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Available libraries of observed spectra

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Abstract. The current status of libraries of observed spectra available in literature is reviewed, using inputs from the *Asiago Database of Spectroscopic Databases* (ADSD) which censuses, compares and homogenizes to common grounds 294 libraries of ultraviolet, optical and infrared spectra. Suggestions are derived concerning targets for future observational efforts and the necessity for improvements in the observation/data reduction process.

Key words. Astronomical data bases – Spectrophotometry – Standard stars – Stellar spectroscopy

1. Introduction

The aim of this talk is to review the current status and content of the libraries of stellar spectra that the astronomical community has assembled and used over the years, and use this to highlight a few of the areas where it would be advisable to invest future observational efforts. Given the limited space available, only a few topics will be touched and only relative to the optical range. A much more extensive set of information, extending also to the ultraviolet and infrared spectral domains, is available in the Asiago Database of Spectroscopic Databases (ADSD; Sordo & Munari 2005), that is a census of a total of 294 libraries covering 16046 different stars. To be included in the ADSD a spectroscopic database (*i*) must be accompanied by a public available publication that document the data (preferably on a refereed journal), (*ii*) the data must be directly accessible, thus excluding the datasets that need to be requested to and/or negotiated directly with the Authors, and (*iii*) the library must contain spectra of a minimum of ∼10 different stars.

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2. Types of stars included in optical spectral libraries

The ADSD includes 188 libraries of optical spectra: 95 libraries presents spectra available in electronic form, 48 libraries spectra available in printed tabular form and 46 libraries with spectra available only plotted as figures. The latter we will be not further considered in the rest of this talk. The remaining 95 + 48 = 143 spectral libraries with data accessible either in electronic or printed tabular form (hereafter *E/T optical libraries*) cover 9405 different stars, whose distribution in spectral type, luminosity class and metallicity is given in Fig. 1.

Their vast majority is accounted for by main sequence and local red clump stars, of metallicity close to solar value. Very hot stars of both normal and peculiar types (O-type, WR, WD, CVs) contribute a thin mi-

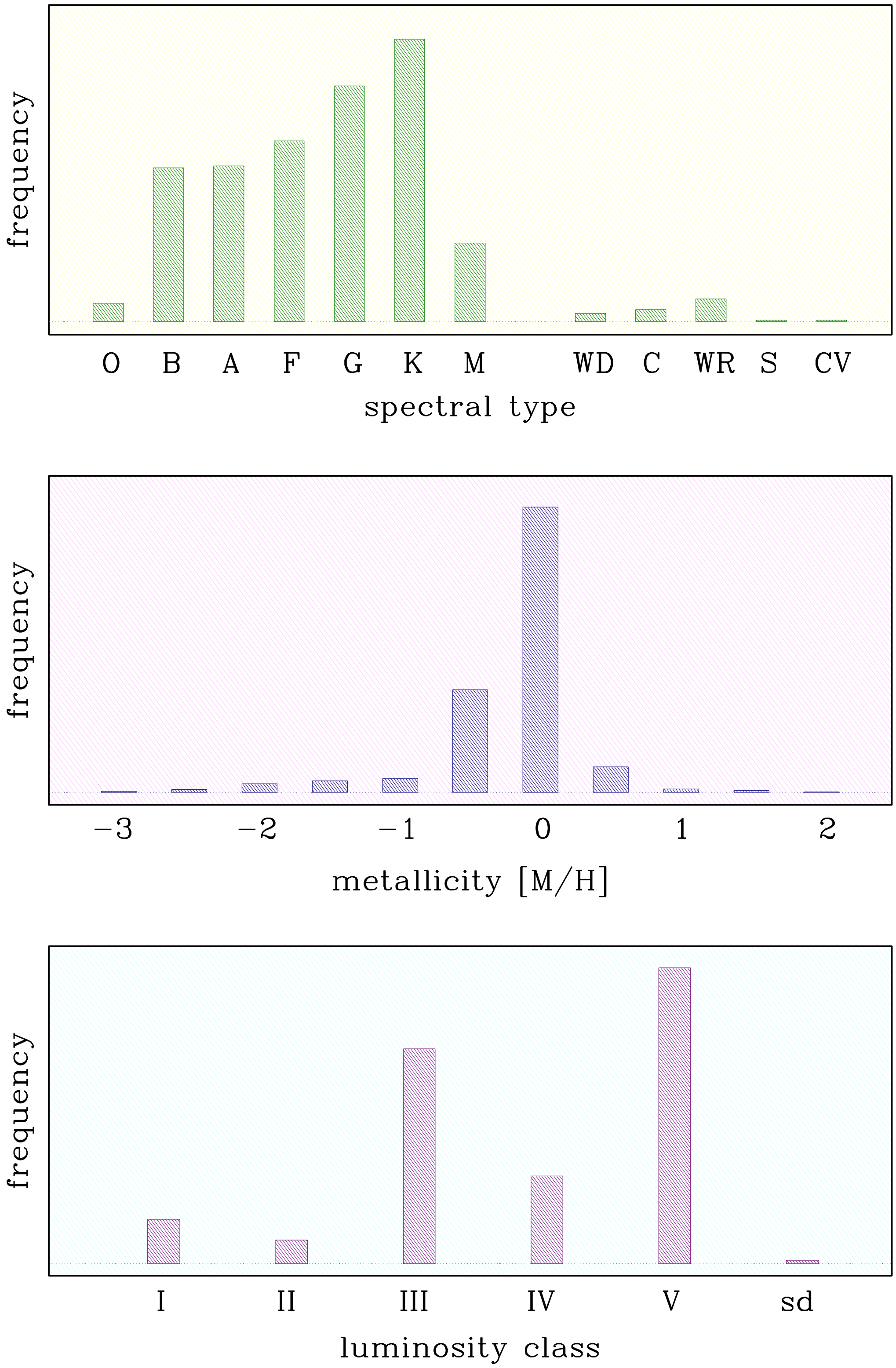

Fig. 1. Distribution in spectral type, metallicity and luminosity class of the 9405 stars whose spectrum is present in at least one of the libraries of optical spectra censused in the *Asiago Database of Spectroscopic Databases* and that have their data available in either electronic or printed tabular form.

nority of the total, while stars dominated by molecular absorptions (M-type, Carbon, S-type) score only a little better. Extreme metallicities ([M/H]$\geq$+1.0 or [M/H]$<-$2.0) and subdwarf types are an exceedingly rarity.

3. Fundamental plane of spectroscopic libraries

How these E/T optical libraries are distributed in terms of length of covered wavelength interval, sampling step, number of spectra, type of stars and type of data is presented in Fig. 2. This is sort of a *fundamental plane* for spectral libraries. It shows how the optical libraries composed by absolute fluxed spectra tend to cluster around a covered wavelength interval of ~4300 Å and a sampling step of ~50 Å. Their number degrades toward finer samplings, becoming a negligible contribution at sampling steps of a few Å. This reverberates into the chronic need for libraries containing high resolution and absolutely fluxed spectra covering a wide wavelength range, suitable for flux calibration of Echelle spectra. Their lack forces observers into elaborate, tedious and problematic efforts that usually involve synthetic spectra to remap at higher spatial frequencies the spectral energy distribution of conventional spectrophotometric standards.

Fig. 2 also highlights other striking evidences. The libraries of spectra calibrated as relative fluxes have a smoother distribution over the whole plane, while the libraries containing continuum normalized spectra are restricted to samplings finer than 1–2 Å. The latter is a manifestation of the difficulty (and minor interest for a wide range of applications) to calibrate into fluxes (either absolute or relative) high resolution observations, especially those originating from multi-order Echelle spectra. Quite interesting is the paucity of libraries of peculiar and/or selected type of stars calibrated into fluxes (either absolute or relative). This characteristic and the shorter length of the covered wavelength interval indicate how the driving goal in building those libraries is generally limited to document/measure individual spectral features and emission/absorption lines with respect to the adjacent, local continuum.

4. Best observed stars

Among the 9405 stars whose spectrum is included in at least one of the 145 E/T optical libraries there is little and uneven commonality between fluxed and high resolution spectra. Tab. 1 lists all the stars that are included in (*i*) at least two libraries presenting absolutely fluxed spectra covering continuously the 3500-7000 Å range, and that are also included in (*ii*) at least two libraries presenting spectra at a resolving power of at least 40 000. The table lists all the 59 stars satisfying both selection criteria. These are the stars most suited for comparison with the synthetic spectra discussed at this Conference, it being possible to constrain the comparison simultaneously on the overall fluxed spectral energy distribution as well as on the individual high-resolution absorption lines. However, these 59 stars are essentially only solar type main sequence stars and early K giants. No hot star, or supergiant, or molecular band, or chemically peculiar star shows up in Tab. 1.

For completeness it must be said that a few stars (most notably α Lyr) did not enter Tab. 1 because their high resolution spectra were published individually and not as part of a database. Such stars are however very few and their inclusion would not appreciably alter the scenario depicted by Tab. 1.

The extension of Tab. 1 toward other regions of the HR diagram and toward chemical peculiar stars would certainly be an interesting area to consider in future observational efforts.

5. Flux accuracy

The vast majority (120) of the 145 E/T optical libraries present their spectra calibrated into absolute or relative fluxes. How accurate are these fluxes? To answer the question we have first looked into the ADSD searching for the stars that are present in the largest number of fluxed libraries, and then we have compared their fluxed spectra. As an example, the case of γ Gem is presented in Fig. 3 (the other being quite similar). In Fig. 3 the spectra are all normalized to 7000 and 5250 Å, so only differences in the slope show up (those in the zero point, far from being negligible, are elim-

Table 1. The 59 stars that are included in at least two libraries of absolutely fluxed spectra covering entirely the 3500-7000 Å range (identified in the 7th column) and that are also included in at least two libraries of high resolution optical spectra with a resolving power larger than 40 000 (identified in the 8th column). The identification numbers refer to the card numbering system in the *Asiago Database of Spectroscopic Databases*, and their correspondence is *7*: Alekseeva et al. (1997), *9*: Allende Prieto et al. (2004), *12*: Bagnulo et al. (2003), *18*: Burnashev (1985), *28*: Glushneva et al. (1992), *30*: Glushneva et al. (1998b), *32*: Griffin & Griffin (1979), *43*: Kharitonov et al. (1988), *48*: Le Borgne et al. (2003), *55*: Montes & Martin (1998), *64*: Prugniel & Soubiran (2001), *68*: Soubiran et al. (1998), *74*: Takeda et al. (2005)

	name	α_{2000}	δ_{2000}	*V*	*spectrum*	*abs. fluxed SED*	*high resolution*
HD 693	6 Cet	00 11 15.9	–15 28 05	4.9	F5 V	18 - 30	64 - 68 - 74
HD 4614	η Cas	00 49 06.3	+57 48 55	3.4	G0 V	7 - 18 - 30 - 43	9 - 64 - 68 - 74
HD 9826	υ And	01 36 47.8	+41 24 20	4.1	F8 V	18 - 43	9 - 55 - 74
HD 10307		01 41 47.1	+42 36 48	4.9	G1.5 V	18 - 28 - 30 - 43	9 - 55 - 64 - 74
HD 10476	107 Psc	01 42 29.8	+20 16 07	5.2	K1 V	18 - 30	9 - 55 - 64 - 68 - 74
HD 10700	τ Cet	01 44 04.1	–15 56 15	3.5	G8 V	7 - 18 - 43	9 - 64 - 68 - 74
HD 13974	δ Tri	02 17 03.2	+34 13 27	4.9	G0.5 V	18 - 28 - 30 - 43	9 - 64 - 68
HD 19476	κ Per	03 09 29.8	+44 51 27	3.8	K0 III	18 - 28 - 30 - 43	64 - 68
HD 19994	94 Cet	03 12 46.4	–01 11 46	5.1	F8 V	18 - 30	64 - 74
HD 20630	κ Cet	03 19 21.7	+03 22 13	4.8	G5 V	18 - 30	9 - 55 - 74
HD 22049	ε Eri	03 32 55.8	–09 27 30	3.7	K2 V	7 - 18 - 43	9 - 12 - 64 - 68 - 74
HD 22484	10 Tau	03 36 52.4	+00 24 06	4.3	F9 IV-V	18 - 28 - 30 - 43	9 - 12 - 64 - 74
HD 23249	δ Eri	03 43 14.9	–09 45 48	3.5	K0 IV	7 - 18 - 30 - 43	9 - 12
HD 26965	40 Eri	04 15 16.3	–07 39 10	4.4	K1 V	18 - 28 - 30	9 - 68
HD 29139	α Tau	04 35 55.2	+16 30 33	0.9	K5 III	43 - 18 - 30	12 - 64 - 68
HD 34411	λ Aur	05 19 08.5	+40 05 57	4.7	G1.5 IV-V	18 - 28 - 30 - 43 - 48	9 - 64 - 68 - 74
HD 38393	γ Lep	05 44 27.8	–22 26 54	3.6	F7 V	7 - 18	9 - 12
HD 39587	54 Ori	05 54 23.0	+20 16 34	4.4	G0 V	43 - 48	9 - 64 - 74
HD 61421	α CMi	07 39 18.1	+05 13 30	0.3	F5 IV-V	7 - 18 - 28 - 30 - 43	9 - 12 - 32 - 64 - 74
HD 62509	β Gem	07 45 19.0	+28 01 34	1.1	K0 IIIb	7 - 18 - 28 - 30 - 43	9 - 64
HD 85503	μ Leo	09 52 45.8	+26 00 25	3.9	K2 III	7 - 18 - 28 - 30 - 43	64 - 68
HD 86728	20 LMi	10 01 00.7	+31 55 25	5.4	G3 V	43 - 48	55 - 64 - 68 - 74
HD 102224	χ UMa	11 46 03.0	+47 46 46	3.7	K0.5 IIIb	43 - 48 - 18 - 30	64 - 68
HD 102870	β Vir	11 50 41.7	+01 45 53	3.6	F9 V	7 - 18 - 28 - 30 - 43 - 48	9 - 64 - 68 - 74
HD 109358	β CVn	12 33 44.5	+41 21 27	4.3	G0 V	18 - 43	9 - 64 - 68 - 74
HD 110897	10 CVn	12 44 59.4	+39 16 44	6.0	G0 V	43 - 48	64 - 68 - 74
HD 113226	ε Vir	13 02 10.6	+10 57 33	2.8	G8 III	7 - 18 - 43 - 48	64 - 68
HD 114710	β Com	13 11 52.4	+27 52 41	4.3	G0 V	7 - 18 - 43	9 - 64 - 68 - 74
HD 115383	59 Vir	13 16 46.5	+09 25 27	5.2	G0 V	48 - 18 - 30	12 - 64 - 74
HD 117176	70 Vir	13 28 25.8	+13 46 44	5.0	G5 V	18 - 28 - 30 - 43 - 48	64 - 74
HD 121370	η Boo	13 54 41.1	+18 23 52	2.7	G0 IV	7 - 18 - 30 - 43	9 - 74
HD 124850	ι Vir	14 16 00.9	–06 00 02	4.1	F7 IV	18 - 30 - 43 - 48	12 - 64 - 74
HD 124897	α Boo	14 15 39.7	+19 10 57	0.0	K1.5 III	7 - 18 - 28 - 30 - 43	9 - 12 - 64 - 68 - 89
HD 128167	σ Boo	14 34 40.8	+29 44 42	4.5	F2 V	7 - 18 - 30 - 48	12 - 64 - 74
HD 131156	37 Boo	14 51 23.4	+19 06 02	4.6	G8 V	18 - 30 - 43 - 48	9 - 74
HD 139195	16 Ser	15 36 29.6	+10 00 37	5.3	K0 III	18 - 30	64 - 68
HD 141004	λ Ser	15 46 26.6	+07 21 11	4.4	G0 V	7 - 18 - 43 - 48	9 - 64 - 68 - 74
HD 142373	χ Her	15 52 40.5	+42 27 05	4.6	F8 Ve	48 - 18 - 30	68 - 74
HD 142860	γ Ser	15 56 27.2	+15 39 42	3.9	F6 IV	18 - 43	9 - 64 - 74
HD 143761	ρ CrB	16 01 02.7	+33 18 13	5.4	G0 V	18 - 30 - 7	68 - 74
HD 150680	ζ Her	16 41 17.2	+31 36 10	2.9	G0 IV	7 - 18 - 30 - 43	9 - 64 - 68
HD 161797	μ Her	17 46 27.5	+27 43 14	3.4	G5 IV	7 - 18 - 30 - 43	9 - 64 - 68 - 74
HD 165341	70 Oph	18 05 27.3	+02 30 00	4.0	K0 V	48 - 18 - 30	9 - 64 - 68 - 74
HD 168723	η Ser	18 21 18.6	–02 53 56	3.3	K0 III-IV	7 - 18 - 43	64 - 68
HD 185144	σ Dra	19 32 21.6	+69 39 40	4.7	K0 V	18 - 30 - 7	9 - 55 - 64 - 68 - 74
HD 187642	α Aql	19 50 47.0	+08 52 06	0.8	A7 V	7 - 18 - 43	9 - 12
HD 187691	*o* Aql	19 51 01.6	+10 24 57	5.1	F8 V	7 - 18 - 30 - 43	64 - 68 - 74
HD 188512	β Aql	19 55 18.8	+06 24 24	3.7	G8 IV	7 - 18 - 43	9 - 64 - 68
HD 188947	η Cyg	19 56 18.4	+35 05 00	3.9	K0 III	18 - 43	64 - 68
HD 191026	27 Cyg	20 06 21.8	+35 58 21	5.4	K0 IV	18 - 30	64 - 68
HD 196755	κ Del	20 39 07.8	+10 05 10	5.1	G5 IV	18 - 30	64 - 68 - 74
HD 197989	ε Cyg	20 46 12.7	+33 58 13	2.5	K0 III	7 - 18 - 28 - 30 - 43	64 - 68
HD 198149	η Cep	20 45 17.4	+61 50 20	3.4	K0 IV	7 - 18 - 43	9 - 64 - 68
HD 201091	61 Cyg A	21 06 53.9	+38 44 58	5.2	K5 V	18 - 30	55 - 64 - 68
HD 201092	61 Cyg B	21 06 55.3	+38 44 31	6.0	K7 V	18 - 30	55 - 64
HD 206778	ε Peg	21 44 11.2	+09 52 30	2.4	K2 Ib	18 - 28 - 30 - 43	12 - 64
HD 216385	σ Peg A	22 52 24.1	+09 50 08	5.2	F7 IV	18 - 30	64 - 68 - 74
HD 222368	ι Psc	23 39 57.0	+05 37 35	4.1	F7 V	18 - 28 - 30 - 43	9 - 64 - 74
HD 222404	γ Cep	23 39 20.8	+77 37 56	3.2	K1 IV	7 - 18 - 43	9 - 64 - 68

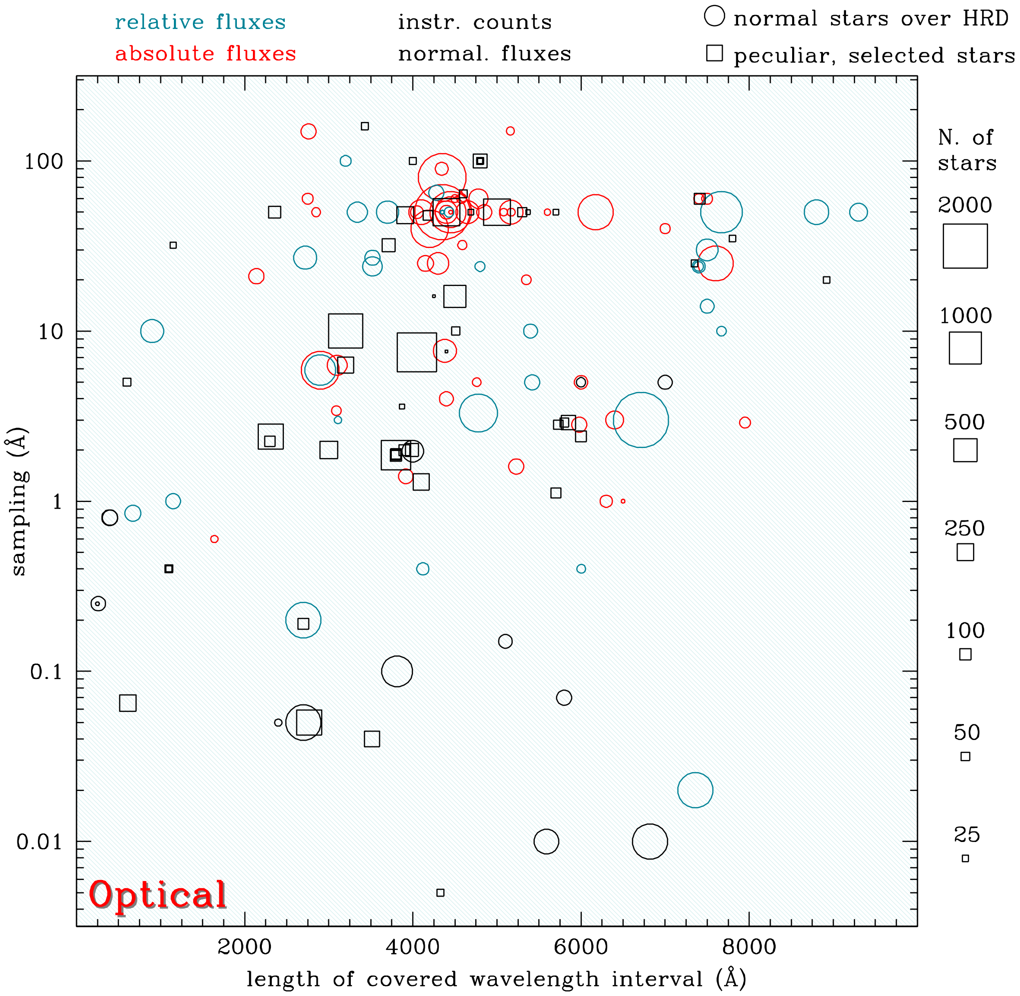

Fig. 2. The *fundamental plane* for the optical spectral libraries with data available either in electronic or printed form.

inated by the normalization process). Apart from many glitches here and there, the difference in the slopes account for large discrepancy in broad-band colors going from one library to another.

It is worth noticing that γ Gem has been found highly photometrically stable by Hipparcos and that it is a secondary spectrophotometric standard (α Lyr being the primary standard) used to flux calibrate several different spectral libraries. There being such differences between various SEDs of γ Gem (and similarly for other secondary standards), it comes as no surprise that at least a similar level of uncertainty generally affects fluxed spectra when a library is compared to another one.

It seems difficult to significantly improve the fluxing quality of future spectrophotometric libraries by copying the current observational procedures that involve the importing of adopted SEDs of standard stars from external sources. A self consistent, autonomous, iteractive global re-calibration of a set of (secondary)

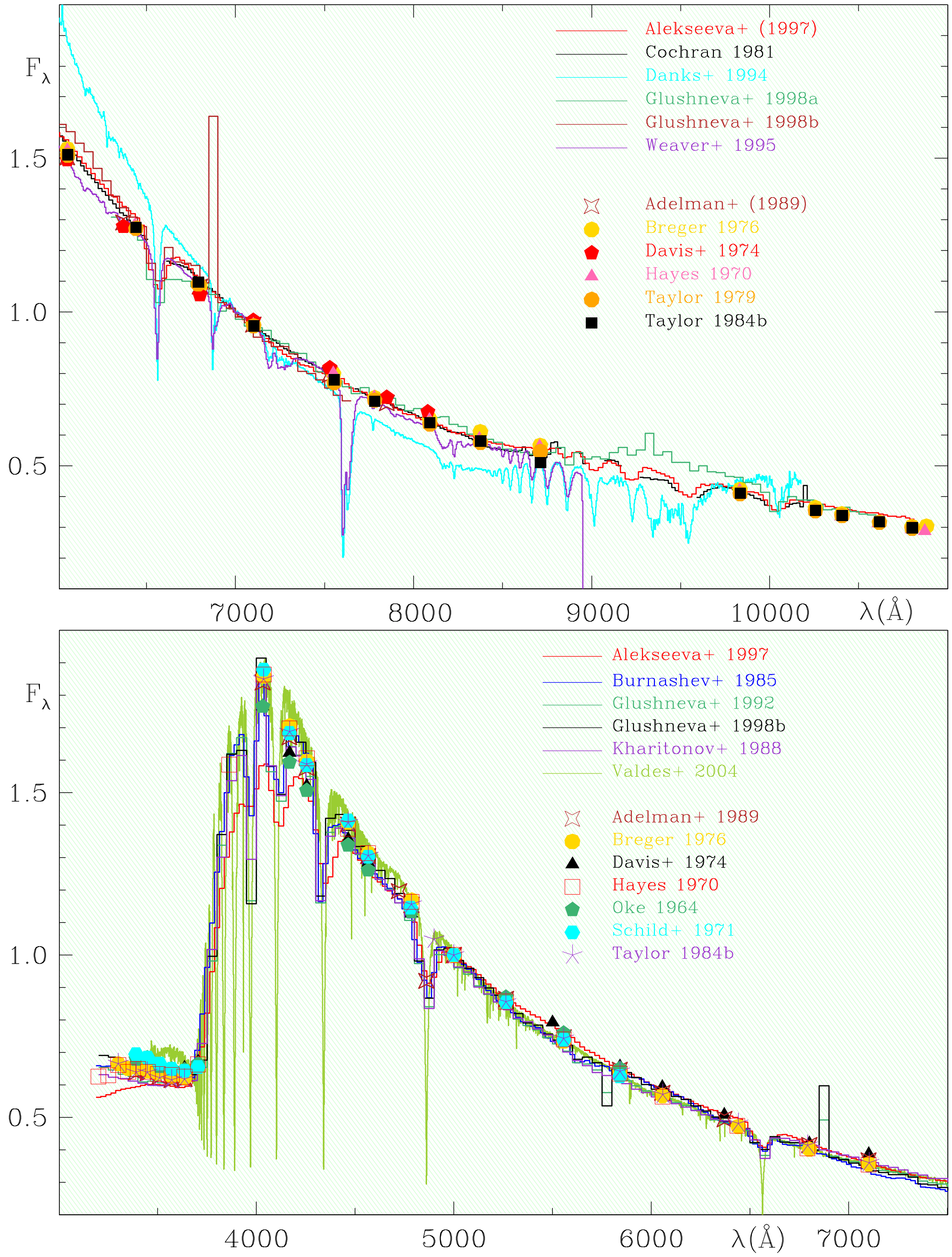

Fig. 3. Comparison between available SEDs of γ Gem (A0 IV), normalized to 1.0 at 5250 Å and at 7000 Å.

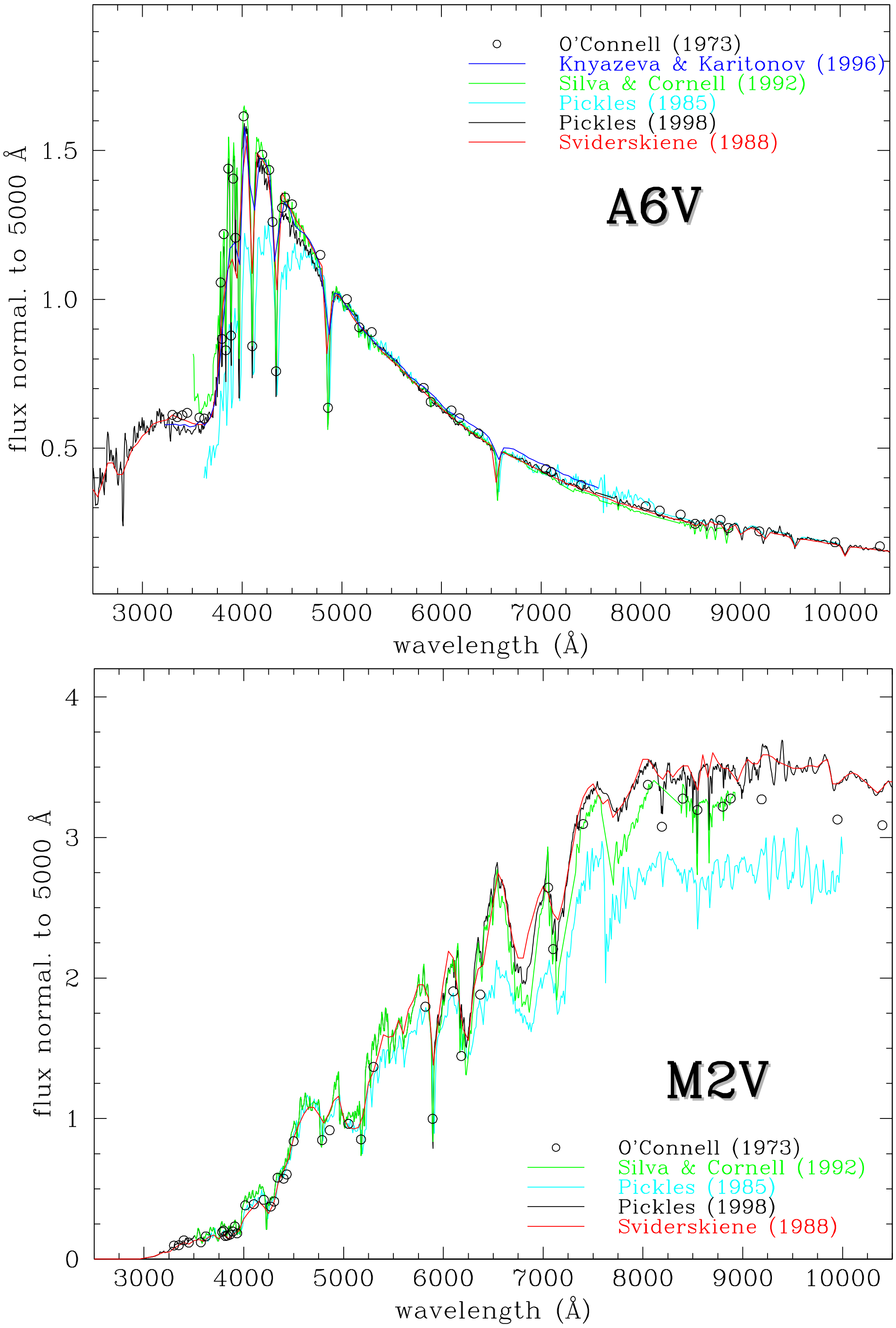

Fig. 4. Comparison between libraries of mean spectra for the spectral types A6V and M2V.

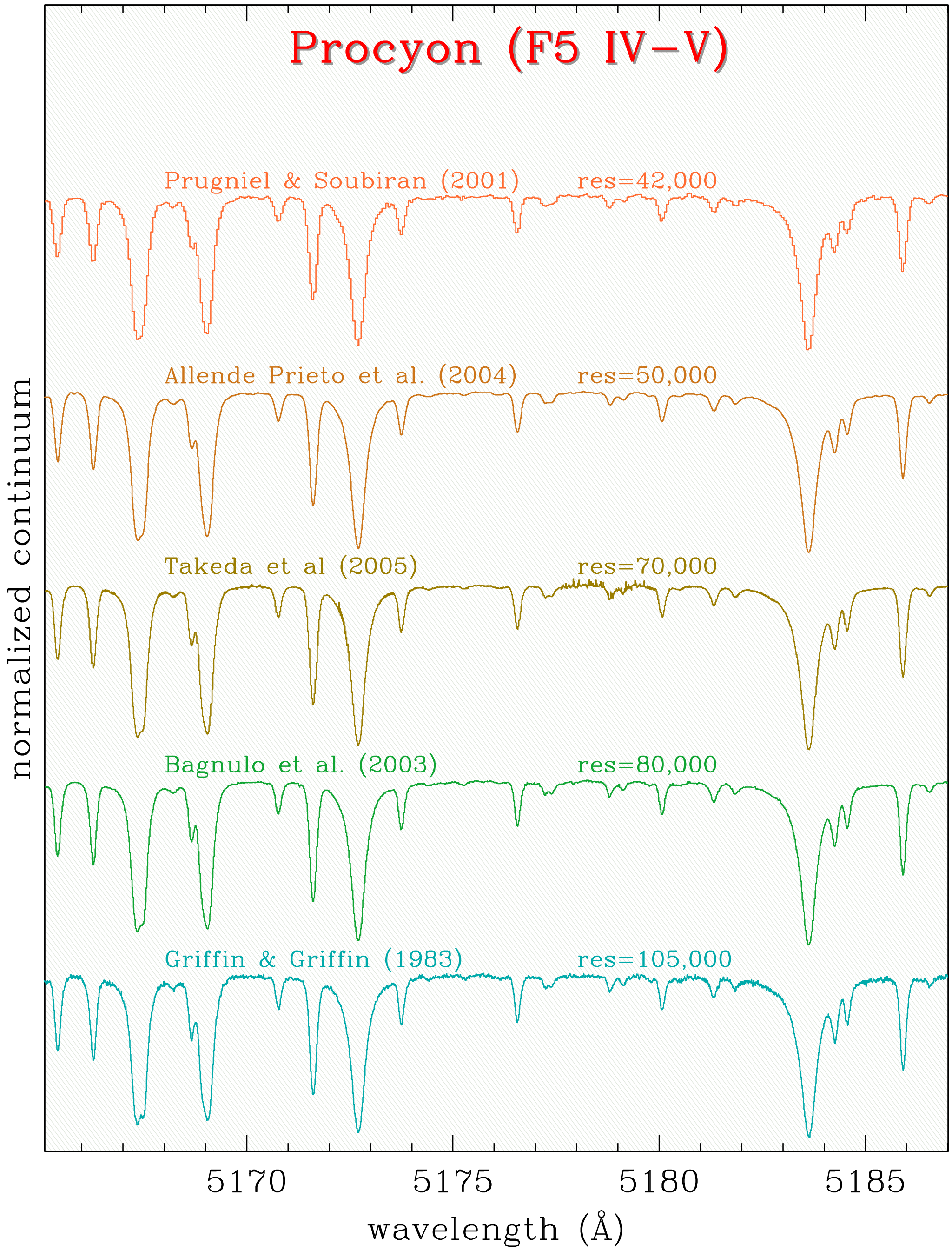

Fig. 5. Comparison between the spectral libraries that include a spectrum of Procyon (α CMi) obtained at a resolving power larger than 40 000.

standards appears as a necessary pre-requisite for a new season in absolute spectrophotometry, as it will be required in the pre-flight calibration of an all-sky network of faint standards necessary to define and tracking the in-flight drifts of the Gaia photometric system. Hopefully, the ASTRA project discussed in these proceedings (cf Adelman et al.) will provide a much welcome step in improving upon spectrophotometric calibration procedures.

6. Mean Spectra

An obvious follow-up of the reasoning in previous section is the extension to mean spectra: given the fact that they are built by averaging observations of several individual stars (sometimes coming from different libraries), are their fluxes more accurate and are there less differences from one library to another?

Fig. 4 compares the mean optical spectra for types A6 V and M2 V using all available catalogs. Similar plots apply to the other stellar types.

The scatter in Fig. 4 between the various mean spectra is quite large, amounting up to $\Delta(V\text{-}I)\sim0.3$ mag. It is well known (e.g. Knyazeva & Kharitonov 1996, Straižys 1995) that field single stars with identical spectral classification display a range of reddening-free photometric colors, supposedly a manifestation of a spread in metallicity, rotation, microturbulent velocity and evolutionary state. Some differences are therefore to be expected among mean spectra that comes from observations of different individual stars. The spread in Fig. 4 nevertheless appears larger than accountable for simply by the cosmic spread in source individual stars, and points to inaccurate source observations and/or following data treatment leading to the combined average spectra, like missing de-reddening of source spectra before merging them into a mean spectrum (a possible explanation for the largely deviating Pickles 1985 library).

In conclusion, the libraries of mean optical spectra appear (*a*) scarce in number, with (*b*) a limited quantity of individual source spectra used to built up mean spectra (less than five single spectra per mean spectrum on average), with (*c*) recent spectral classification of individual source stars sometimes different from that originally adopted (e.g., all the seven stars used by Sviderskiene 1988 to derive his mean B7V spectrum are all still classified as B7V stars by SIMBAD in 2005; on the contrary, all the six stars he used to built the mean M0V spectrum are now reported as K7V in SIMBAD), and with (*d*) sometimes missing reddening correction of source spectra. Libraries of mean spectra are therefore to be used with the same care as those of individual star spectra, and this is certainly an area susceptible of large improvements in the future.

7. High resolution libraries

There is a significant amount of libraries of high resolution spectra of stars. The same portion of the spectrum of Procyon (α CMi, F5 IV-V) is displayed in Fig. 5 for libraries characterized by a resolving power ≥40 000. Comparing the finer spectral details, their progression well follow the declared resolving power. Altogether, the high resolution libraries in Fig. 5 present spectra of 1410 stars well distributed over the HR diagram. Other similar high resolving power and high S/N libraries of normal stars are presented by Montes and Martin (1998, 48 stars), and Soubiran et al. (1998, 211 stars), while that of Barnbaum (1994) is entirely devoted to 89 Carbon stars.

The mentioned high resolution spectral libraries however significantly differ among them in the (*i*) treatment of 'bad' pixels (left un-removed/uncorrected in Takeda et al. 2005, and only simply masked in Prugniel and Soubiran 2001), (*ii*) extension of the covered wavelength range and absence of gaps (with Allende Prieto et al. 2004 and Bagnulo et al. 2003 best scoring), (*iii*) transformation of the wavelength scale to null radial velocity (missing in Bagnulo et al. 2003, and Takeda et al. 2005). None of them correct for and remove the telluric absorption lines (Prugniel and Soubiran 2001 mask them), and none flux calibrate the spectra (except for Bagnulo et al. 2003 that present the spectra in relative fluxes).

Investing future telescope time on high resolution and high S/N survey observations seems better worth if directed toward chemically peculiar, extreme metallicity or well defined specific types of objects (cf Castelli & Hubrig 2004). New high resolution surveys of normal field stars appears justified only if the spectra will satisfy at the same time most of the following requirements: (*a*) accurate cleaning of cosmic rays and bad pixels, (*b*) accurate flat fielding, fringing compensation, blaze function removal, (*c*) correction for telluric absorption lines, (*d*) reduction of the wavelength scale to null radial velocity, (*d*) (absolute) fluxing of the spectra, (*e*) covering a wide fraction of the whole optical range, and (*f*) absence of significant gaps in the covered range (as for the single gap centered right on the key Ca II triplet feature in the otherwise highly valuable UVES survey spectra of Bagnulo et al. 2003).

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