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Spectra of late type stars from 4800 to 9000 Å*

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Abstract. — We present optical spectra of 21 stars from 4800 to 8920 Å, covering essentially the late spectral types, G, K, M and the luminosity classes I and III. Half of the stars are super metal rich (SMR) ones. The spectra were obtained at a resolution of 1.25 Å using the Aurelie spectrograph, equipped with a linear array CCD-like detector, attached to the OHP 1.52 m telescope. Also presented are the spectra of 7 stars, covering the region 5000−9783 Å at a resolution of 8.5 Å , observed at the CFHT with the Herzberg spectrograph. The spectral types are F, G, K, M and the luminosity classes III and V. Five stars are SMR. These spectra have been obtained with the aim of extending existing libraries used for population synthesis purposes. The inclusion of SMR stars in a stellar library dedicated to the study of stellar populations in the central part of galaxies is crucial as abundance gradients have been observed in the optical range.

Key words: stars: fundamental parameters — stars: late type — stars: abundances — stars: supergiants — atlases

1. Introduction

Spectral synthesis of the stellar population of galaxies requires homogeneous and complete stellar libraries. Several such libraries are available and used for this purpose, however part of them are of poor spectral resolution and they usually are restricted to solar abundance stars. Super metal rich (SMR) stars are, in particular, very important when synthetizing the stellar populations in the nuclear regions of galaxies.

There are several published stellar libraries covering the optical range and extending in the near infrared. We briefly review the more widely used. Gunn & Stryker (1983), with a library of 175 stars between 3130 and 10800 Å at a spectral resolution of 20/40 Å, cover all spectral types and the I, III and V luminosity classes. Jacoby et al. (1984) present an atlas of 171 stars of all spectral types and luminosity classes. The wavelength range is smaller, 3510−7427 Å but the spectral resolution is much higher, 4.5 Å. Pickles (1985) observed, between 3600 and 10000 Å, 200 stars assembled in 48 standard spectral groups. They cover all spectral types (except O) and the III and V luminosity classes. Some SMR and metal-weak stars are included. The spectral resolution is $\simeq$ 15 Å but whenever Pickles was lacking data, mainly in the near infrared, he includes the Vilnius Standard Spectra library (Straižys & Sviderskiene 1972) whose resolution can be as low as 50 Å. The Pickles & van der Kruit (1990) library combines data from Pickles (1985), Jacoby et al. (1984) and a number of SMR G and K giant stars from NGC 6522. The final library is defined on a grid of 6 Å per pixel between 3000−10000 Å. The stellar library of Kirkpatrick et al. (1991) has 39 stars, between 6300 and 9000 Å, of spectral types K and M and luminosity classes III and V. The resolution is 18 Å for dwarfs and 8 Å for giants. Silva & Cornell (1992) display 72 groups of stars of all spectral types and luminosity classes, over the 3510−8930 Å wavelength range at 11 Å resolution. Here again some SMR and metal-weak stars are included. Torres-Dodgen et al. (1993) present spectra of O to M stars, luminosity classes Ib, III and V in the wavelength range 5800−8900 Å at 15 Å resolution. The atlas of Danks & Dennefeld (1994) has 126 MK standards, between 5800 and 10200 Å, of all spectral types and 3 luminosity classes (I, III and V) at a resolution of 4.3 Å.

Gunn et al., Kirkpatrick et al., Danks et al. do not have any SMR star in their libraries and no atmospheric correction is performed. Also, except for Jacoby et al. and Danks & Dennefeld which have a resolution of approximately 4.5 Å, the spectral resolution is quite low. Pickles has a few SMR stars but lacks supergiants. Silva & Cornell do not correct for the atmospheric absorption,

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*Based on observations collected at the Canadian-French-Hawaiian Telescope, Hawaii, and the Observatoire de Haute-Provence, France leaving cuts in the spectra where it stands. This is a real problem when one wants to measure the equivalents widths of lines in the whole spectrum. In particular, the TiO bands found in late type stars near the O_2 A and B bands are quite affected.

Since we are involved in the study of stellar populations in the central part of galaxies and particularly in Active Galactic Nuclei, we are interested in the 5000–10000 Å range where the underlying absorption spectrum is more likely to appear in contrast to any emission. Therefore, a stellar library with a good sampling of G, K and M stars is needed as those spectral types most contribute to the total flux in this wavelength range. Moreover, the inclusion of SMR stars in such a stellar library is crucial as abundance gradients have been observed in the optical range with overabundances as high as a factor 5 compared to the solar vicinity in the central part of galaxies (Cayrel de Strobel 1991; Vila-Costas & Edmunds 1992; Davidge 1992; Delisle & Hardy 1992).

Therefore, in view of the existing libraries and the boundary of our problems, we observed cool stars, with a great proportion of SMR, in the optical and near infrared range, i.e. 5000–9000 Å, at a medium resolution. The observational data and reduction are reported in the next section. The libraries are presented in Sect. 3 with comments on the behaviour of some prominent features.

2. Observations and data reduction

The observations were obtained on two telescopes equipped with different instrumentations.

The largest part of our star sample was observed in June 1994, at the Observatoire de Haute Provence, France, with the Aurelie spectrograph attached to the 1.52 m telescope. The detector is a double linear array TH7832 of 2036 photodiodes (Gillet et al. 1994). The entrance aperture is a fixed 3″ diameter circular one. Grating 4, with 300 lines/mm, gives a spectral coverage of 880 Å (0.43 Å per pixel) thus covering the 4800–8920 Å range in 6 separate observations. The achieved spectral resolution is 1.25 Å. Flat fields were taken with an internal tungstene lamp at same wavelength and similar counts level as the science frames. No sky observation was performed, as for $m \leq 12$ stars, read out noise overcomes the sky level. Thorium/argon lamp spectra were taken frequently during the nights to provide wavelength calibration. The reproductibility of the lamp spectra was really good. Table 1 gives the central wavelength and the spectral coverage of each segment[1]. Not all nights were photometric; the seeing was always less than or of the order of the aperture.

The remaining of the sample was obtained in January 1990, at the CFHT, Hawaii, during the course of a run mainly dedicated to the study of the central part of active galaxies. The Herzberg long slit spectrograph was equipped with a 516×516 pixels PHX CCD camera (spatial resolution along the slit of 0.57″ per pixel). The 300 lines/mm grating, with a projected slit width of 1.2″ on the sky gives a spectral resolution of 8.5 Å with a pixel sampling of 3.3 Å. A wavelength coverage 5000–9780 Å is obtained in 3 separate overlapping observations. Flat fields were taken with an internal tungstene lamp and on the dome. Some sky flats were observed as well. Wavelength calibration was provided by observations of iron/argon lamps before and after each star exposure. The slit was always set parallel to the parallactic angle. Seeing ranged between 1″ and 1.5″.

Table 1. OHP spectrum composition

	$\lambda_{\mathrm{central(\AA)}}$ (Å)	total coverage (Å)
1st	5240	4800–5680
2nd	5970	5530–6410
3rd	6700	6240–7140
4th	7430	6990–7870
5th	8160	7720–8600
6th	8890	8450–9330

All spectra were reduced using the ESO-MIDAS package. After removal of bias and dark current, frames were flat fielded. Due to an extreme sensitivity of the OHP chip to the temperature, flux instabilities appear in the first 200 pixels (Gillet et al. 1994). Therefore these pixels were dropped out in all OHP frames, leaving an overlap of about 70 Å between adjacent spectra. Wavelength calibration was performed; this was done row by row for the 2D CFHT frames. During calibration the spectra were rebinned to 0.43 Å and 3.3 Å for OHP and CFHT respectively.

Atmospheric extinction and instrument sensitivity corrections were applied to all spectra. Wavelength dependent extinction curves provided by the observatories were used (CFHT User's manual; M.P. Veron, private communication for the OHP). Flux calibration was performed in each wavelength range using absolute energy distribution of standard stars observed in the same way as the program stars throughout the nights. Vega (Tüg et al. 1977) and secondary standard stars (Glushneva et al. 1992) were observed at OHP. Tüg et al. data are poorly determined in the Paschen area where the Glushevna standards were used instead. At the CFHT, spectra of BD+8 2015 (Stone 1977), HD 84937 and HD 19445 (Oke & Gunn 1983) were taken. Response of the 2D detector was found quite uniform along the slit, so an average calibration curve was derived to be applied to each row individually. A weighted mean calibration curve for each domain of each night was built.

[1] Due to low sensitivity of the spectrograph in the far red, the 6th part was used only till 8920 Å.

Compression of CFHT frames to a one-dimension spectrum was made by summing all rows with a signal higher than 10 times the sky background. Typical count numbers are 10^4 to 1.5 10^4 in rows of maximum flux and 30 to 40 in the sky rows.

Finally, due to the number of segments and as nights were not photometric, median flux ratio in the overlapping region was used to normalize one segment to the next one. Thus only relative flux calibration is achieved, being the form of the spectra correct. For both runs, the individual spectra merged smoothly in the overlapping wavelength region. The final spectra were normalized to 100 at 5450 Å.

We took special care to telluric absorption correction as some metallic lines of interest for synthesis purposes are quite affected by it. Ideally, if one wants to obtain really good atmospheric bands cancellation, one should observe an early-type star at same airmass and quasi-simultaneously to the program star as atmospheric absorption is variable in time and with zenithal distance. During both runs, many O and B stars were observed but it was not, in practice, done at same airmass so that the correction cannot be made directly. Instead one weighted mean normalized atmospheric spectrum over each night is created. In addition to the O_2 A and B bands, there is quite a number of H_2O features visible in the spectra. Identification of the bands was based on the work of Pierce & Breckinridge (1973). Comparison of the strength of the O_2 and H_2O bands in the atmospheric standards shows that during the CFHT run, the relative contribution of O_2 and H_2O remained constant within each night but not from one night to the other. Each stellar spectrum has been divided by $[1-(1-atm)*K]$ where atm is the normalized atmospheric band spectrum and K a factor around 1 which varies whenever the features in atm are deeper or smoother than the atmospheric bands present in the star. A similar procedure was applied to the OHP spectra but as the nights were non-photometric and the segments composing a spectrum not necessarily taken on the same night, O_2 and H_2O may not contribute with the same intensity, the intensity being dependent on the observing night. Therefore a different K factor may have to be applied for each of the O_2 and each of H_2O bands.

Figure 1 shows two typical atmospheric spectra, one from the OHP and the other from the CFHT data. Note how much bigger the water vapor content is at the OHP compared to the CFHT.

Finally, all stellar spectra were corrected for interstellar reddening using the Schild (1977) reddening law. Values of $E(B-V)$ were derived by direct comparison to the Jacoby et al. (1984) library in the common wavelength range (4800−7430 Å). The common coverage with Silva & Cornell is larger but their library merges, in a same group, several stars of different types, dereddened by different amount with a different extinction curve than the one we use. However, as in the case of HD 112127, no star of same spectral type and luminosity class is available in Jacoby et al. library, we compared to Silva & Cornell. This is a favourable case as this very star, and only this one composes the K2III group with $E(B-V)$=0.0. However we do find a different extinction: $E(B-V)$=0.1. It is difficult to compute an error on the extinction. The value derived here is the one leading to the smallest residuals in the comparison between the stellar template and our spectrum. To get noticeable variations of the residuals, $E(B-V)$ should vary by at least 0.02. Note that the comparison with Jacoby et al. and Silva & Cornell has to be done at same spectral resolution. All the spectra were degraded as necessary by convolution with a gaussian.

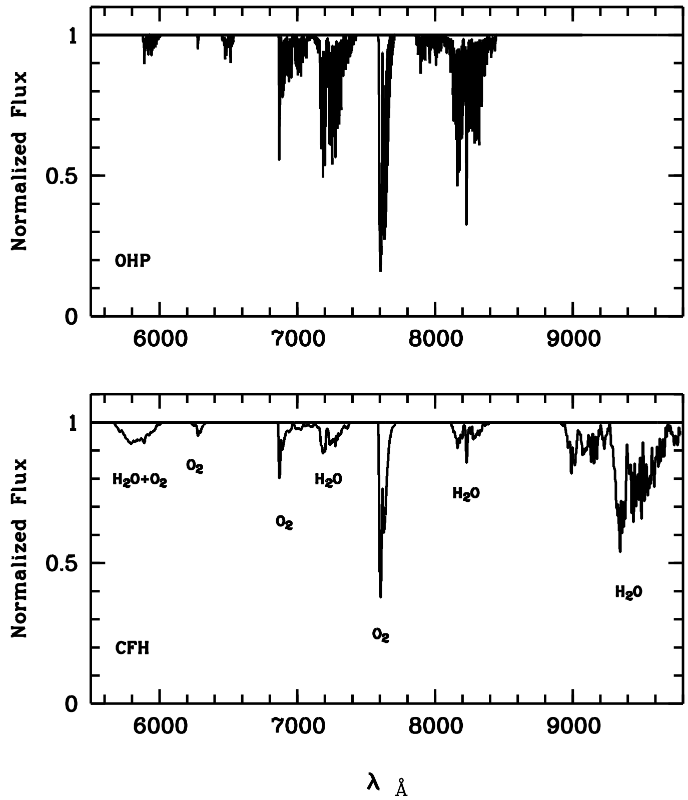

Fig. 1. Mean atmospheric spectra observed at OHP and CFH

The OHP and CFHT samples are listed in Tables 2 and 3 respectively[2], along with their spectral type and luminosity class, coordinates, V magnitude, metallicity (when known) and its source, adopted $E(B-V)$. Values of [Fe/H] are taken primarily from Cayrel de Strobel et al. (1992) and adjusted to a solar zero point when necessary. A dash for the metallicity denotes an unknown metallicity, that will be considered as solar in the following discussion.

[2]References to Tables 2 and 3:
CS: Cayrel de Strobel et al. 1992; BG: Barbuy & Grenon 1990; FFBG: Faber et al. 1985; T: Taylor 1991.

Table 2. The OHP stars

HD	BS	sp. type	α (2000)	δ (2000)	V	[Fe/H]	Ref.	$E(B-V)$
160762	6588	B3 IV	17 39 27.8	46 00 22.5	3.8	-		0.02
120315	5191	B3 V	13 47 32.9	49 18 48.5	1.9	-		0.01
145675	-	K0 V	16 10 12.9	43 50 09.0	6.7	0.31	CS	0.05
121370	5235	G0 IV	13 54 25.5	18 25 46.1	2.7	0.16	CS	0.08
161797	6623	G5 IV	17 46 15.6	27 43 58.5	3.4	0.32	CS	0.25
148856	6148	G7 IIIa	16 29 59.2	21 30 05.4	2.8	0.00	CS	0.15
163993	6703	G8 III	17 57 45.8	29 14 52.0	3.7	0.27	CS	0.00
139195	5802	K0 III	15 36 29.6	10 00 36.5	5.2	-0.15	CS	0.00
112127	-	K2 III	12 53 39.6	26 48 35.3	6.9	0.30	CS	0.10
176670	7192	K3 III	19 00 00.7	32 08 43.4	5.0	0.09	T	0.20
181984	7352	K3 III	19 15 40.9	73 20 38.6	4.5	0.39	FFBG	0.00
139669	5827	K5 III	15 31 34.8	77 22 03.6	5.0	0.20	CS	0.30
141477	5879	M0.5 III	15 48 29.6	18 09 33.8	4.0	-		0.10
123657	5299	M5 III	14 07 42.4	43 52 51.0	5.3	-0.03	CS	0.00
180809	7314	K0 II	19 16 22.0	38 08 01.2	4.4	-0.10	CS	0.23
156283	6418	K3 II	17 14 51.3	36 48 54.3	3.2	0.32	CS	0.25
168532	6860	K4 II	18 19 10.6	24 26 45.3	5.3	-0.09	T	0.00
159181	6536	G2 Iab	17 30 18.5	52 18 18.4	2.8	0.30	CS	0.05
196725	7892	K3 Ib	20 38 43.9	13 18 54.0	5.8	0.22	CS	0.35
185622	7475	M0 Iab	19 39 25.3	16 34 16.7	6.4	-		0.35
206936	8316	M2 Ia	21 43 30.3	58 46 48.2	4.0	-		0.90

Table 3. The CFHT stars

HD	BS	sp. type	α (2000)	δ (2000)	V	[Fe/H]	Ref.	$E(B-V)$
88815	4016	F2 V	10 18 01.7	73 04 27.5	6.4	-		0.00
38858	2007	G4 V	05 48 34.7	-4 05 29.0	6.0	-		0.00
93800	-	K0 V	10 49 32.3	-6 46 13.0	9.0	0.43	BG	0.00
39715	-	K3 V	05 54 28.1	02 09 06.0	8.8	0.33	BG	0.00
36395	-	M1 V	05 31 24.8	-3 38 54.0	8.0	0.60	CS	0.15
72324	3369	G9 III	08 33 00.3	24 05 07.4	6.4	0.17	FFBG	0.07
72184	3360	K2 III	08 32 55.3	38 01 07.5	5.9	0.34	FFBG	0.00

3. Results and discussion

Figures 2 to 5 display the spectra of all stars observed. For the sake of the presentation the OHP spectra were degraded, by convolution with a gaussian, down to a resolution of 8.5 Å. In this way, direct comparison is possible between the two sets of data.

We cut HD 39715 spectrum at 8800 Å as the signal to noise ratio above this wavelength was too low due to the rapid decreasing detector sensitivity in the red, the low magnitude of the star and a too short exposure time.

The aim of these observations is not to create a new library but instead to develop existing ones, adding in particular SMR and/or supergiant stars. Although it is commonly thought that a dedicated library should be observed for each given synthesis study, we do believe that it is more a problem of knowing how different libraries can merge. In particular it is fundamental to measure line strengths and do synthesis at an homogeneous spectral resolution taking care of matching the velocity dispersion of the galaxy. The most complete library, at a resolution close to that of CFHT being Silva & Cornell's one, we have chosen to compare our spectra to the groups in Silva & Cornell (1992) with same spectral type. We do exclude M groups as they include several stars of nearby but different types which due to the increasing presence of TiO can make the comparison meaningless.

Figure 6 shows this comparison in the 3 cases where not only the spectral type is the same, but also one of the stars we observed is included in the group. The bottom panel displays the residuals defined as the difference

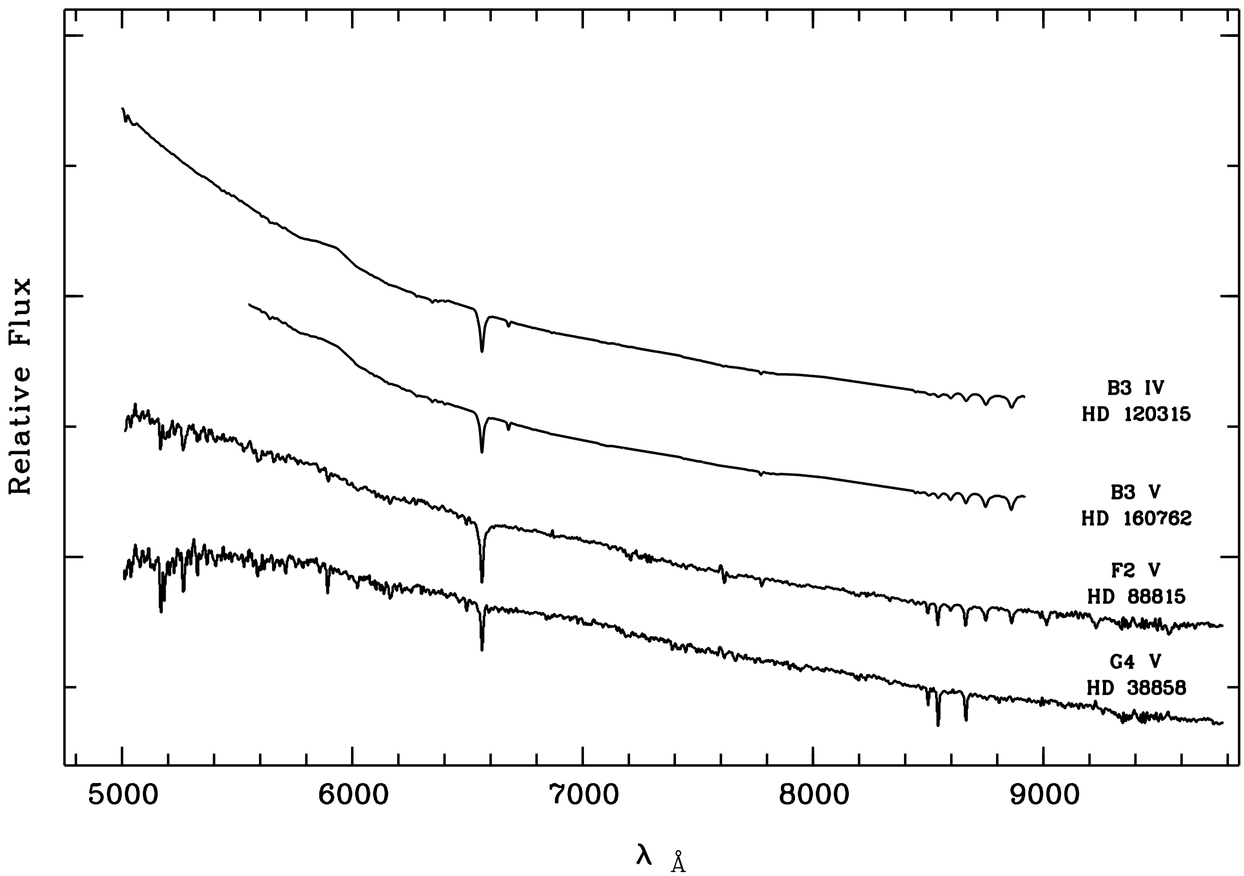

Fig. 2. Spectra of the dwarf stars with solar abundance

between our spectrum and Silva & Cornell's one normalized to ours. For such a comparison it was necessary to degrade the resolution of our spectra down to 11 Å. The agreement is fairly good for the K0III and K2III groups. In the case of the third one, the distortion is probably due to a difference in metallicity as the two other stars belonging to the group have higher quoted metallicity. In Fig. 7, a similar comparison between OHP and CFH data is shown. Residuals are 10% at maximum for the SMR K0V. First, those two stars have different metallicities. Second, we should mention that the spectrum of HD 93800 is closer to Jacoby et al. G9V where the dip around 6000 Å is less prominent than in K0 stars.

Equivalent widths (EW) of some prominent absorption features have been measured. Both the OHP and CFHT samples were measured at 8.5 Å resolution to be comparable. A 'global' continuum has been applied to each star, which accounts for the general shape of the spectrum. To evaluate the continuum shape in the bluest part, the spectra were compared to stars of the same spectral type from the Jacoby et al. (1984) library which extends down to 3500 Å. The continuum was defined considering both sets of stars.

The use of a local continuum (in opposition to a 'global' one) is interesting if one wants to separate the contribution of several elements. For example, the measurement of the CaII triplet or of MgIλ8807 with a 'global' continuum has a strong contribution of TiO, specially for the late type stars. The choice of a local continuum would eliminate this problem. However for M stellar types, TiO bands are so strong that atomic lines are embedded in the molecular absorptions and a local continuum would strongly underestimate the atomic lines and even lead to negative EW (Alloin & Bica 1989). We therefore concentrated on a 'global' continuum, keeping in mind that for cool stars a large contribution of the EW is due to molecular bands. Note that for stellar population synthesis, the use of a 'global' continuum is crucial as the whole constituents would play a role in the composite galactic spectrum.

Measurements were made with the MEASURE package developed by D. Pelat and M. Caillat at Meudon Observatory (see Rola & Pelat 1994, for a presentation of the method). Errors are generally less than 5%, except for very weak lines where they can be as large as 30%. Measured wavelength intervals for each line are indicated in Table 4.

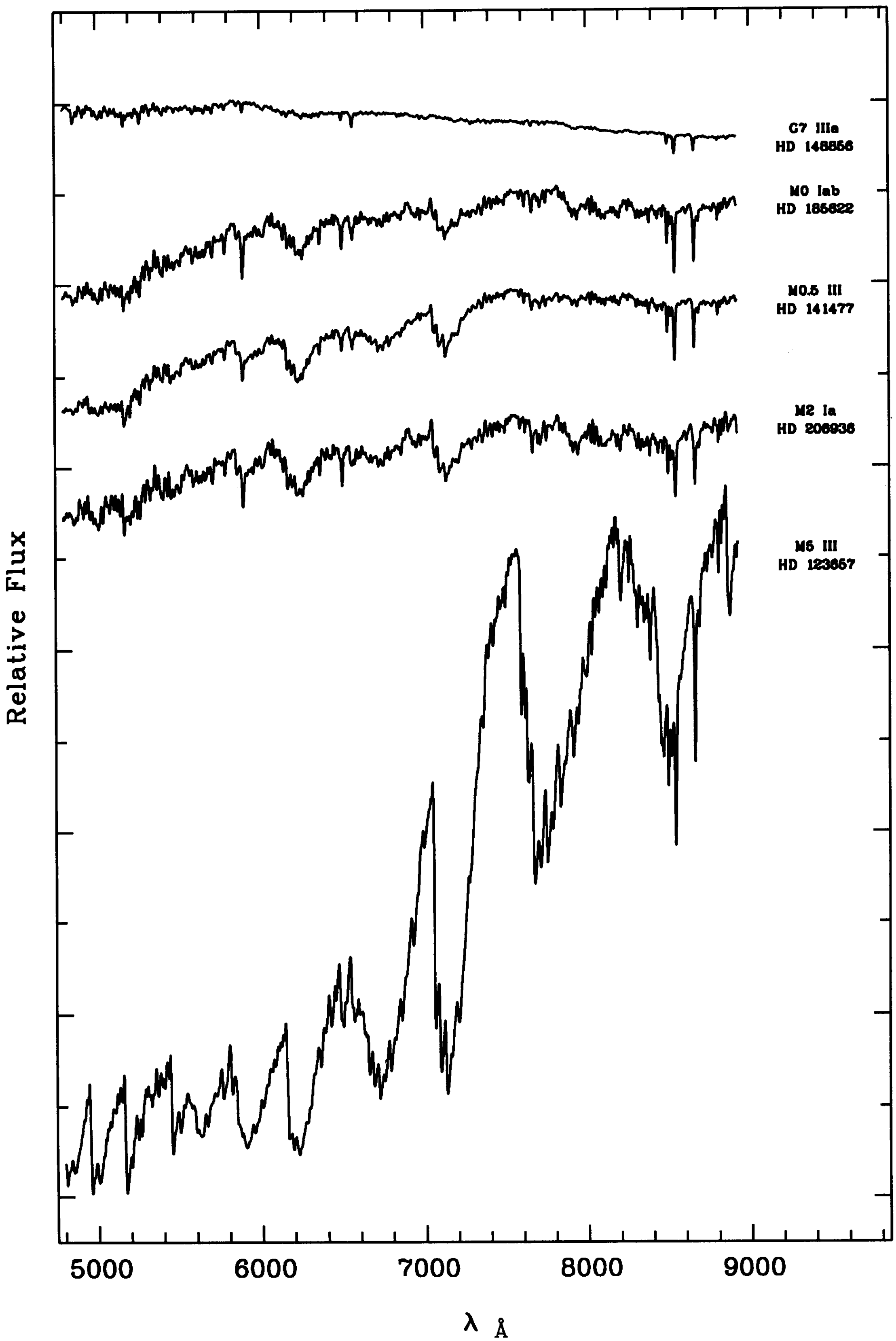

Fig. 3. Spectra of the giants and supergiants stars with solar abundance

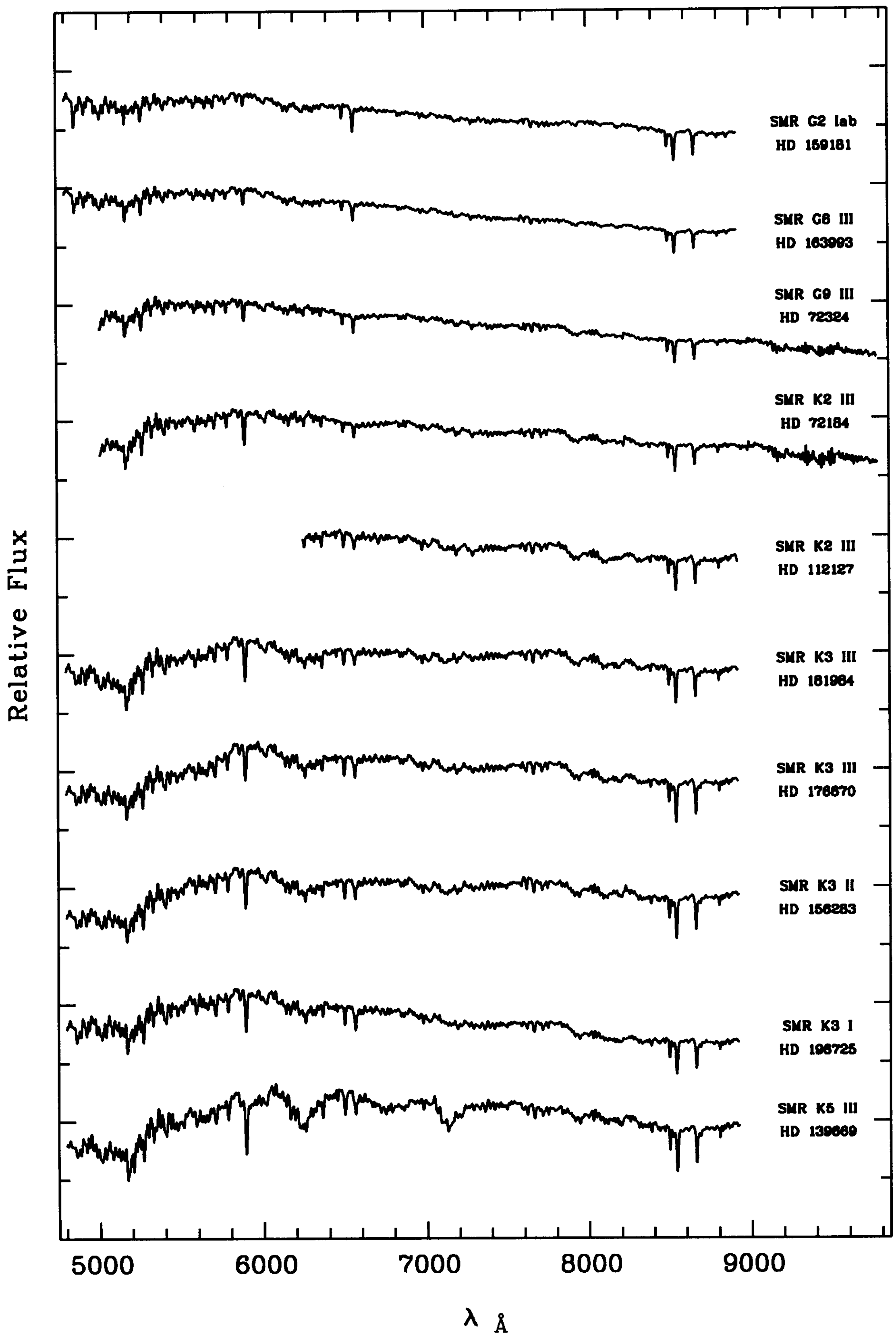

Fig. 4. Spectra of the SMR giants and supergiants

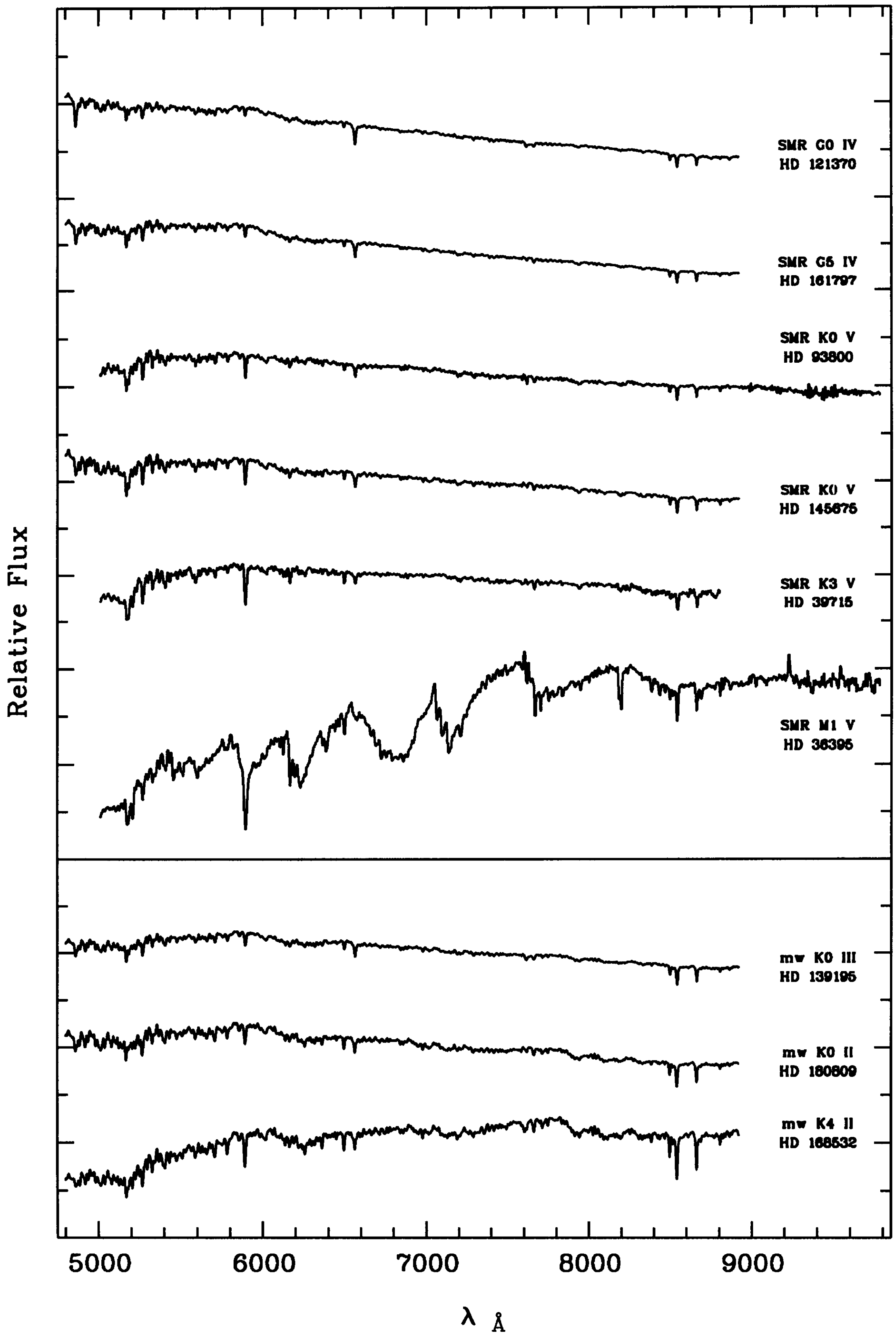

Fig. 5. Spectra of the SMR dwarfs and of the metal weak stars

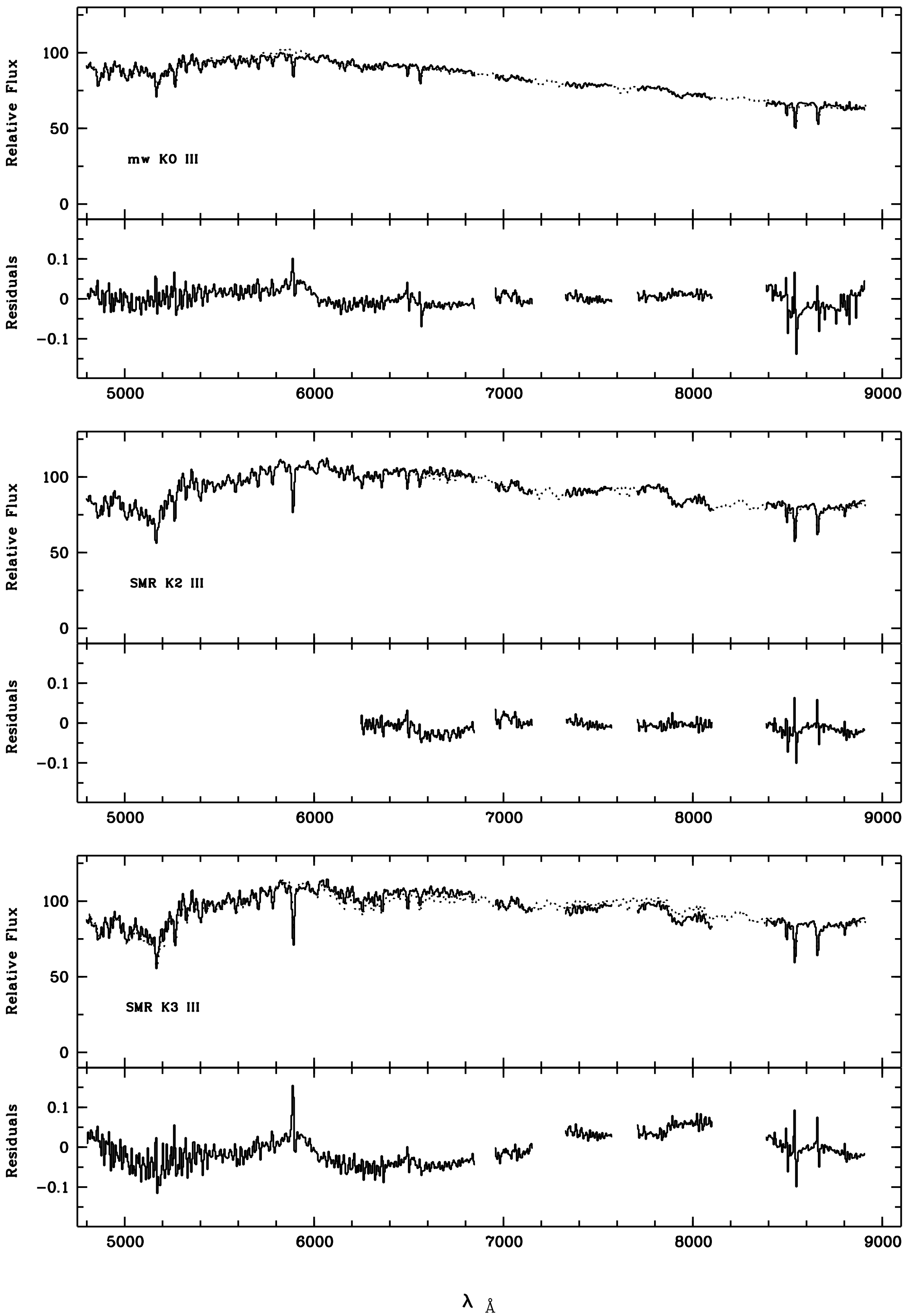

Fig. 6. Comparison between the OHP spectra (dotted line) and the Silva & Cornell library (solid line) for the K0III, SMR K2III and SMR K3III. Cuts in the spectra are where the atmospheric bands stand. On this graphic, our data are degraded down to 11 Å

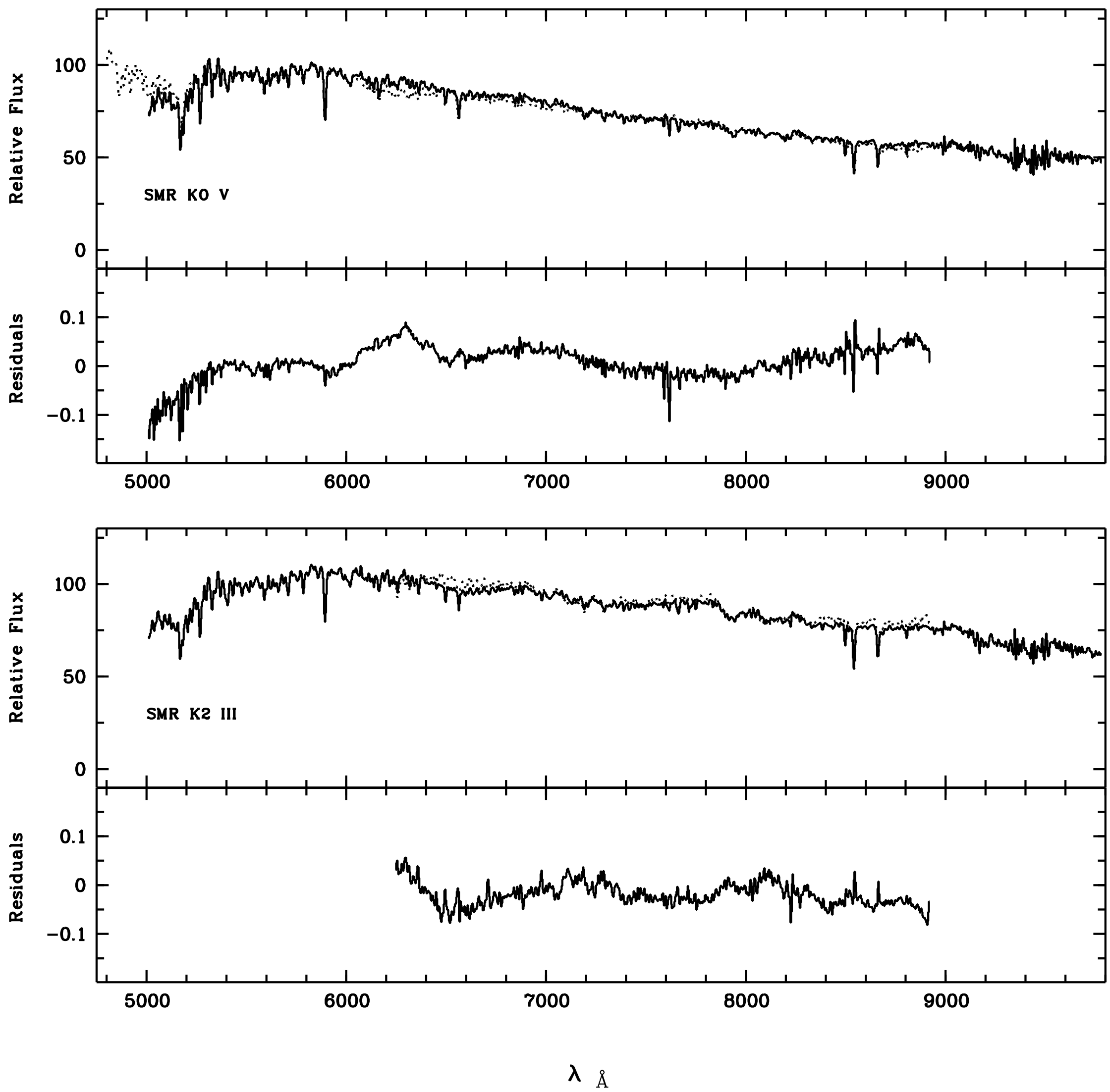

Fig. 7. Comparison between the OHP spectra (dotted line) and CFH (solid line) for the SMR K0V and SMR K2III

Table 4. The measured intervals

ident.	spectral range (Å)
NaI D	5874-5914
FeI	6487-6506
H_α	6557-6567
TiO	6622-6651
NaI	8172-8213
CaII	8645-8677

Figures 8 and 9 display the measured equivalent widths versus spectral type. Different symbols correspond to different luminosity classes (o = I and II, $\triangle$ = III, $\diamond$ = IV and V), open symbols are for stars with metallicity higher than solar and filled ones for metallicity solar and below solar. Whenever its metallicity is not known, a star is plotted as solar. Since the sample is quite limited, we observe only tendencies in the behaviours. The metallicity dependence suffers from lack of data and, for types earlier than G8, we have only dwarf stars preventing any discussion about luminosity discrimination.

Our graphics are in agreement with similar plots published in previous studies as O'Connell (1973), Jones et al. (1984), Pickles (1985), Carter et al. (1986), Alloin & Bica (1989), Diaz et al. (1989), Xu (1991), Torres-Dodgen et al. (1993) and Danks & Dennefeld (1994) among others.

The known behaviour of Hα with the spectral type is reproduced although our sample does not include the strong hydrogen stars (A0-F0). No dependence on luminosity class is seen as most stars gather on the plateau where luminosity classes are quite mixed. FeI 6495 Å

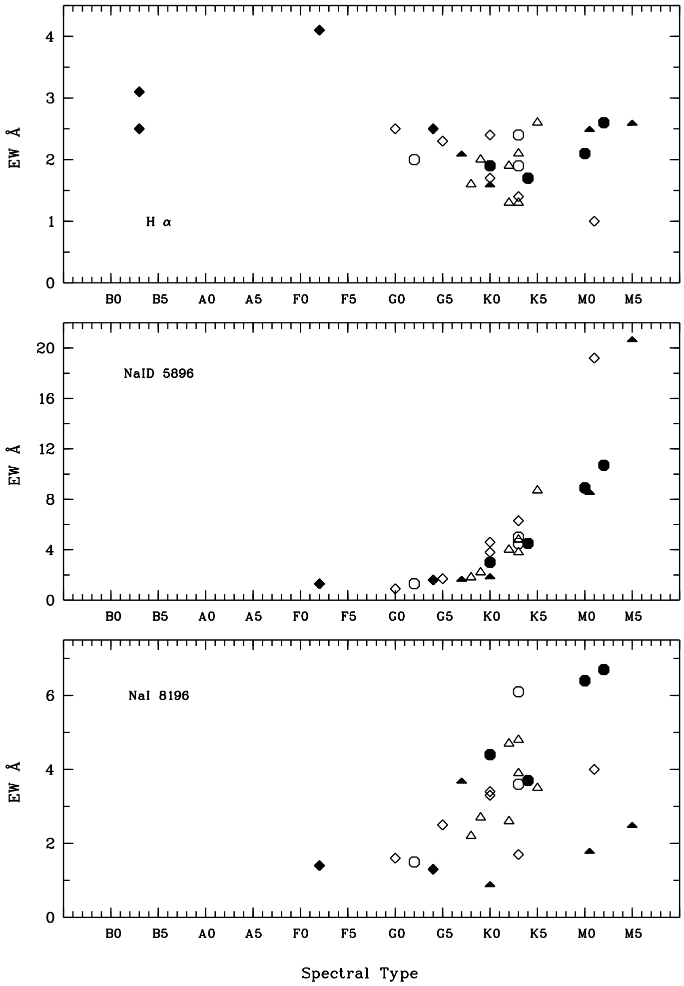

Fig. 8. Equivalent widths of Hα, NaID 5896 and NaI 8196 versus spectral type. Different symbols are used for the different luminosity classes: o = I and II, $\triangle$ = III, $\diamond$ = IV and V. Open symbols are for SMR stars and filled ones for metallicity solar, below solar or unknown

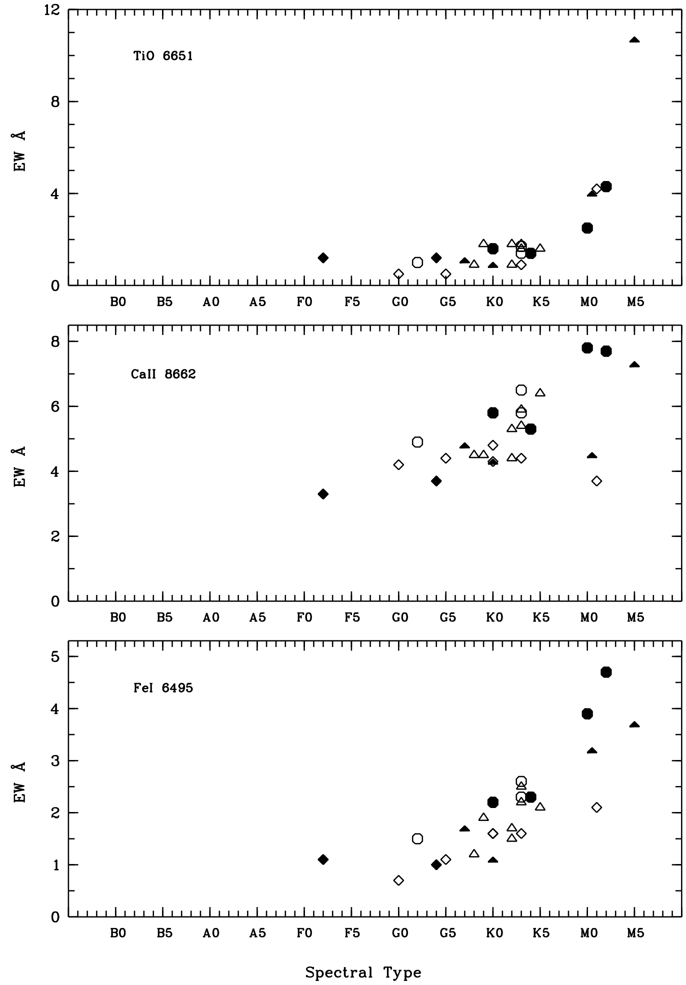

Fig. 9. The same as Fig. 8, for TiO 6651, CaII 8662 and FeI 6495

grows steadily with spectral type. The same behaviour is observed for other lines of FeI (5328, 5397, 7500, 8080, 8514 Å). TiO 6651 Å shows a strong increase for types later than M0. Also, by inspection of Figs. 3 and 4, it can be seen how the TiO bands start to appear for the late type stars. Only the CaII 8662 Å line is plotted versus spectral type, the results being similar for the three lines of the triplet. Note that for the F2V star, this line is blended with Paschen (P13) while for late type stars, the contribution of TiO increases. Nevertheless and albeit we do not sample all luminosity classes for all spectral types, the plot is consistent with the luminosity dependence previously known. NaID 5896 Å show the expected trend of metals increasing with decreasing temperature. However, this behaviour has to be taken with care since this line is contaminated with interstellar absorption and also, in the late type stars, TiO is increasingly overtaking NaI. Plot of the NaI line at 8195 Å does not allow to differentiate dwarfs from more luminous stars as we are lacking solar metallicity cool dwarfs. Yet it can be seen that, if giants are actually faint, supergiants are strong, even stronger than the SMR dwarf. Previous analyses we are aware of are seriously lacking supergiants. Furthermore, let us recall that using a local continuum in a region where TiO dominates leads to strong underestimation of NaI. Indeed, in Fig. 6 of Alloin & Bica (1989), supergiants lay between dwarfs and giants contrary to our results.

HD 36395 exhibits a strange behaviour in Figs. 8 and 9 as its EW are generally weaker than expected from its metallicity: it is known as a SMR star with one of the highest [Fe/H] (=0.6). In fact the high Fe/HI ratio is probably due to the very weak intensity of the hydrogen lines (see Fig. 8). Stauffer & Hartmann (1986) already suggested that either the intrinsic photospheric Hα is extremely weak or there is an active emission region in the chromosphere so that globally the emission fills in the background absorption line. Our graphics show that the metallic abundance of HD 36395 could be quite normal.

4. Conclusions

Spectra of 28 stars (mainly late type stars), including a major percentage of SMR stars have been presented. The spectral resolution is 1.25 Å or 8.5 Å, making them suitable to combine with other stellar libraries available in the literature which lack SMR or supergiant stars. To create a stellar library merging our spectra to existing libraries, it is necessary to degrade all the data down to the lowest spectral resolution.

We have measured the equivalent widths of the main absorption features which agree with the previously known correlations with temperature and surface gravity thus attesting the quality and utility of the data for stellar population synthesis.

A digital version with all the spectra presented here is available in electronic form via the CDS in Strasbourg, France.

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