Mem. S.A.It. Suppl. Vol. 8, 180

Memorie della
Supplementi

An overview of high-resolution synthetic stellar libraries.

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Abstract. We present the main properties of seven libraries of synthetic stellar spectral energy distributions at high resolution (Brott & Hauschildt, MARCS, Munari et al., Martins et al., Coelho et al., UVBLUE, and BLUERED). We also show a qualitative comparison of the spectral behaviour of these grids.

Key words. Stars: atmospheres

1. Introduction

In the past few years we have witnessed a flourishing of libraries of synthetic stellar spectra at high spectral resolution. Such theoretical tools were much needed in order to match the high quality that observations have achieved with the current generation of telescopes and spectrographs.

Nowadays, detailed spectroscopic data are not restricted to the local universe, but also high-redshift galaxies can be observed at a rest-frame resolution smaller than 10 Å (e.g., the K20 survey, Cimatti et al. 2002; the Gemini Deep Deep Survey, Abraham et al. 2004), which makes the old grids of theoretical stellar spectral energy distributions (SED) (e.g., Kurucz 1993a) not suitable to analyse those data without loss of information.

The improvement in observational capabilities has motivated the creation of improved empirical libraries of stellar spectra (e.g., STELIB, Le Borgne et al. 2003; Indo-US, Valdes et al. 2004; UVES POP Bagnulo et al. 2003). The most important shortcoming of these libraries is that they are mainly formed by stars from the solar vicinity which have undergone the same chemical evolution and show an abundance pattern similar to the Sun. The need to have spectra with suitable metallicities to understand the SEDs from stellar systems with a very different chemical enrichment history makes theoretical stellar libraries very useful.

In order to compute a spectrum at high resolution each absorption line profile must be taken into account individually (this is, it is not possible to use a statistical treatment of the line opacity such as the use of opacity distribution functions [ODF; Strom & Kurucz 1966]). Therefore, a large amount of line data must be gathered and processed, but the improvement, both in speed and memory, of the computing facilities now allows one to compute a large number of model atmospheres and spectra at high resolution over a wide wavelength interval in a reasonable amount of time. If the sampling of the evolutionary phases is good enough, these grids can be coupled to population synthesis codes to analyse stellar aggre-

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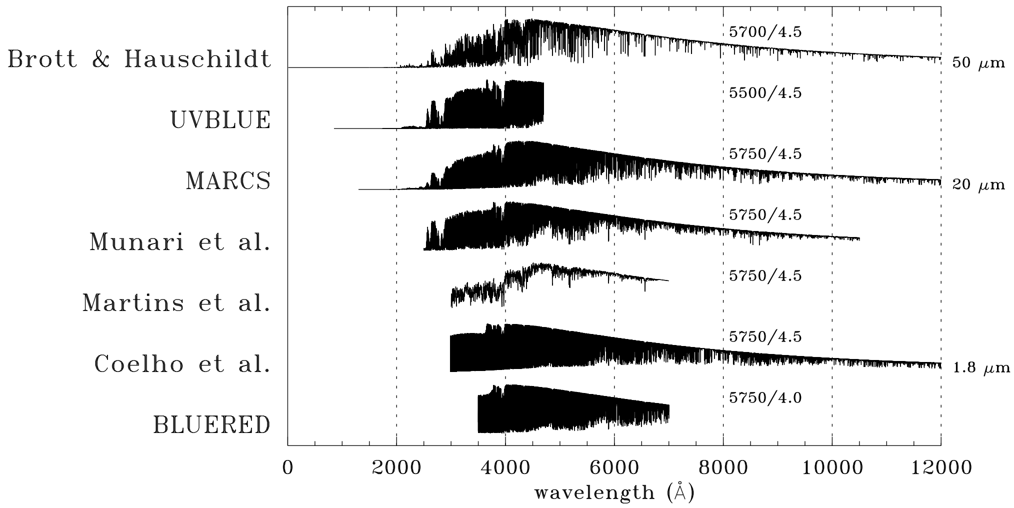

Fig. 1. Synthetic spectra with (near) solar physical parameters, which are not equal for all cases. Note how the spectral resolution reflects on the aspect of each spectrum. The wavelength limit is set to 1.2 μm, however the Brott, MARCS and Coelho spectra extend to longer wavelengths.

gates. In fact, this reason has been the main driver for the computation of many of the new stellar libraries. Here we present grids which cover a quite large part of the Hertzsprung-Russell diagram and whose data are available on the web (apart from the BLUERED, see next section) [1].

2. The libraries of synthetic stellar spectra.

In this work we took into account seven grids of synthetic stellar spectra: Brott & Hauschildt (2005 hereafter called Brott), UVBLUE (Rodriguez-Merino et al. 2005), MARCS (Gustafsson et al. 2003, 2005), Munari et al. (2005 hereafter called Munari), Martins et al. (2005 hereafter called Martins), Coelho et al. (2005 hereafter called Coelho), BLUERED (Bertone et al. 2003).

Here we briefly outline some major properties and we refer for a deeper description to the papers where the libraries are presented. In Figure 1 we plot an example of a spectrum with near solar parameters for each library, showing up the wavelength coverage and the different spectral resolution. The main properties of the libraries are reported in Table 1. Usually, the computation of a high-resolution spectrum is a two step process: the first one is to produce the model atmosphere, which is then used to synthetize the emerging spectrum at any desired resolution. However, thanks to the present computing performances, model atmosphere codes, which use an opacity sampling method to account for the line absorption, can directly produce as output a well sampled flux distribution; this is the case of the PHOENIX and MARCS codes. In Table 2 we report the model atmospheres and spectrum synthesis codes which were used to compute each grid.

[1] Other collections of high-resolution synthetic spectra have been computed. For the sake of space they have not been included in this work, but they also deserve a detailed analysis. We just list here some of them: Chavez et al. (1997), Leonardi & Rose (2003), Zwitter et al. (2004), Murphy & Meiksin (2004), OSTAR2002 (Lanz & Hubeny 2003).

Table 1. Main properties of the libraries of synthetic stellar spectra.

Library	λ (Å)	sp. res.	$T_{\rm eff}$ (K)	$\log g$ (dex)	[M/H] (dex)	[α/Fe] (dex)	geom.	l/H_p	ξ (km s^{-1})
Brott	10	2 Å/px	2700	-0.5	-4.0	-0.2	sph	2.00	2.0
	30,000		10,000	5.5	+0.5	+0.8			
UVBLUE	850	50,000	3000	0.0	-2.0		pp	1.25	2.0
	4700		50,000	5.0	+0.5				
MARCS	1300	20,000	4000	-1.0	-5.0	0.0	sph/	1.50	0.0
	20 μm		8000	5.0	+1.0	+0.4	pp		5.0
Munari	2500	2000	3500	0.0	-2.5	+0.4	pp	1.25	1
	10,500	20,000	47,500	5.0	+0.5				4
Coelho	3000	0.02 Å/px	3500	0.0	-2.5	+0.4	pp	1.25	1
	1.8 μm		7000	5.0	+0.5				2.5
Martins	3000	0.3 Å/px	3000	-0.5	-1.0		sph/	1.25	var.
	7000		55,000	5.5	+0.3		pp	2.00	
BLUERED	3500	500,000	4000	0.0	-3.0		pp	1.25	2.0
	7000		50,000	5.0	+0.3				

Notes: in columns 2, 3, 4, 5, 6, 7, and 9 the number in the two consecutive rows indicates the range of the quantity; in column 3, the resolving power, $R = \lambda/\Delta\lambda$, or the dispersion, in Å/px, are given; in column 8, the geometry adopted in the model atmosphere is given (*sph* for spherical simmetry, *pp* for plane parallel layers); column 9 gives the mixing length parameter; column 10 reports the microturbulence velocity ξ.

Table 2. Model atmospheres and spectrum synthesis codes.

Library	Model Atmospheres	Spectrum Synthesis Codes
Brott	PHOENIX	PHOENIX
UVBLUE	ATLAS9 (old)	SYNTHE
MARCS	MARCS	MARCS
Munari	ATLAS9 (new)	SYNTHE
Coelho	ATLAS9 (new)	FANTOM
Martins	PHOENIX/ ATLAS9 (old)/ TLUSTY	PHOENIX/ SPECTRUM/ SYNSPEC
BLUERED	ATLAS9 (old)	SYNTHE

2.1. Brott and Hauschildt

This library has been produced to form part of the data base of theoretical models for the GAIA astrometric mission.

The flux distributions of this library have been obtained with the stellar atmosphere code PHOENIX v13 (Hauschildt & Baron 1999). A huge list of atomic and molecular lines has been made, reaching a total of more than 700 million entries. The inclusion of the opacity of hundreds of molecular species makes this code particularly suitable to model stars at the cooler edge of the temperature scale.

The emerging flux from 10 Å to 3 μm is sampled with a typical step of 2 Å, but the wavelength points are dynamically chosen in order to better describe particularly interesting features. The irregularity of the mesh among the different spectra should be carefully taken into account. A coarser sampling is used to represent the stellar SEDs up to 50 μm. The wavelength scale is in vacuum.

The LTE model atmospheres have been computed adopting a spherical symmetry, with a fixed mass of 1 $M_{\odot}$; however mass scaling produces small changes in the emerging spectrum (Hauschildt et al. 1999). The newer versions of PHOENIX models adopt a mixing-length to pressure scale-height ratio l/H_p=2. A NLTE extension to effective temperature greater than 10,000 K is planned.

The approximately 44,000 synthetic spectra are available at the ftp site ftp.hs.uni-hamburg.de/pub/outgoing/phoenix/GAIA.

2.2. MARCS

The MARCS model atmospheres (Gustafsson et al. 1975, 2003) have been continuously improved since the mid-1970s. The synthetic spectra presented here are part of the last generation, which can adopt either spherical (at low surface gravity regime) or plane-parallel geometry. A large effort has been done to achieve realistic models for low-$T_{\rm eff}$ stars, by including the major sources of molecular opacity in M-type stars and by adjusting the oscillator strength of a few thousand strong absorption lines. The LTE atmospheric structure is computed in both the above-mentioned geometries and various non solar-scaled chemical composition are explored.

The flux distribution is sampled with a non-constant wavelength step given by $R = \lambda/\Delta\lambda = 20,000$, which can result in a poor representation of the line profiles. The wavelength are given in the vacuum scale. The grid, which is made up of about 9000 model atmospheres and SEDs, has a $T_{\rm eff}$ range (4000–8000 K) that can restrict its application to stellar population analyses, due to the lack of spectra for O, B, A, and M-type stars.

All the data can be downloaded from the MARCS web page http://marcs.astro.uu.se/
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2.3. UVBLUE

This library has been conceived to study the UV behaviour of stars at high resolution and to provide an up-dated tool for stellar population synthesis codes. The spectra, computed using the SYNTHE codes (Kurucz 1993b), are based on the ATLAS9 LTE model atmospheres (Kurucz 1993a), which use the solar abundances by Anders & Grevesse (1989) and the "old" set of ODFs. Therefore, all the pros and the cons of these Kurucz models apply to this library. The "predicted" atomic lines (generated from theoretically computed transitions), present in the Kurucz (1992) list, were not included in the computation, due to their large wavelength uncertainty, which would make the comparison with high-resolution observations inconsistent. As these lines are usually weak, their inclusion would cause a depression in the pseudo-continuum level.

The high spectral resolution makes this library suitable to match in detail the observations from the UV spectrographs onboard the current generation of satellites, providing a positive feedback for a much needed improvement of the line list in the ultraviolet (e.g., Peterson et al. 2001).

The library has 1770 entries and is publicly available. A R=10,000 release can be found at http://www.inaoep.mx/~modelos/uvblue/uvblue.html or http://www.bo.astro.it/~eps/uvblue/uvblue.html.

2.4. Munari et al.

This very large library contains the spectra of 51,288 combination of physical parameters. It is based on the revised Kurucz's ATLAS9 LTE model atmospheres (Castelli & Kurucz 2003), which use the solar abundances by Grevesse & Sauval (1998) and a "new" set of ODFs (Castelli & Kurucz 2003). The synthetic spectra has been computed using the SYNTHE code and the Kurucz's (1992) atomic and molecular line lists, except for the TiO, for which the larger data base of Schwenke (1998) was adopted.

The main goal was to provide a theoretical tool to match stellar spectra coming from present and foreseen large spectral surveys (such as SLOAN, RAVE, GAIA), therefore greater care was taken to reproduce the spectral features rather then providing a correct broadband behavior. This led to the exclusion of the "predicted" lines from the adopted line list. The grid cover a very large volume in the parameter space and also include the effect of rotation velocity up to 500 km s^{-1}. The synthetic spectra are provided with different resolving power and wavelength sampling. In this work we are using the $R = 20,000$ spectra with 1 Å/px dispersion. The spectra are available at http://archives.pd.astro.it/2500-10500 or at http://gaia.esa.int/spectralib/.

2.5. Coelho et al.

The study of old and intermediate-aged stellar systems has been the main driver for the genesis of this spectral library. As it is focused to provide synthetic spectra for F to M-type stars, the upper $T_{\rm eff}$ limit is set to 7000 K.

The 2705 synthetic spectra, which cover a large wavelength interval from the mid ultraviolet to the near infrared, have been generated using the FANTOM synthesis code (Cayrel et al. 1991), using the new ODFs ATLAS9 models (Castelli & Kurucz 2003) for microturbulence velocity ξ=2 km s^{-1}. However, the spectra assumed a different ξ, depending on the surface gravity, varying from 1.0 km s^{-1} for dwarfs to 2.5 km s^{-1} for supergiants. The opacity data from both atomic and molecular transitions have been carefully gathered to make up a list which includes about 1.5 million lines of nine biatomic molecules (C_2, CN, CO, CH, NH, OH, MgH, FeH, TiO), which are dominant opacity sources in late-K and M stars. This line list is an updated version of the one in Barbuy et al. (2003).

Since the abundance pattern of the Galaxy bulge and elliptical galaxies show an overabundance of α-elements with respect to the solar composition (e.g., McWilliam & Rich 1994; Worthey et al. 1992), a grid with [α/Fe]=+0.4 and a subset of α-enhanced spectra with [Ca/Fe]=0.0 are also included.

The absolute flux distributions were calibrated using the continuum level of the ATLAS9 models. The data are available at http://www.mpa-garching.mpg.de/PUBLICATIONS/DATA/SYNTHSTELLIB/syntheticstellarspectra.html.

2.6. Martins et al.

This library was also built for using as an input for stellar population synthesis. It is composed using different theoretical models and synthesis codes (see Table 2), with the purpose of adopting the most suitable ones for the different regions in the HR diagram. The PHOENIX spherical LTE model atmospheres have been adopted for stars with $T_{\rm eff}\leq$4500 K, while TLUSTY non-LTE models (Hubeny & Lanz 1995) were used for $T_{\rm eff}\geq$27,500 K. In between, the LTE ATLAS9 models (Kurucz 1993a) have been chosen. The spectra were synthetized using three codes: PHOENIX (3000–4500 K), SPECTRUM (4750–8250 K; Gray & Corbally 1994), and SYNSPEC (>8250 K; Hubeny et al. 1995). The microturbulence and rotational velocities increase with increasing temperature: the first varies from 2.0 to 10 km s^{-1}, the latter assumes the values of 10, 50, and 100 km s^{-1}. Martins et al. (2005) show that adopting multiple sources and codes (which also means using different ingredients, e.g. solar abundances) does not introduce dramatic discontinuities in the spectral properties along the grid.

This library of 1654 entries extends over a 4000 Å-wide optical interval. It covers almost all the significant stellar loci in the HR diagram and is available at http://www.iaa.csic.es/~rosa.

2.7. BLUERED

This optical library was built to test the spectral properties of stars and stellar population at very high resolution and over a large range of metallicity. Its wavelength range encompasses the entire set of Lick spectrophotometric indices (e.g., Worthey et al. 1994). BLUERED is based on the Kurucz's LTE models (ATLAS9 with "old" ODFs), synthesis codes (SYNTHE) and line list (Kurucz 1992), with the inclusion of the TiO lines by Schwenke (1998). The 832 spectra span over a parameter space which reflects the extension of the Kurucz's model atmosphere grid; however, the lower $T_{\rm eff}$ limit is set to 4000 K, because of the lack of polyatomic molecules in the opacity calculation.

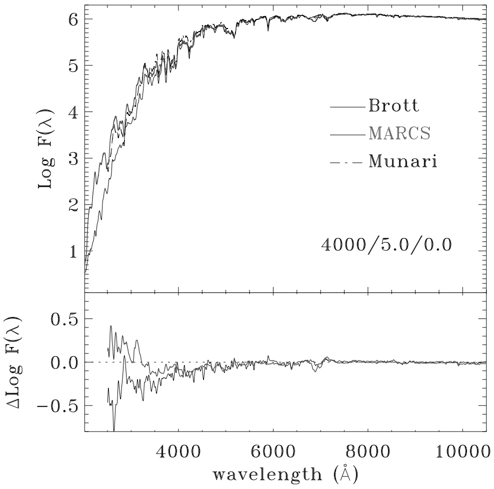

Fig. 2. The spectral energy distribution of three models from the Brott, MARCS and Munari spectral libraries, from the mid-UV to the near infrared. The parameters of the models are indicated on the plot as T_{eff}/log g/[M/H]. The lower panel shows the logarithmic residuals with respect to the Munari spectrum.

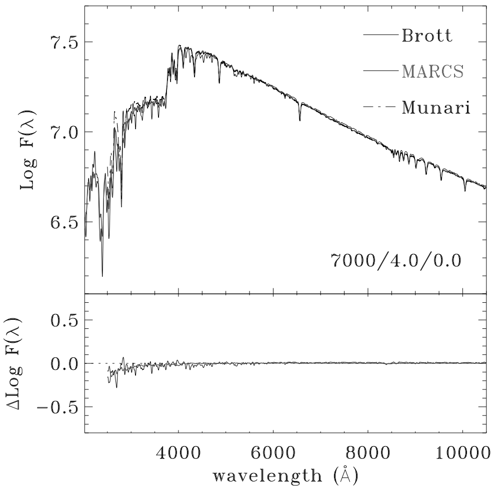

Fig. 3. Same as Fig. 2, but for a warmer model with T_{eff}=7000 K.

Table 3. Solar abundances for the first 30 elements.

el.	MARCS	Brott	old ODFs	new ODFs
H	12.00	12.00	12.00	12.00
He	10.93	10.99	10.99	10.93
Li	1.10	3.31	1.16	1.10
Be	1.40	1.15	1.15	1.40
B	2.79	2.60	2.60	2.55
C	8.41	8.55	8.56	8.52
N	7.80	7.97	8.05	7.92
O	8.66	8.87	8.93	8.83
F	4.48	4.56	4.56	4.56
Ne	8.08	8.08	8.09	8.08
Na	6.33	6.33	6.33	6.33
Mg	7.58	7.58	7.58	7.58
Al	6.47	6.47	6.47	6.47
Si	7.55	7.55	7.55	7.55
P	5.45	5.45	5.45	5.45
S	7.33	7.21	7.21	7.33
Cl	5.28	5.50	5.50	5.50
Ar	6.40	6.52	6.56	6.40
K	5.12	5.12	5.22	5.12
Ca	6.36	6.36	6.36	6.36
Sc	3.17	3.10	3.10	3.17
Ti	5.02	5.02	4.99	5.02
V	4.00	4.00	4.00	4.00
Cr	5.67	5.67	5.67	5.67
Mn	5.39	5.39	5.39	5.39
Fe	7.50	7.50	7.67	7.50
Co	4.92	4.92	4.92	4.92
Ni	6.25	6.25	6.25	6.25
Cu	4.21	4.21	4.21	4.21
Zn	4.60	4.60	4.60	4.60

Note: the scale is 12 + log(n_{el}/n_H). Column 4 and 5 report the abundances adopted in the ATLAS9 models with "old" and "new" ODFs.

3. The comparison.

We present here a qualitative comparison of the stellar spectra of the libraries described in the previous section. The differences that appear in the computed flux of spectra which are labelled with the same nominal physical parameters can have various origins: for instance, the input model atmospheres, the solar abundances adopted (see Table 3), the atomic and molecular species and the number of absorption lines taken into account, the line parameters, the convection treatment, or the algorithms used by the codes. In what follows, we

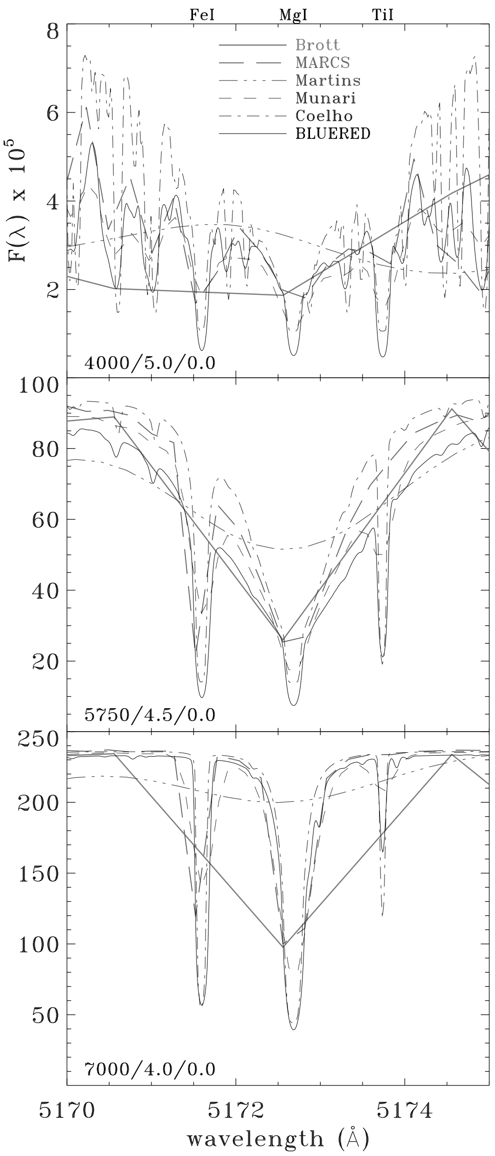

Fig. 4. A 5-Å spectral interval centered on the Mg I λ5172 line. The absolute flux calibrated spectra are shown for three different parameter combinations ($T_{\rm eff}$/log g/[M/H]), as reported in each panel. The Brott spectrum in the central panel has $T_{\rm eff}$=5800 K (50 K higher than the other models).

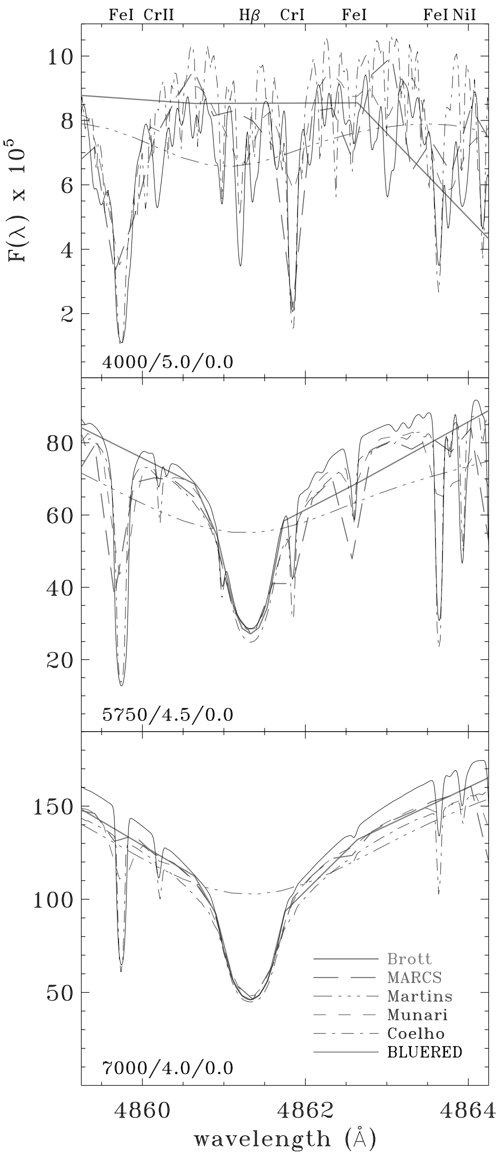

Fig. 5. Same as Fig. 4, but for an interval around the Hβ line.

tranformed all wavelengths to the air reference frame. We present comparisons of spectra from solar metallicity models.

Figures 2 and 3 show the energy distributions computed for model atmospheres of typical main sequence stars of $T_{\rm eff}$=4000 K and 7000 K by PHOENIX (the Brott spec-

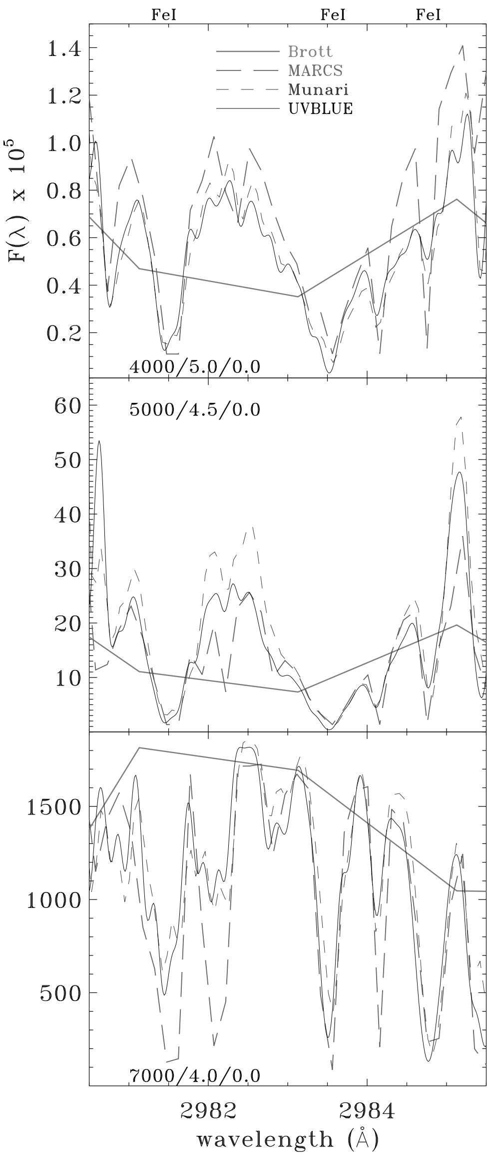

Fig. 6. Same as Fig. 4, but for a 5 Å interval in the mid-UV. The UVBLUE spectra are broadened to R=20 000 to make the plots more readable. The middle panel show spectra of $T_{\rm eff}$=5000 K.

trum), MARCS and ATLAS (the Munari spectrum) codes. The spectra have been broadened to an equal resolution of FWHM=25 Å. The logarithmic flux distributions point out that the larger differences appear in the ultraviolet interval. The differences are larger at the lower temperature, where the PHOENIX SED has a systematically lower flux than the Munari spectrum for wavelengths shorter than ∼5000 Å, while the MARCS flux becomes greater at wavelengths shorter than about 3200 Å. At $T_{\rm eff}$=7000 K the discrepancies are on the whole less significant, being almost negligible (in the logarithmic scale) in the optical and near infrared.

Figures 4–6 show the behavior of the synthetic spectra in three 5 Å wide intervals around the Mg I λ5172 line, the Hβ line, and in a mid-UV interval affected by strong iron opacity. Apart from the UVBLUE case in Fig. 6, all spectra are plotted at their own resolving power and wavelength sampling. One of the aim of the figures is to cast light on the effects of the resolution on the spectral morphology. For the cases of the libraries of lower resolution (Brott and Martins), the opacity at each wavelength is produced by the contribution of a blend of absorption lines. In the upper and middle panel of Fig. 4, the Coelho spectra display narrower wings of the Mg I λ5172 line. This is most probably mainly due to different line parameters (oscillator strength and/or damping constants), as the Mg abundance is the same for all models (see Table 3). The discrepancy decreases at $T_{\rm eff}$=7000 K.

The differences caused by the adoption of different line lists and line parameters are easiest to detect for the grids at higher resolving power (in the optical, Coelho and BLUERED), but in some cases they are strong enough to be detected also at lower resolution: see for instance the lines at about 2981.5, 2982.0, and 2984.2 Å in Fig. 6 for the $T_{\rm eff}$=7000 K panel. In this figure, the UVBLUE spectra have been broadened to R=20,000, the same nominal resolving power of the MARCS and Munari grids, to highlight the effect of the different content of Fe in the solar composition, which is 0.17 dex lower for MARCS and Munari with respect to UVBLUE. However, the iron line profiles of Munari and UVBLUE are quite similar, while larger deviations appear in the MARCS spectra.

It is therefore of great importance to produce more complete and reliable line lists, both of atomic and molecular species, using the valuable feedback that the use of the current set of high resolution synthetic libraries will provide from the match with high-quality spectroscopic observations.

Acknowledgements. The author would like to thank Miguel Chávez for the helpful discussions. This work received financial support from the Mexican CONACyT via grant SEP-2004-C01-47904.

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