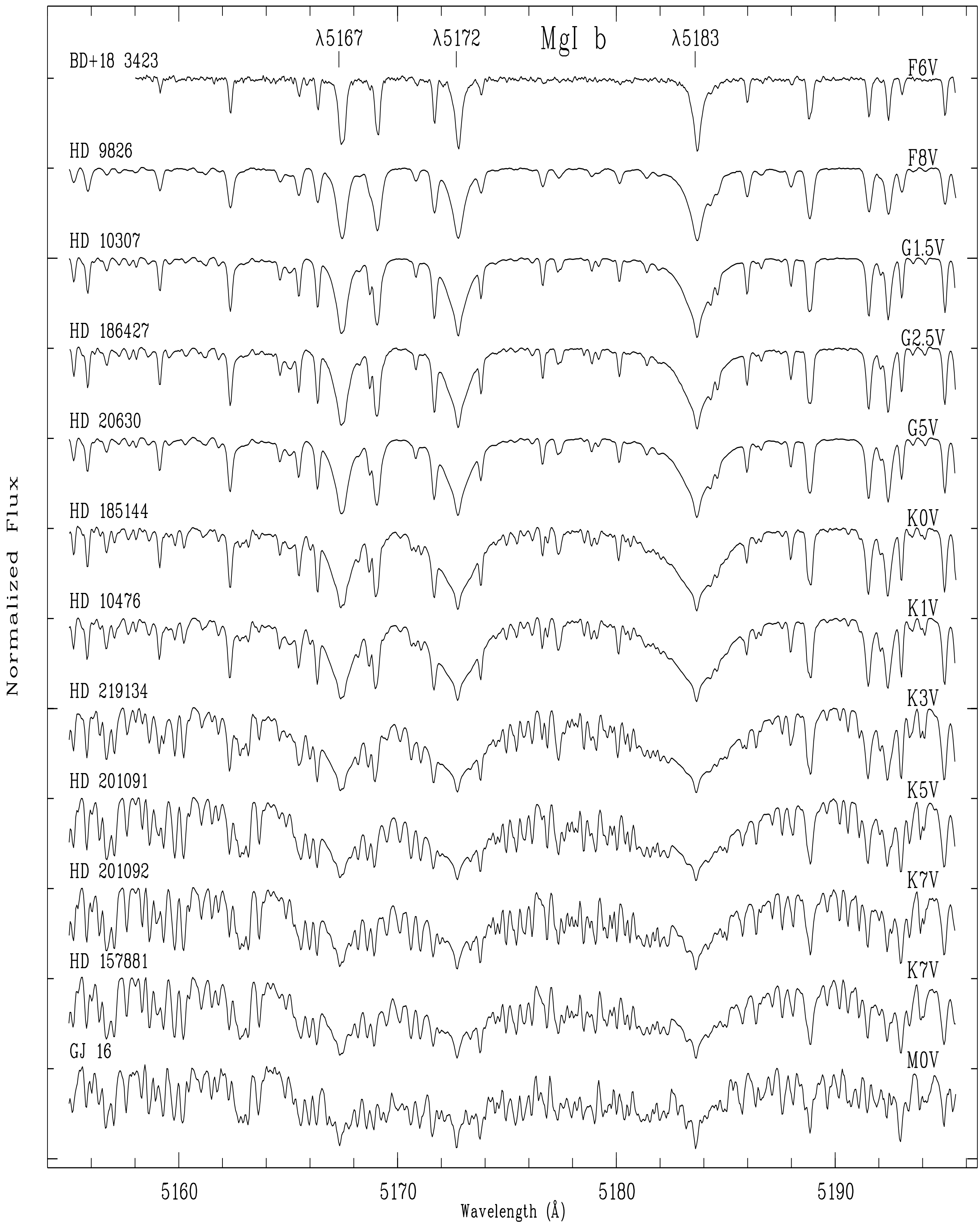

Fig. 3. Spectra in the Mg I b triplet lines region

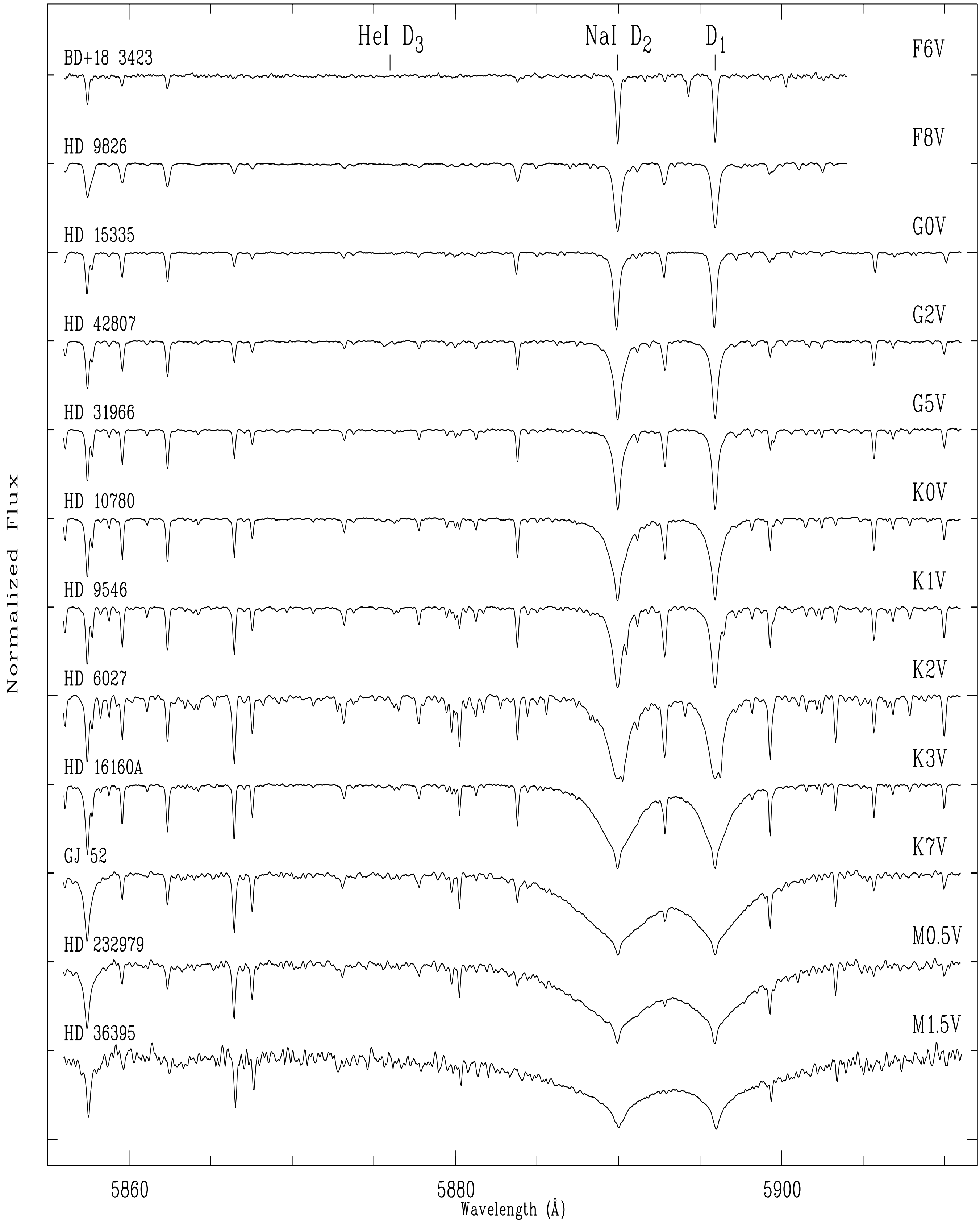

Fig. 4. Spectra in the Na I D_1, D_2 and He I D_3 lines region

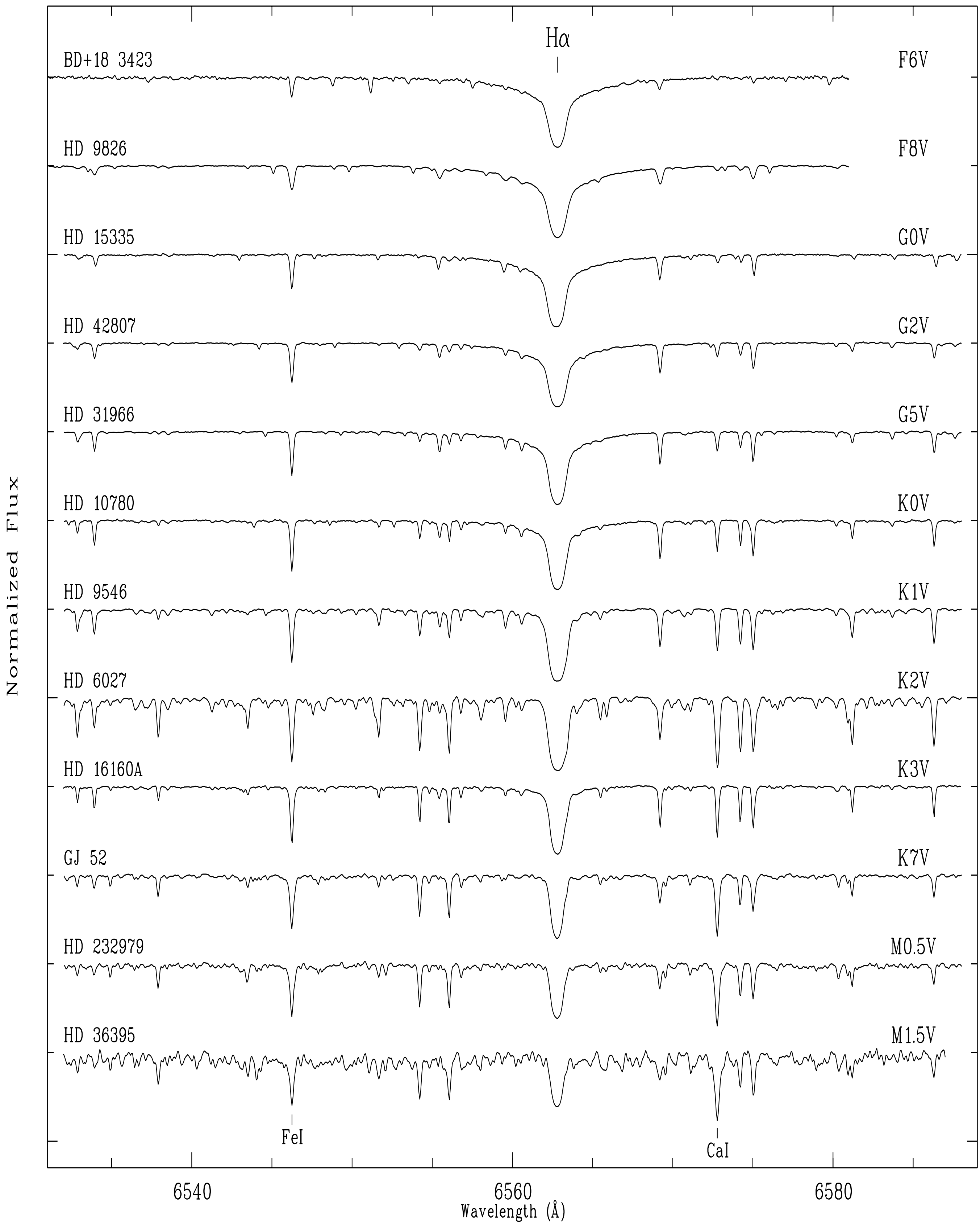

Fig. 5. Spectra in the Hα line region

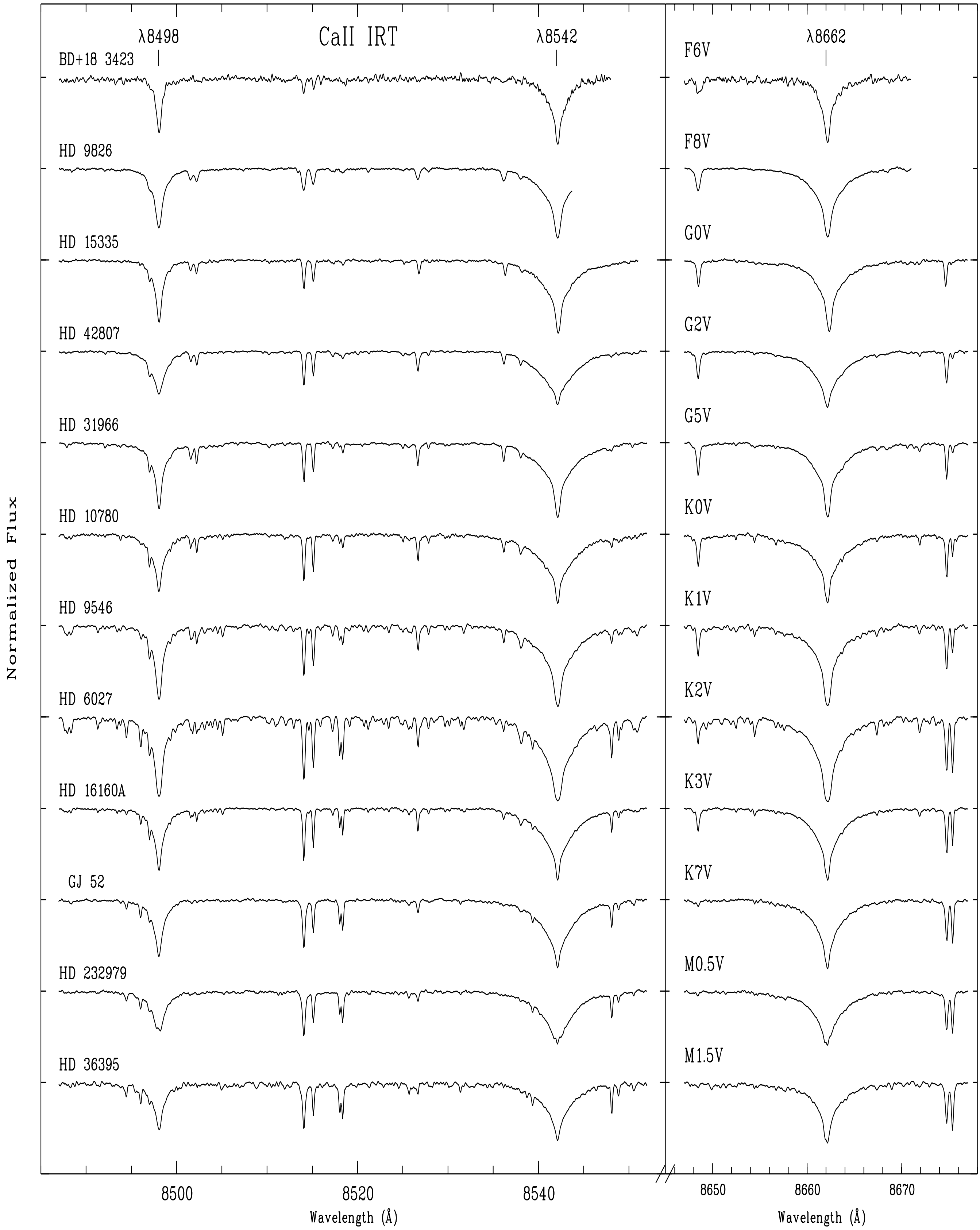

Fig. 6. Spectra in the Ca II IRT λ8498, 8542, 8662 lines region