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An Atlas of the infrared spectral region

II. The late-type stars (G − M)*

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Abstract. This Atlas illustrates the behavior of late type stars (F, G, K and M) in the near infrared 8400 − 8800 Å region with a resolution of about 2 Å. Seventeen figures illustrate the spectral sequence and luminosity classes V, III, Ib and Ia. Four figures illustrate peculiar spectra, namely those of Am stars, composites, weak metal stars and S and C type objects. The complete Atlas is also available as FITS files from the CDS de Strasbourg and other data centers.

Key words: atlases — stars: fundamental parameters — stars late type — infrared: stars

1. Introduction

In a previous paper (Ginestet et al. 1994) we have shown the interest of the near infrared region for the accurate classification of the cooler components of composite spectra. This is due to the fact that the magnitude difference favors the late-type giant or supergiant companions. In that paper we examined in detail the behavior of the MK standards and we found that with the exception of a few (6%), the MK standards can also be used as standards in the near infrared domain (8380 − 8780 Å). We provided a number of classification criteria using the equivalent widths (W_λ) of a number of features (due for instance to FeI, TiI, CaII, blend at 8468, etc ...) plotted against the MK spectral type and luminosity class of the star. We remarked however that it is not enough to apply simply the criteria, but that the whole spectrum has to be examined carefully. This is entirely in line with similar remarks by the authors of the MK system. We thought therefore that it would be worthwhile to reproduce the spectra themselves, which lead quite naturally to the present Atlas.

The present Atlas (Part II) covers the later type stars and is to be taken as a continuation of Part I, which presented the early type stars (Andrillat et al. 1995). Both parts are based on spectra obtained with the same instrument and the same dispersion (33 Å/mm) covering the same spectral interval. It should be added that a few peculiar stars, signaled in the text, have been obtained with the AURELIE spectrometer. We would like to recall that the near infrared has been studied by a number of authors which we would like to mention briefly.

The infrared region has been studied:

- to emphasize the interest it presents for the obtention of luminosity criteria (Merrill 1934; Keenan & Hynek 1945)
- for the classification of later type stars, essentially those of type M (Sharpless 1956; Parsons 1964; Solf 1978; Barbieri et al. 1981; Kirkpatrick et al. 1991; Huang et al. 1994).

Very often the infrared CaII triplet lines alone have been analysed for a classification of the late type stellar components of galaxies (Jones et al. 1984; Carter et al. 1986; Alloin & Bicca 1989; Diaz et al. 1989; Zhou 1991; Mallik 1994).

Two atlases should also be signaled, based upon material obtained on a much lower scale. The first one is by Danks & Dennefeld (1994) and is based upon southern MK standards observed over an extended region (5800 − 10200 Å) at a dispersion of 171 Å/mm and the other one is by Torres-Dodgen & Weaver (1993). The latter covers the region 5800 − 8900 Å at approximately 15 Å resolution.

In what follows we shall describe first the material used and the reduction procedure (for more details see Ginestet et al. 1994) and then the atlas itself and the classification procedure.

2. Observations and reduction procedure

Essentially all spectra reproduced in this Atlas were obtained with the CARELEC spectrograph (Lemaître et al.

* based upon observations carried out at the Observatoire de Haute-Provence (CNRS).

Table 1. MK standard stars

HD	HR	Nom	SP	α 2000 h m s	δ ° ′ ″	V	B-V	R-I
1326			M2 V	00 18 23.3	+44 01 24	8.10	+1.56	
6903	339	81φ Psc	G0 III	01 09 49.2	+19 39 30	5.55	+0.68	
10307	483		G1.5 V	01 41 47.2	+42 36 49	4.96	+0.61	+0.33
10465			M2 Ib	01 43 11.1	+48 31 01	6.90	+2.00	
10494			F5 Ia	01 44 11.5	+61 51 00	7.29	+1.22	
17709	843	17 Per	K5.5 III	02 51 30.8	+35 03 35	4.54	+1.56	+0.95
18391			G0 Ia	02 59 48.7	+57 39 48	6.89	+1.94	
20630	996	96 κ[1] Cet	G5 V	03 19 21.7	+03 22 13	4.83	+0.68	+0.36
23886			A5V	03 49 25.8	+24 14 54	7.96	+0.18	
26630	1303	51 μ Per	G0 Ib	04 14 53.9	+48 24 34	4.16	+0.96	+0.54
27371	1346	54 γ Tau	K0- IIIab	04 19 47.6	+15 37 39	3.65	+0.82	+0.47
27534			F5V	04 21 31.8	+18 25 05	6.74	+0.44	
27836			G1 V	04 24 12.5	+14 45 30	7.62	+0.60	
30652	1543	1 π3 Ori	F6 V	04 49 50.4	+06 57 41	3.19	+0.45	+0.26
38944	2011	31 υ Aur	M0 III	05 51 02.4	+37 18 20	4.74	+1.62	+1.07
52005	2615	41 Gem	K3 Ib	07 00 15.8	+16 04 44	5.69	+1.65	+0.85
52877	2646	22 σ CMa	K7 Ib	07 01 43.1	-27 56 05	3.47	+1.73	+1.00
54719	2697	46 τ Gem	K2 III	07 11 08.4	+ 30 14 43	4.40	+1.26	+0.63
58946	2852	62 ρ Gem	F0V	07 29 06.6	+31 47 04	4.18	+0.32	+0.19
61064	2927	25 Mon	F6 III	07 37 16.7	-04 06 40	5.13	+0.44	
63302	3026	QY Pup	K1 Ia-Iab	07 47 38.5	-15 59 27	6.33	+1.75	
76830	3577		M4 III	08 59 10.7	+18 08 06	6.38	+1.55	
85503	3905	24 μ Leo	K2III	09 52 45.8	+26 00 25	3.88	+1.22	+0.58
87696	3974	21 LMi	A7V	10 07 25.7	+35 14 41	4.48	+0.18	+0.07
109011			K2 V	12 31 18.9	+55 07 08	8.10	+0.94	
109358	4785	8 β CVn	G0 V	12 33 44.5	+41 21 27	4.26	+0.58	+0.31
113139	4931	78 UMa	F2V	13 00 43.7	+56 21 59	4.93	+0.36	+0.21
124752			KO V	14 12 27.1	+67 35 10	8.54	+0.80	
126660	5404	23 θ Boo	F7V	14 25 11.7	+51 51 03	4.05	+0.50	+0.25
160365	6577		F6 III	17 38 57.7	+13 19 45	6.12	+0.56	
161239	6608	84 Her	G2 IIIb	17 43 21.5	+24 19 40	5.71	+0.65	+0.33
193896	7788		G5 IIIa	20 23 00.8	-09 39 17	6.29	+0.91	
201091	8085	61 Cyg A	K5 V	21 06 54.6	+38 44 45	5.21	+1.17	+0.65
201092	8086	61 Cyg B	K7 V	21 06 55.3	+38 44 31	6.04	+1.36	+0.83
206859	8313	9 Peg	G5 Ib	21 44 30.7	+17 21 00	4.33	+1.17	+0.55
206936	8316		M2- Ia	21 43 30.5	+58 46 48	4.08	+2.35	+1.76
208606	8374		G8 Ib	21 55 20.6	+61 32 30	6.15	+1.60	
209750	8414	34 α Aqr	G2 Ib	22 05 47.0	- 00 19 12	2.95	+0.97	+0.49
210745	8465	21ζ Cep	K1.5 Ib	22 10 51.3	+58 12 05	3.35	+1.57	+0.78
216946	8726		K5 Ib	22 56 25.9	+49 44 02	4.97	+1.79	+1.05
219734	8860	8 And	M2 III	23 17 44.7	+49 00 55	4.83	+1.66	+1.26
221861	8952		K0 Ib	23 34 59.0	+71 38 32	5.84	+1.80	
232979			M0.5 V	04 37 41.0	+52 53 38	8.63	+1.42	

Table 2. Stars with spectral peculiarities

HD/BD	HR	Name	SP	α 2000 (h m s)	δ 2000 (° ′ ″)	V	B-V	R-I	*figures*
6582	321	30 μ Cas	G5Vp	01 08 16.3	+54 55 14	5.17	+0.69	+0.42	*20*
19445			sd G5	03 08 26.3	+26 20 35	8.05	+0.46		*20*
27749	1376	63 Tau	A1m	04 23 25.0	+16 46 38	5.64	+0.30	+0.16	*18*
59604			G2III+A2	07 30 56.6	+08 33 08	7.20			*19*
83632			K2III	09 40 34.2	+26 00 17	8.01	+1.39		*20*
92839	4195	VY UMa	C-N5 C_2 4.5	10 45 03.9	+67 24 41	6.00	+2.39	+1.27	*21*
93903	4237	41 Sex	Am	10 50 18.0	-08 53 52	5.79	+0.16	+0.07	*18*
112127			C-R3 III C_2 1.5	12 53 55.6	+26 46 48	6.91	+1.26		*21*
+44°2267			S3 Zr3 Ti1.5	13 21 18.0	+43 57 00	9.74	+1.90		*21*
184759	7441	9 Cyg	G8III+A2V	19 34 50.8	+29 27 47	5.38	+0.55		*19*
187796	7564	χ Cyg	S6+ Zr2 Ti6.5 e	19 50 33.8	+32 54 51	4.23	+1.82	+2.68	*21*

1990) mounted on the 193 cm telescope of the OHP observatory. Nine spectra (Figs. 20 and 21) were obtained with the AURELIE spectrograph (Gillet et al. 1994) mounted on the 152 cm telescope of the OHP. The dispersion of 33 Å/mm is the same in both cases and leads, with the receivers used (CCD Thomson or Tektronix), to a resolution of the order of 2 Å.

The reduction of the observations was made at the OHP with the IHAP program. The images are treated first to eliminate the observational noise (subtraction of an off-set field) and to eliminate the defects of the receiver (division of the spectrum by a flat field given by a tungsten lamp). The spectra were then calibrated in wavelength, using a Ne lamp as calibration source. Next the spectra are straightened and normalised to the continuun, and finally plotted with an HP tracer. Each spectrum is thus an intensity tracing as a function of wavelength, the intensity of the continuun always being set equal to unity.

3. Content of the Atlas

The Atlas presents 36 MK standards distributed on 17 sheets (Figs. 1 to 17) illustrating the spectral type sequence and the luminosities classes. The four following figures illustrate some peculiar spectra: Am stars, composite spectra, metal deficient stars and S and C stars.

All stars are listed in Tables 1 and 2: Table 1 refers to MK standards and Table 2 to stars with spectral particularities. The tables provide the identifications (HD and HR numbers, name), the spectral classification, the equatorial coordinates for equinox 2000.0, the visual magnitude, the $B-V$ and $R-I$ colour indices, and lastly the number of the figures where the spectrum of the star is illustrated.

The data were taken from Hoffleit & Jaschek (1982), Garcia (1989), Keenan & McNeil (1976) or from the SIMBAD data base of the Centre de Données de Strasbourg.

a. MK standards

Nine figures concern the spectral type sequence:

F6-K2 V	F6-K0 III	G0-G8 Ib	F5-M2 Ia
K2-M2 V	K0-M0 III	G8-K5 Ib	
	M0-M4 III	K5-M2 Ib	

Eight figures illustrate the luminosity effects at the following spectral types: F5-6, G0, G2, G5, K0, K2, K5, M2. The F-type spectra in the figures permit to make the link with Part I of the Atlas and are used also for comparison with the Am stars.

In Table 3 we list the stars, ordered by spectral type and luminosity class, so as to permit a quick overview of our coverage. The stars are specified by their HD number.

All MK standards are taken from the list of Garcia (1989) which integrates the different lists given by Morgan and Keenan and their collaborators. The only exception is HD 61064 (F6III) which figures only in the list of Morgan & Abt (1972).

An identification of the principal lines and features visible on our spectra was made with the help of the solar spectrum (Moore et al. 1966) and is given in Figs. 1 (dwarfs) and 9 (supergiants).

b. Peculiar stars

- Am stars: Fig. 18.

Even if these stars are of early type, we have included them in this part of the Atlas because very often there do exist confusions between the Am stars and the stars with composite spectra when classified in the 3800 – 4700 Å region.

Table 3. MK standard stars ordered by spectral type and luminosity class (identified by n°HD and illustrated in Figs. 1 to 17)

Spectre	V	III	Ib	Ia
F5				10494
F6	30652	61064 160365		
G0	109358	6903	26630	18391
G1	27836			
G2	10307 (G1.5)	161239	209750	
G5	20630	193896	206859	
G8			208606	
K0	124752	27371	221861 (G9)	
K1				63302 (K1Ia-Iab)
K2	109011	54719	210745 (K1.5)	
K3			52005	
K5	201091	17709 (K5.5)	216946	
K7	201092		52877	
M0	232979 (M0.5)	38944		
M2	1326	219734	10465	206936
M4		76830		

Their presence in the Atlas shows that even in the near infrared region there exists resemblance between an Am object with a late metallic line type and a composite spectrum of an early A type dwarf and an early G type giant, like in the case of HD 27749, Am, and HD 59604, G2III+A2. The difference appears in the TiI lines 8426 Å and 8435 Å which are very sharp in stars with composite spectra. Also the appearance of the blend 8468 Å permits a separation between the two types of objects.
The three characteristics of the Am stars in our spectral region are:

- the OI 8446 Å line is generally narrow and deep,
- the FeI 8688 Å line is also generally narrow and deep,
- the CaII lines have a very particular aspect, because of their narrowness and the blend with Paschen lines.

In Fig. 18 we show the spectra of two Am stars of very different metallicities: HD 93903 has Paschen lines similar to those of an A4-5 star, whereas the metallic lines (for instance FeI 8688 Å) correspond to an early F type; HD 27749 presents Paschen lines similar to those of an A7 star, whereas the metallic lines correspond to a late F type.

- Stars with composite spectra: Fig. 19.
The composite spectra are produced by the superposition of the spectrum of an early type dwarf of type B or A and that of a late G, K and M giant or supergiant. In the 3800 – 4800 Å region generally the earlier type spectrum predominates, whereas in the region here reproduced, the spectrum of the late companion is little perturbed by the early type (Ginestet et al. 1994).
Figure 19 presents the spectra of the composites HD 59604 – 5 and HD 184759 – 60:
In HD 59604 – 5 the hydrogen lines P12 and P14, as well as the OI 8446 Å lines show the presence of a hot object in the system. It should be noticed that the P12 and P14 lines are very weakened because they seem to correspond in intensity to an F2 object, whereas the hotter component is really of type A2. The metallic lines (CaII, FeI, TiI) permit to determine the type of the cool star as being G2III.
In the case of HD 184759 – 60, the P12 and P14 lines of the hotter companion are even weaker than in the previous case, they seem to correspond to an F5 star whereas it is really of type A. The metallic lines permit to classify the cool star as being G8III.

- Weak lined stars: Fig. 20.
Figure 20 illustrates the spectra of three metal weak stars: one dwarf HD 6582, μ Cas, one subdwarf HD 19445 and one giant HD 83632. These spectra are compared to those of two MK standards of type G5V and K2III.
In the spectrum of HD 19445 the CaII lines are very weak and the metallic lines have practically disappeared, except FeI 8688 Å which is faintly visible. The classification attributed in the blue, G5 is difficult to justify a priori on the basis of the near infrared.
HD 83632 appears at a first glance to be a dwarf, but the depth of CaII is larger than in dwarfs and moreover the weakness of FeI 8688 Å does not correspond at all to a dwarf.

- S and C stars: Fig. 21.
Figure 21 shows the spectra of four S and C stars: BD +44° 2267 and HD 112127 may be classified as giant K stars; ZrO bands are weakly noticeable in their spectrum. HD 187796 (χ Cyg) presents the CaII triplet in emission and enhanced absorptions of TiO whereas HD 92839 is strongly marked by the rotation bands of the red system of CN. The search of the molecular bands was made with the help of Pearse & Gaydon (1963) for CN, Solf (1978), Huang et al. (1994) for TiO, Davis & Hammer (1981) for ZrO.

4. Classification criteria

The spectral region is dominated by the CaII triplet lines at 8498 Å, 8542 Å and 8662 Å. The Paschen lines disappear at G0 for class V and III and at G2 for supergiants. Many lines of FeI and TiI become visible and strengthen with advancing spectral type. We quote specially the FeI lines at 8621 Å, 8688 Å and 8514 Å and the TiI lines at 8426 Å, 8435 Å and 8518 Å. Notice also the appearance of molecular bands of TiO in the coolest stars. All these features can be used for the determination of the spectral type.

Luminosity effects are evident in the line depth. Lines become wider and deeper with higher luminosity (see Figs. 4 to 17). This effect is specially noticeable for the CaII triplet lines. Another good luminosity criterion is the behavior of the blend at 8468 Å (TiI and FeI).

We have provided in Figs. 22 to 27 the curves relating measured equivalent widths to spectral type and luminosity class. These curves are averages based on the measurements from many spectra. The measurements itself were given in Ginestet et al. (1994). The purpose of including these figures is twofold. In first place the figures illustrate very well how the different criteria behave in different spectral types and luminosity classes, so that no lengthy explanation regarding the usefulness of each criterion is needed. In second place the figures illustrate that the equivalent widths can be used to refine the classifications based upon the visual inspection of spectra.

From the Atlas it is clear that it should be possible to obtain from the infrared spectral region classifications which are as precise as those obtained from the blue region. This is a point of real interest for the classification of all red and faint objects.

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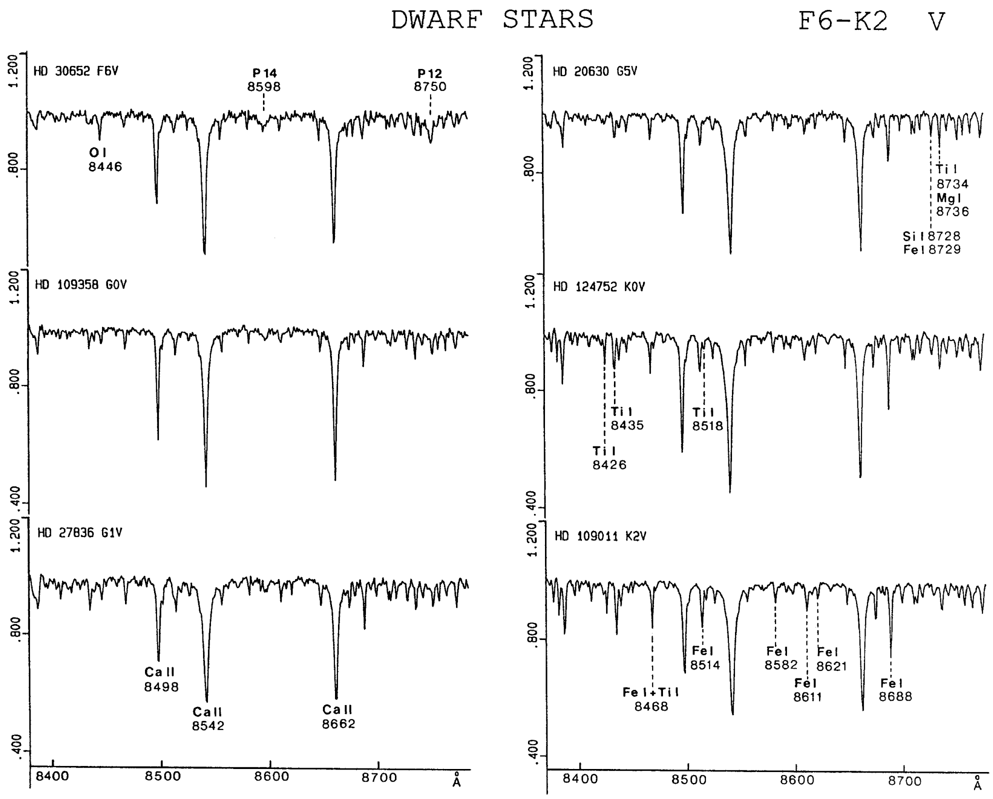
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P12 8750
O I 8446
Ca II 8498
Ca II 8542
Ca II 8662
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Mg I 8736
Si I 8728
Fe I 8729
Ti I 8435
Ti I 8426
Ti I 8518
Fe I 8514
Fe I + Ti I 8468
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Fe I 8688
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.800
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8400
8500
8600
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Å

Fig. 1.

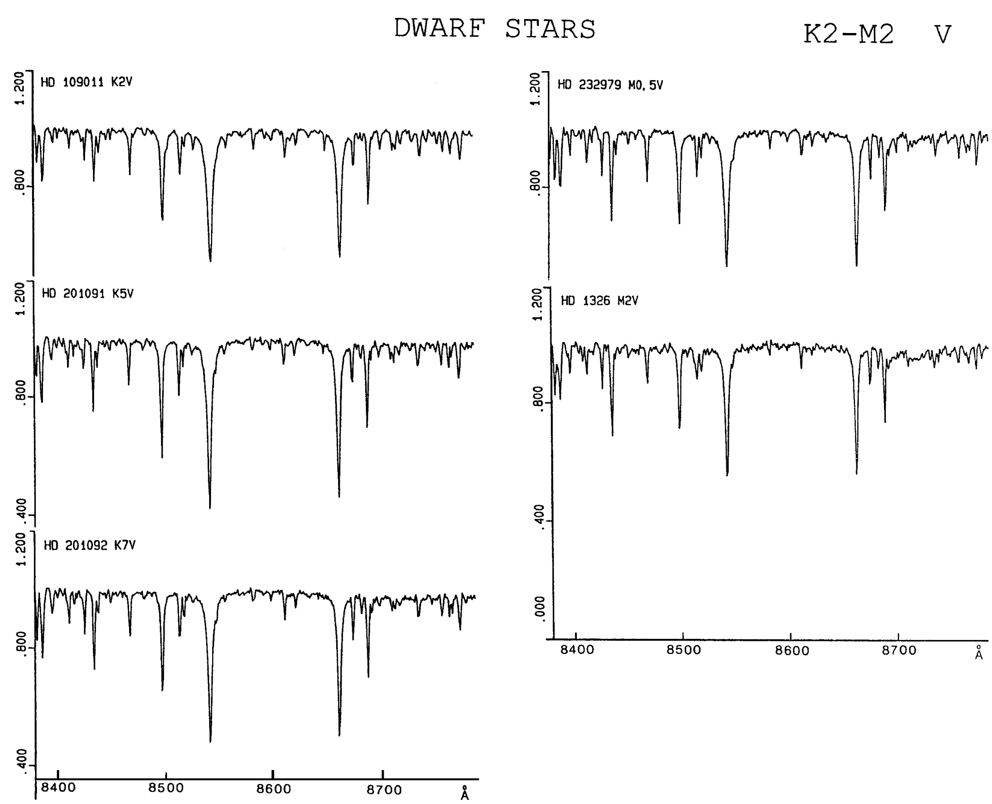
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Fig. 2.

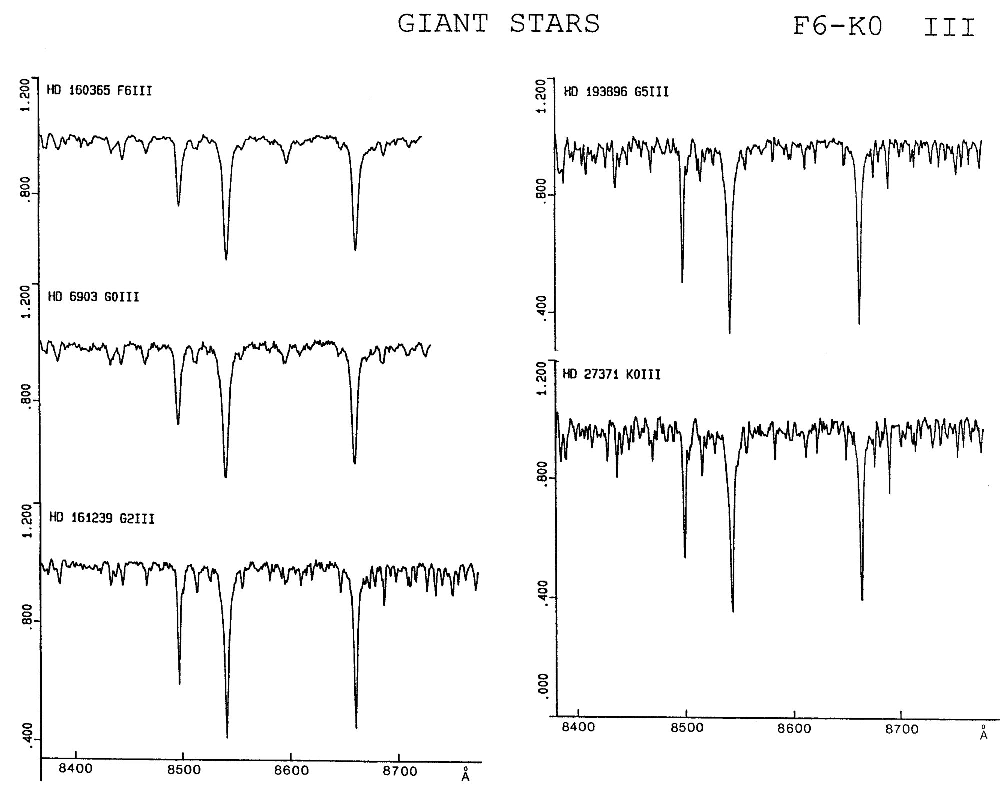
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Fig. 3.

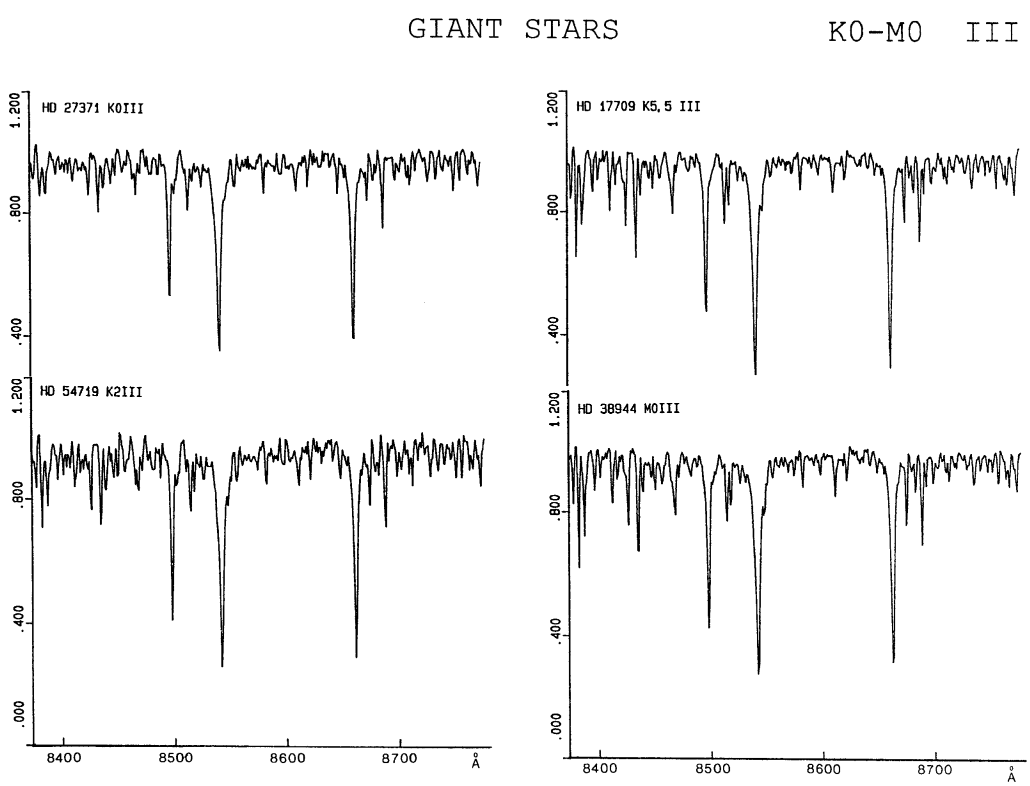
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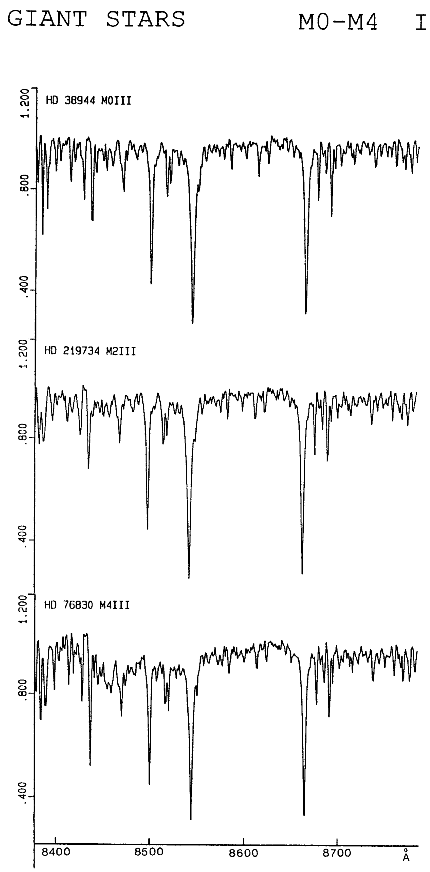
Fig. 4.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8600
8700
Å

Fig. 5.

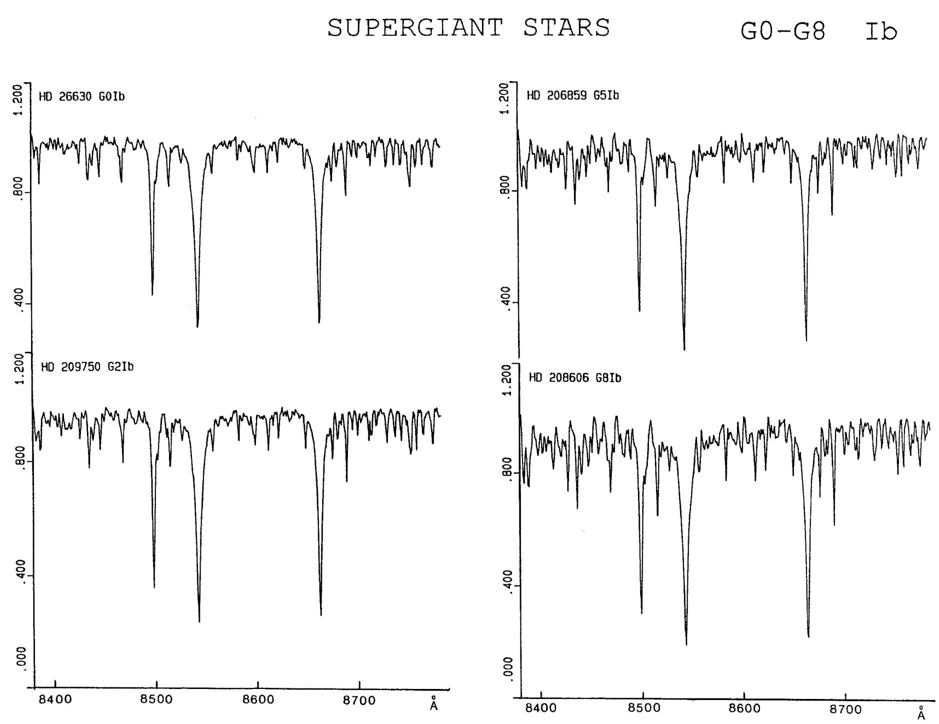
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Fig. 6.

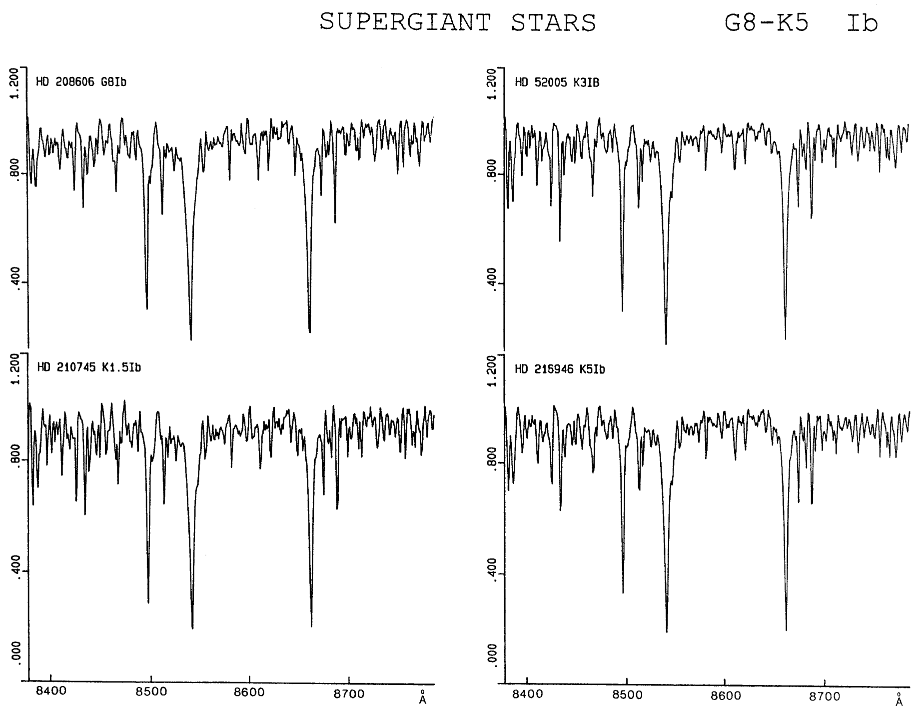
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Fig. 7.

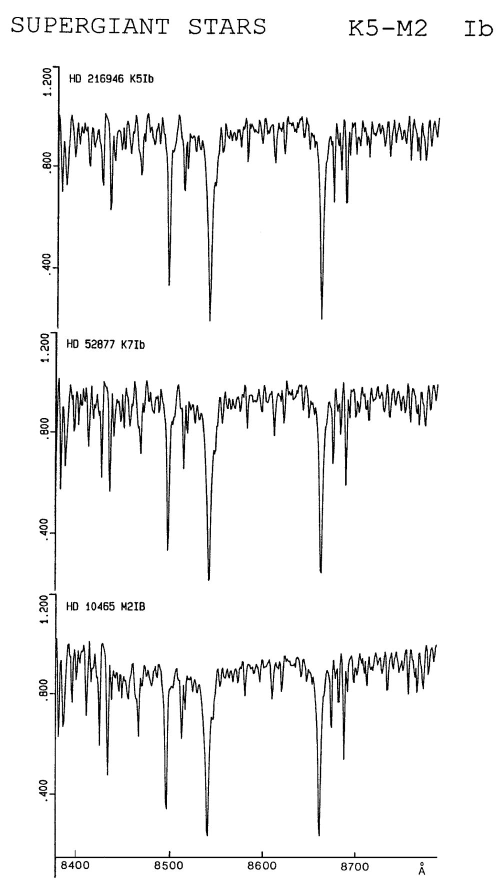
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Fig. 8.

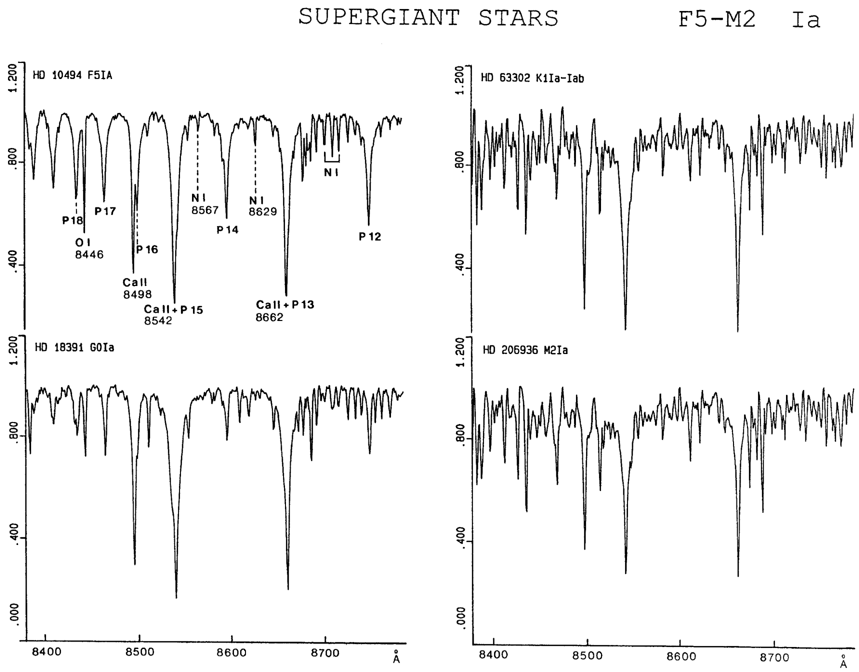

Fig. 9.

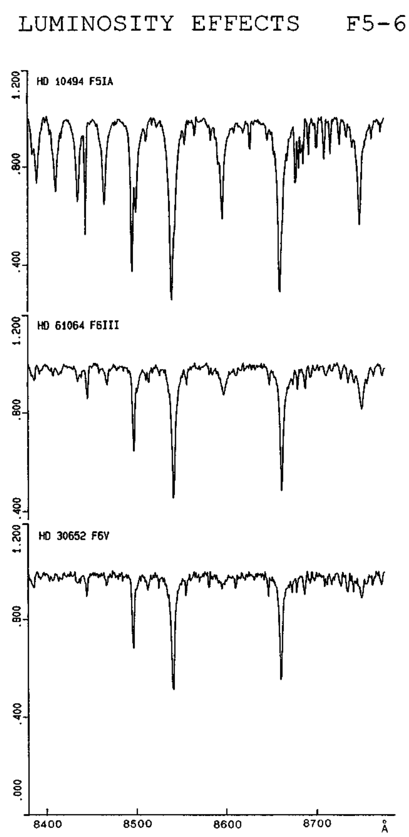

Fig. 10.

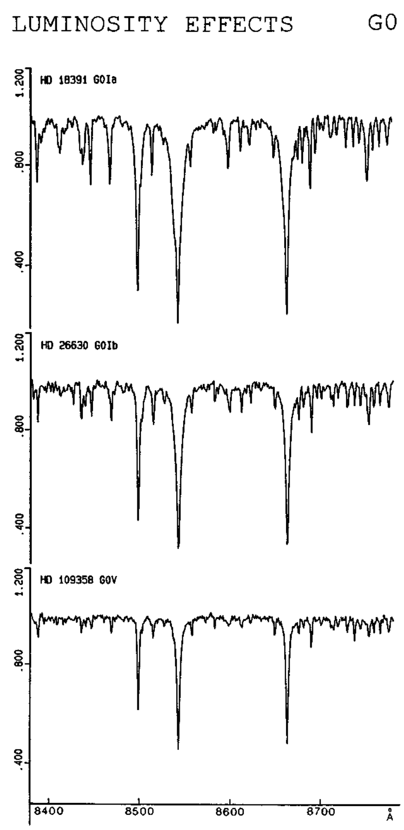

Fig. 11.

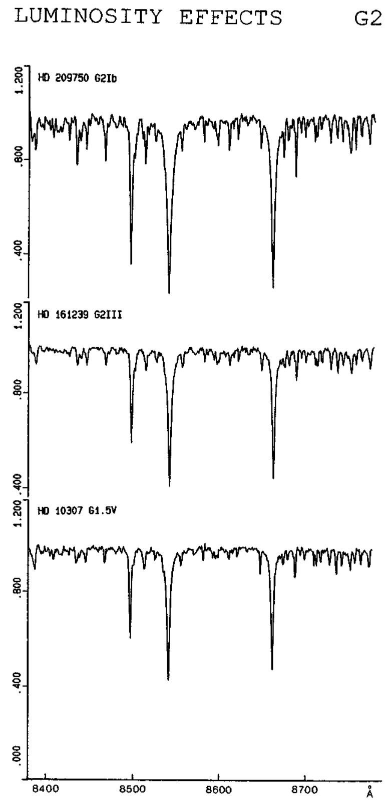

Fig. 12.

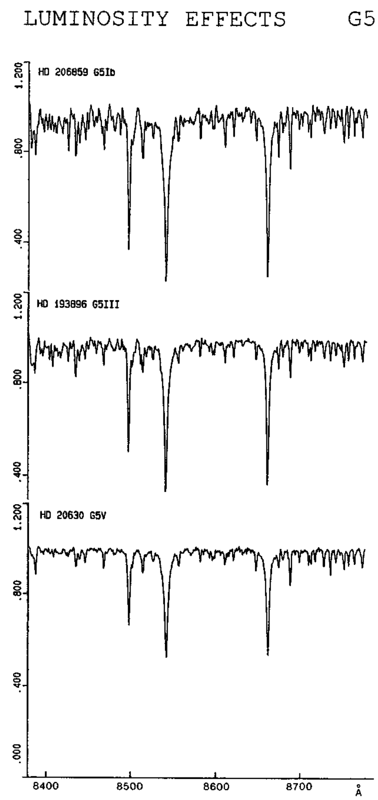

Fig. 13.

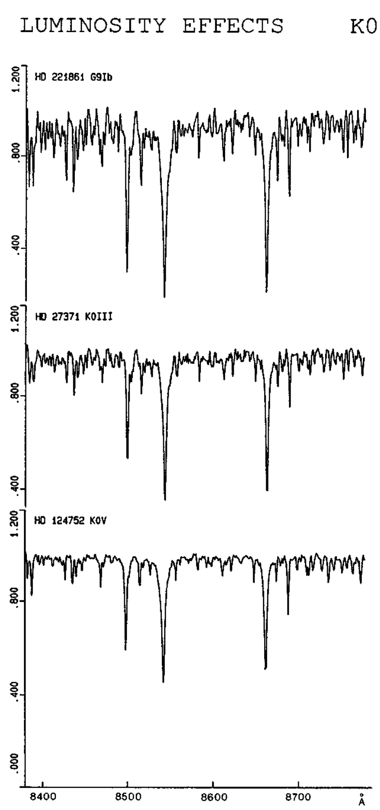

Fig. 14.

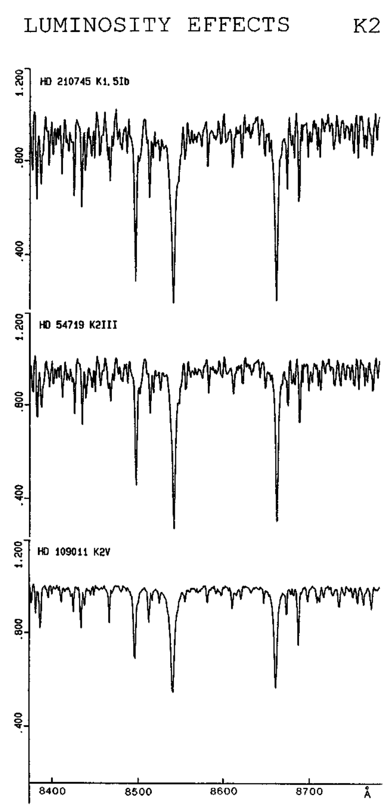

Fig. 15.

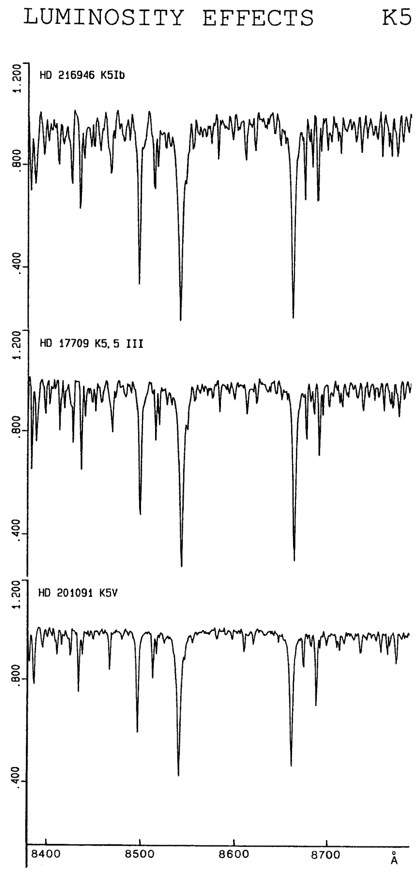
LUMINOSITY EFFECTS K5
HD 216946 K5Ib
HD 17709 K5.5 III
HD 201091 K5V
1.200
.800
.400
8400
8500
8600
8700
Å

Fig. 16.

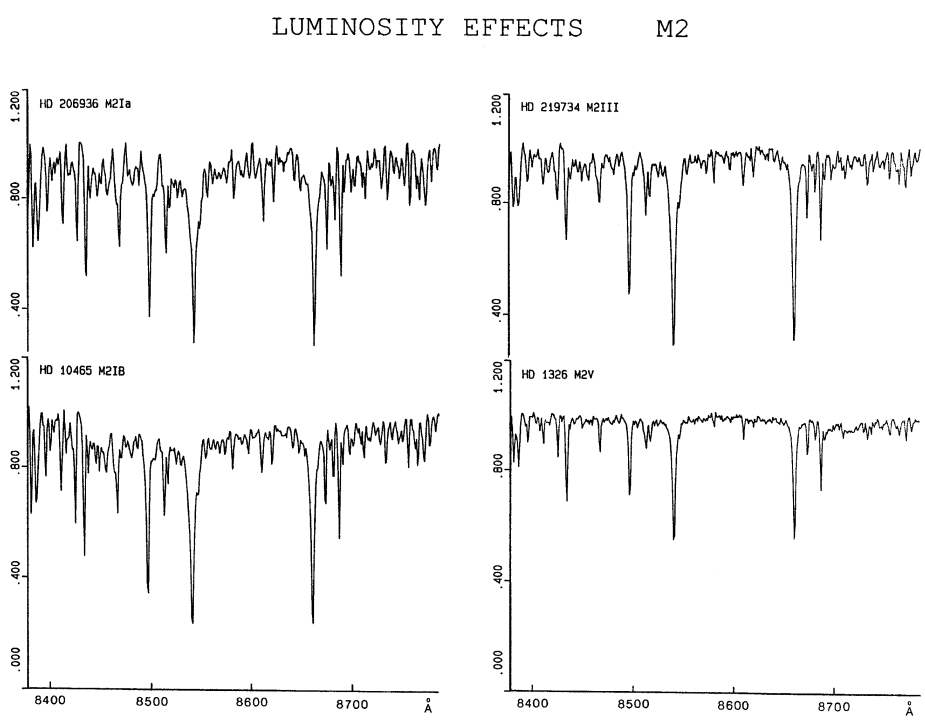
LUMINOSITY EFFECTS M2
HD 206936 M2Ia
HD 10465 M2IB
HD 219734 M2III
HD 1326 M2V
1.200
.800
.400
.000
8400
8500
8600
8700
Å

Fig. 17.

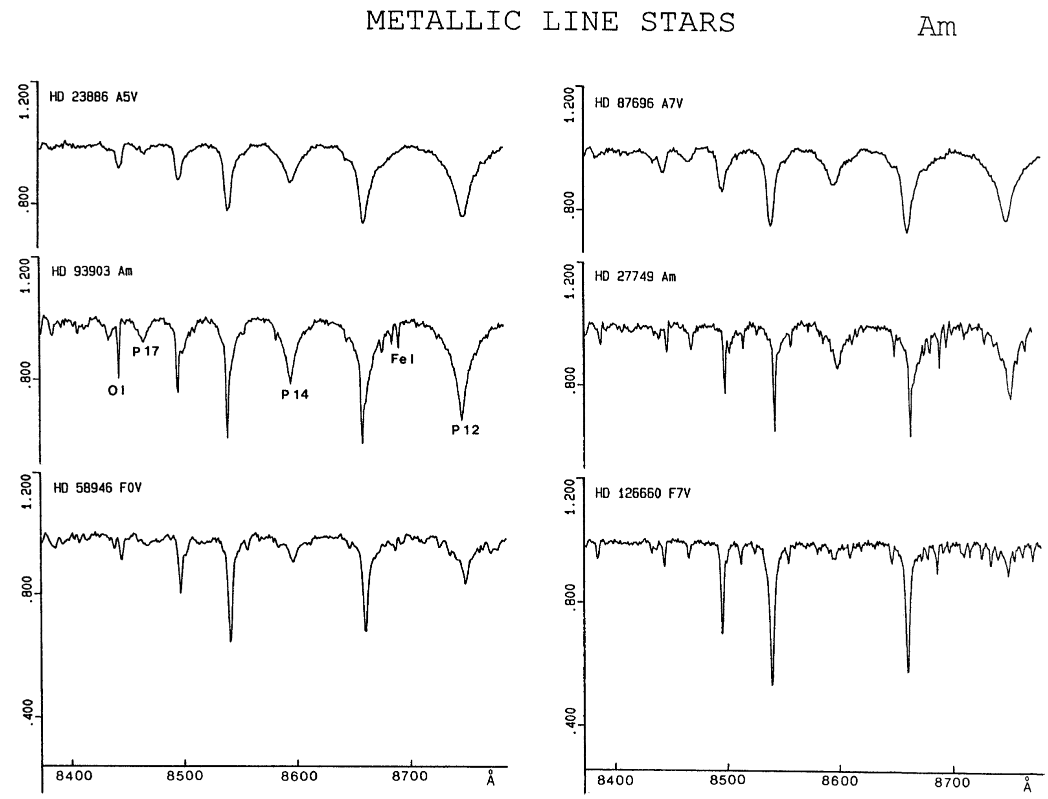
METALLIC LINE STARS
Am
HD 23886 A5V
HD 87696 A7V
HD 93903 Am
HD 27749 Am
HD 58946 F0V
HD 126660 F7V
O I
P 17
P 14
Fe I
P 12
1.200
.800
.400
8400
8500
8600
8700
Å

Fig. 18.

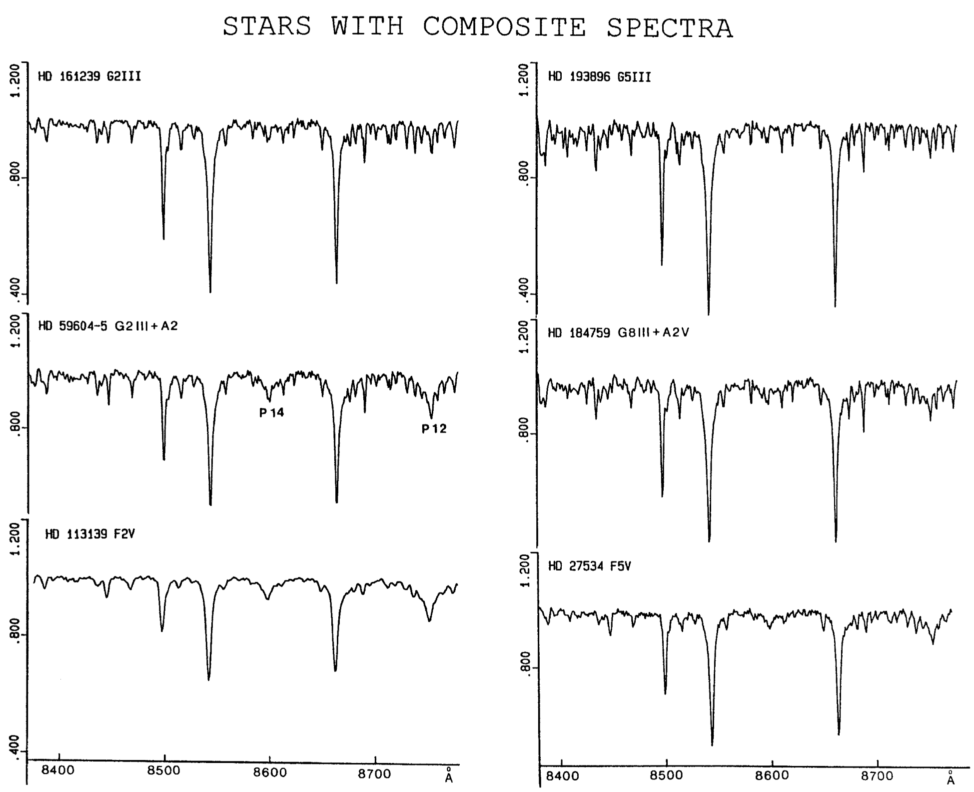
STARS WITH COMPOSITE SPECTRA
HD 161239 G2III
HD 193896 G5III
HD 59604-5 G2 III + A2
HD 184759 G8 III + A2V
HD 113139 F2V
HD 27534 F5V
P 14
P 12
1.200
.800
.400
8400
8500
8600
8700
Å

Fig. 19.

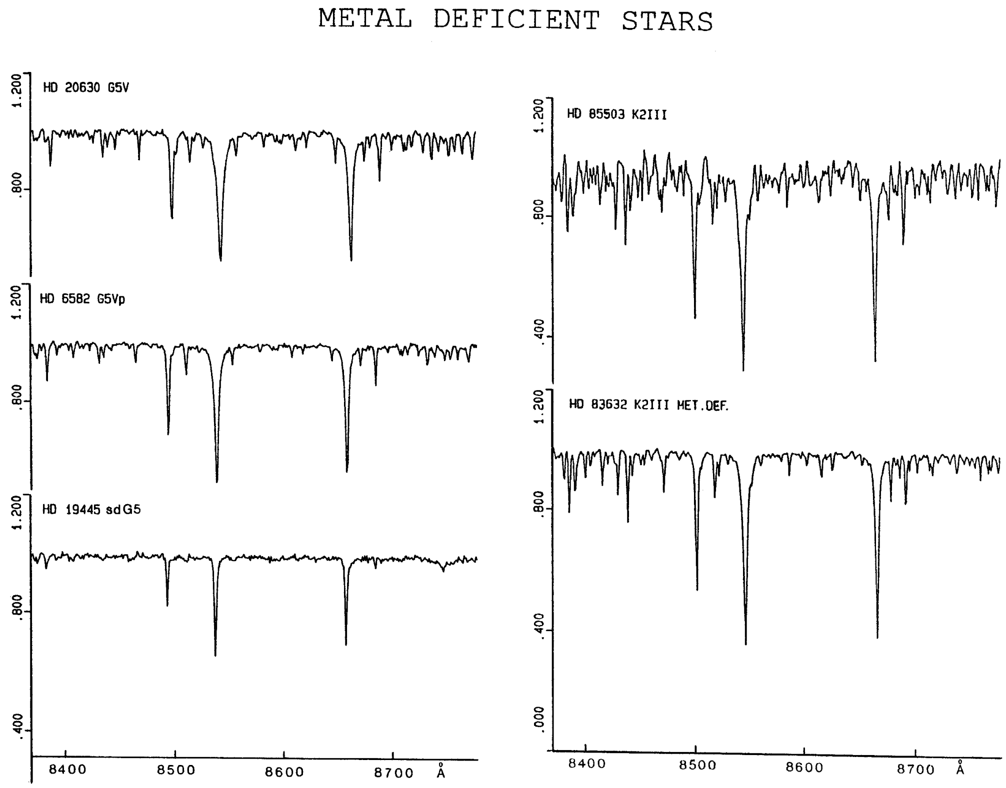
METAL DEFICIENT STARS
HD 20630 G5V
HD 6582 G5Vp
HD 19445 sdG5
HD 85503 K2III
HD 83632 K2III MET.DEF.
1.200
.800
.400
.000
8400
8500
8600
8700 Å

Fig. 20.

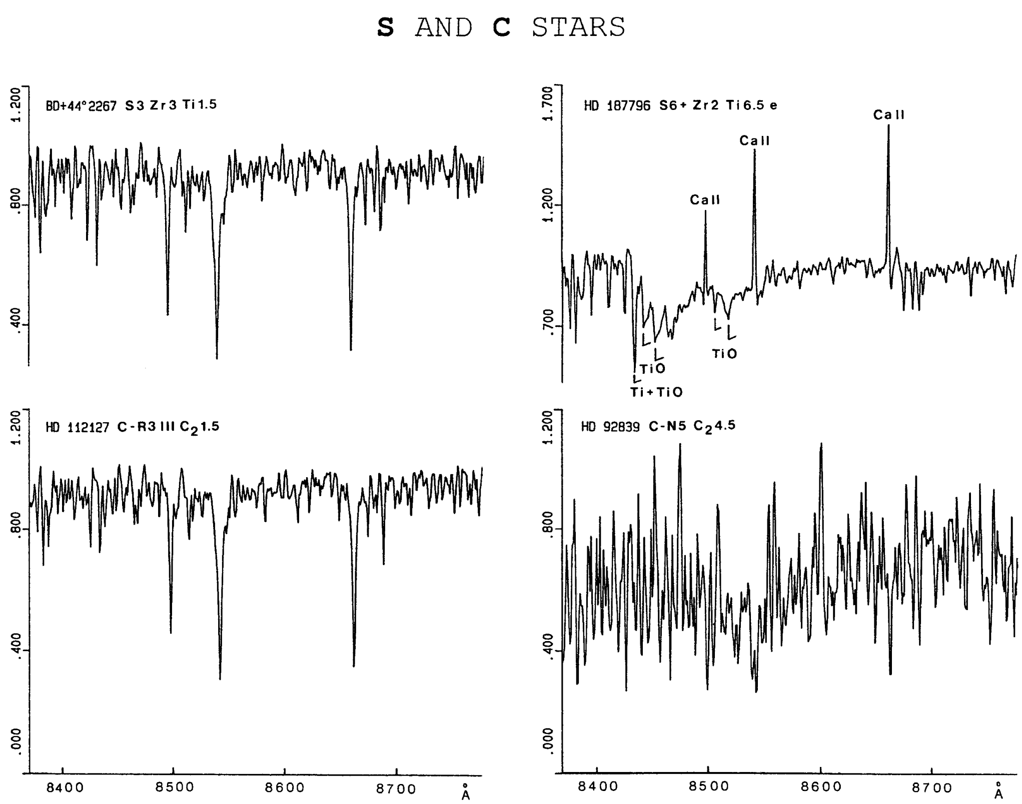
S AND C STARS
BD+44°2267 S3 Zr3 Ti1.5
HD 187796 S6+ Zr2 Ti6.5 e
Ca II
Ca II
Ca II
TiO
TiO
Ti+TiO
HD 112127 C-R3 III C2 1.5
HD 92839 C-N5 C2 4.5
1.700
1.200
.800
.700
.400
.000
8400
8500
8600
8700
Å

Fig. 21.

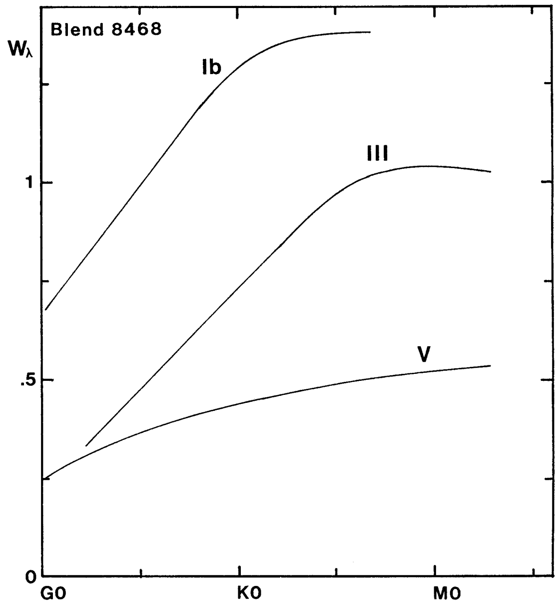

Fig. 22. The equivalent width (in Angström units) of the blend 8468 line as a function of spectral type and luminosity class

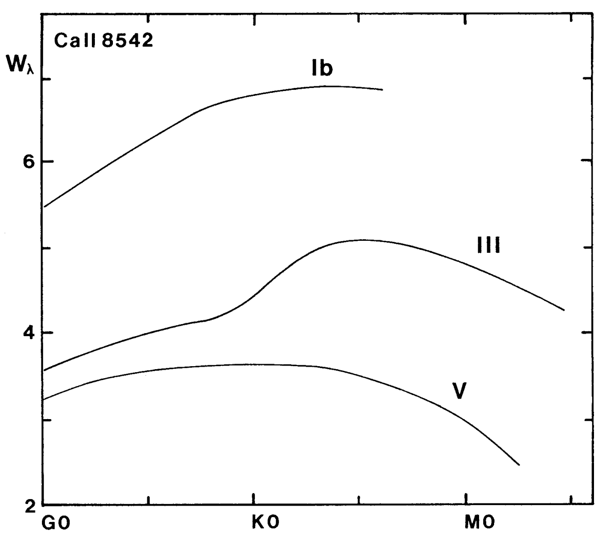

Fig. 23. The equivalent width (in Angström units) of the CaII 8542 line as a function of spectral type and luminosity class

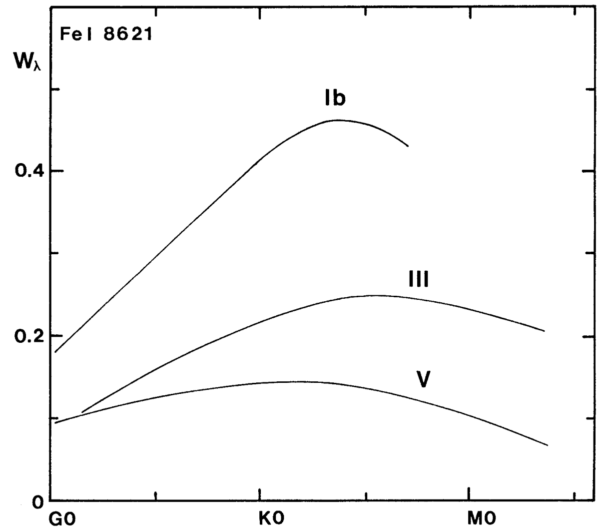

Fig. 24. The equivalent width (in Angström units) of the FeI 8621 line as a function of spectral type and luminosity class

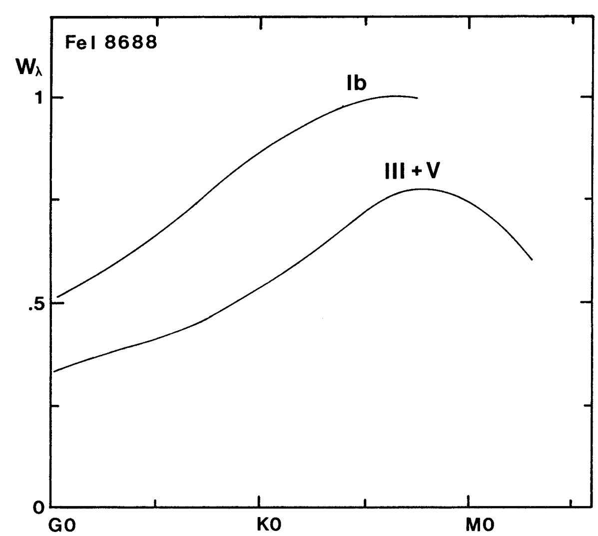

Fig. 25. The equivalent width (in Angström units) of the FeI 8688 line as a function of spectral type and luminosity class

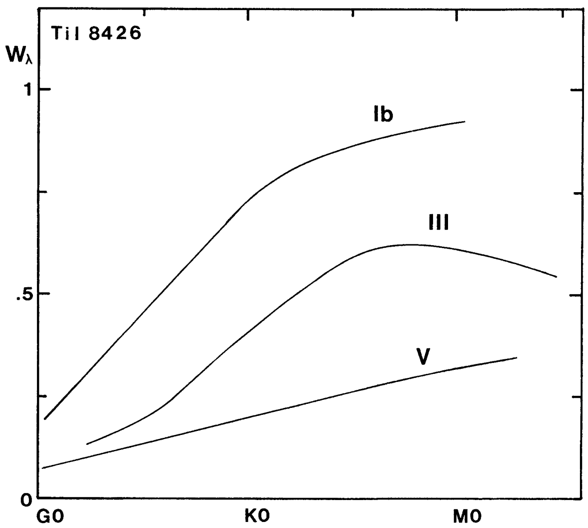

Fig. 26. The equivalent width (in Angström units) of the TiI 8426 line as a function of spectral type and luminosity class

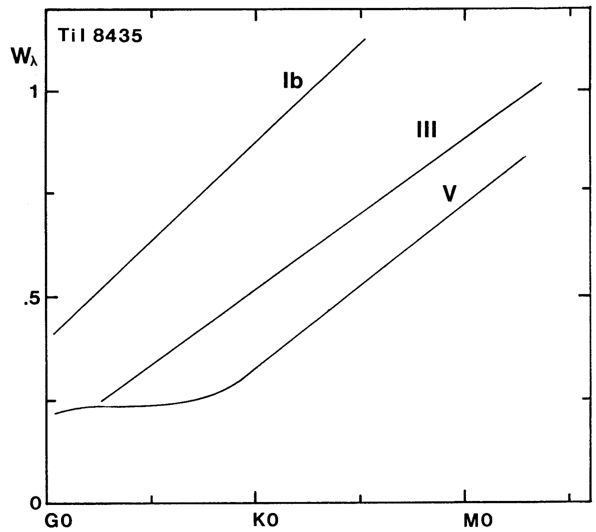

Fig. 27. The equivalent width (in Angström units) of the TiI 8435 line as a function of spectral type and luminosity class