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Computed H_β indices from ATLAS9 model atmospheres*

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ABSTRACT

Aims. Grids of H_β indices based on updated (new-ODF) ATLAS9 model atmospheres were computed for solar and scaled solar metallicities [+0.5], [+0.2], [0.0], [−0.5], [−1.0], [−1.5], [−2.0], [−2.5] and for α enhanced compositions [+0.5a], [0.0a], [−0.5a], [−1.0a], [−1.5a], [−2.0a], [−2.5a], and [−4.0a].

Methods. Indices for $T_{\rm eff}$ > 5000 K were computed with the same methods as described by Lester et al. (1986, LGK86) except for a different normalization of the computed natural system to the standard system. LGK86 used special ODFs to compute the fluxes. For $T_{\rm eff} \le 5000$ K we computed the fluxes using the synthetic spectrum method. In order to assess the accuracy of the computed indices comparisons were made with the indices computed by Smalley & Dworetsky (1995, A&A, 293, 446, MD95) and with the empirical relations $T_{\rm eff}$–H_β given by Alonso et al. (1996, A&A, 313, 873) for several metallicities. Furthermore, for cool stars, temperatures inferred from the computed indices were compared with those of the fundamental stars listed by MD95. The same kind of comparison was made between gravities for B-type stars.

Results. The temperatures from the computed indices are in good agreement, within the error limits, with the literature values for 4750 K $\le T_{\rm eff} \le$ 8000 K, while the gravities agree for $T_{\rm eff}$ > 9000 K. The computed H_β indices for the Sun and for Procyon are very close to the observed values. The comparison between the observed and computed H_β indices as function of the observed H_β has shown a very small trend which almost completely disappears when only stars hotter than 10 000 K are considered. The trend due to the cool stars is probably related with the low accuracy of the fundamental $T_{\rm eff}$ which are affected by large errors for most of the stars.

Key words. stars: atmospheres – stars: fundamental parameters – techniques: photometric

1. Introduction

H_β indices are a useful tool to derive stellar parameters, in particular the temperature for A4-G8 stars ($T_{\rm eff}$ ~ 8000–5500 K), but especially the gravity for B-type stars ($T_{\rm eff}$ ~ 30 000–10 500 K).

Previous last works on synthetic H_β indices from ATLAS9 models are those from Smalley & Dworetsky (1995, hereafter SD95) and Lester et al. (1986, hereafter LGK86). SD95 computed the indices only for the solar metallicity, while LGK provided them for numerous different metallicities.

Both LGK86 and SD95 used the same ATLAS9 models from Kurucz (1979), but they adopted different filter curves and different methods to normalize the computed indices to the observed indices. LGK86 adopted as transmission curves the filter set (212, 214) from Crawford & Mander (1966) and selected five stars (γ Gem (HD 47105), α CMi (HD 61421), β Leo (HD 102647), η UMa (HD 120315), and α Lyr (HD 172167)) to fix the transformation from the natural system of the computed indices to the standard system. SD95 used two Gaussian response functions with widths of 30 Å and 150 Å, respectively. They derived spectroscopic H_β indices from spectra of more than 50 stars observed at medium resolution. The normalization of the spectroscopic indices to the standard system was performed by fitting the spectroscopic indices to the photometric indices. The same procedure was used to obtain synthetic H_β indices that they derived by applying the filters to synthetic spectra centered on the Hβ profile.

Both Castelli (1991) and Napiwotzki et al. (1993) found that the LGK86 indices were not accurate enough for stars hotter than about 15 000 K and indicated the cause of this shortcoming in the values adopted by LGK86 for the model parameters of η UMa. Vice versa, SD95 showed that their synthetic indices closely agree with the photometric indices for stars covering a large range of temperatures and gravities. However, their computed indices are limited only to the solar metallicity.

The H_β indices presented in this paper are based on updated ATLAS9 models atmospheres (new-ODF models, Castelli & Kurucz 2003). The indices were computed both for scaled solar metallicities and scaled solar metallicities with an enhancement of +0.4 dex for the α element abundances. The metallicity ranges from [−2.5] to [+0.5], the temperature from 3500 K to 50 000 K and the gravity from log g = 0.0 to log g = 5.0.

As described in Sect. 2, we used the same response functions as LGK86, but we adopted a different method to scale the computed indices to the observed indices.

To investigate the accuracy of the synthetic H_β indices we compared the $T_{\rm eff}$–H_β relations from our indices with those from MD95 and LGK86, and, for cool stars, with the empirical relations from Alonso et al. (1996). Also the difference of observed and computed H_β indices was plotted as a function of the observed H_β. Finally, we compared stellar parameters $T_{\rm eff}$ and log g inferred from H_β with the parameters of fundamental

* Full Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://www.cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/454/333

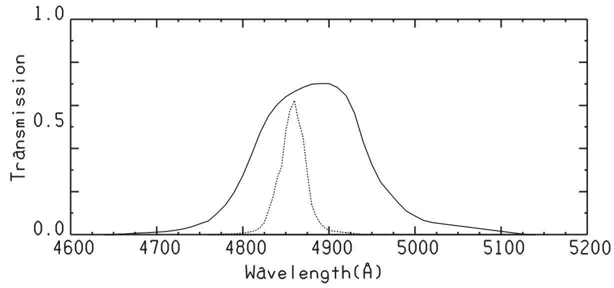

Fig. 1. Transmission curves for the filter set (212, 214) from Crawford & Mander (1966). The dotted line is the narrow filter 212 and the full line is the wide filter 214.

stars as they were determined by SD95 and successive updated papers.

2. Synthetic H_β indices

The H_β index is defined as the magnitude difference corresponding to the ratio of the intensities measured through two interference filters centered on H_β with half-widths of about 30 Å and about 150 Å, respectively. By means of the HBETA code from Kurucz[1] we computed the quantity:

$$H'_\beta = -2.5\left[\log\frac{\int_{\alpha_N}^{\beta_N} F_\lambda S_N(\lambda)\mathrm{d}\lambda}{\int_{\alpha_N}^{\beta_N} S_N(\lambda)\mathrm{d}\lambda} - \log\frac{\int_{\alpha_W}^{\beta_W} F_\lambda S_W(\lambda)\mathrm{d}\lambda}{\int_{\alpha_W}^{\beta_W} S_W(\lambda)\mathrm{d}\lambda}\right]$$

which can be considered as the index in the natural system. $S_N(\lambda)$ and $S_W(\lambda)$ are the response functions of the narrow and wide filters respectively, and F_λ is the computed stellar flux at the star surface.

2.1. The response functions $S_N(\lambda)$ and $S_W(\lambda)$

The adopted transmission curves are the Kitt Peak filter set (212, 214) from Crawford & Mander (1966, Fig. 1). If both filters were symmetric on exactly the same central wavelength, H_β would be free from interstellar reddening and also from atmospheric extinction, provided that simultaneous measurements through the two filters are performed. But the two filters do not have the same central wavelength, which is 4859 Å for the narrow filter and 4890 Å for the wide filter. Therefore, they were corrected in the computations for the atmospheric extinction, for the response function of a standard 1P21 photomultiplier, and for the reflectivity of aluminium (Kurucz 1979). Because all these data are either scattered in the literature or are available only inside Kurucz's programs we have collected them in Appendix A, Table A.1.

2.2. The computed fluxes F_λ

Fluxes F_λ in the H_β region were computed for $T_{\rm eff} \geq 5250$ K by means of the BETA9 code of Kurucz which adds the contribution of an accurately computed Hβ profile (Peterson's subroutine HPROF4 of the SYNTHE[2] code) to the line blanketing yielded by special ODFs. Wavelengths for Hβ were chosen spreading away from line center at 4861.32 Å to give good resolution both to the line and to the two filters. The special ODF's were computed by Kurucz who used all the atomic lines, except Hβ, lying in the region 4700−5200 Å. The line blanketing was tabulated at 10 Å intervals for 56 values of temperature T and 21 values of gas pressure $P_{\rm gas}$. The special ODFs are available for several metallicities at the Kurucz website[3]. They are VMS binary files which have names BDFxxxBETA.DAT, where xxx indicates the metallicity. Each file contains 5 ODFs computed for microturbulent velocities ξ = 0.0, 1.0, 2.0, 4.0 and 8.0 km s^{-1}. We have converted the binary ODFs in ASCII format in order to use them with whichever available operating system. In particular, we computed H_β indices under GNU-Linux.

Because no molecular lines were included in the special ODFs computed by Kurucz, fluxes from ODFs were replaced by fluxes from synthetic spectra for $T_{\rm eff} \leq 5000$ K. The fluxes were computed with the SYNTHE code (footnote 2) at 500 000 resolution using both atomic[4] and molecular[5] Kurucz line lists. No atomic lines from predicted levels were considered.

2.3. Normalization of the H_β index

For the Kitt Peak filters (212, 214) the relation between the natural system and the standard system is not unique for all the stars, but there are two different relations for B and for A, F spectral types (Crawford & Mander 1966). Therefore, we transformed the H'_β indices to the standard system by means of the relations given by Crawford & Mander (1966):

$$H_\beta = 0.374 + 1.305 H'_\beta \quad \text{for B type stars}$$

$$H_\beta = 0.248 + 1.368 H'_\beta \quad \text{for A, F type stars}$$

As further step, the two H_β indices computed for Vega by using the two above relations were forced to match the observed index H_β = 2.904 (Crawford et al. 1972). Namely, the constants 2.258 and 2.151 were added to H_β(Vega) = 0.753 obtained from the first relation and to H_β(Vega) = 0.646 obtained from the second relation. Because we assumed $T_{\rm eff}$ = 10 500 K as limit between B and A, F spectral types we added 2.258 to all the indices computed for $T_{\rm eff} \leq 10\,500$ K, and 2.151 to all those computed for $T_{\rm eff} > 10\,500$ K. We experimented to determine which are the computed indices for Vega if the integrals over the filters (i.e. the denominators in the formula for H'_β) are dropped. We found that they are almost the same. They become H_β = 3.000 and H_β = 2.999 for B and for A, F stars, respectively, so that the constants −0.096 and −0.095 have to be added to all the computed H_β indices. However, the final result is the same indicating that it does not matter whether the integrals over the filters at the denominator are considered or not in the H'_β computations.

The Vega model used to compute H_β is a new-ODF ATLAS9 model (Castelli & Kurucz 2003) with parameters $T_{\rm eff}$ = 9550 K, log g = 3.95, ξ = 2 km s^{-1}, [M/H] = −0.5 (Castelli & Kurucz 1994).

The resulting index for the Sun is H_β = 2.590, in good agreement with H_β = 2.5955 ± 0.0005 observed by Olsen (1976) and 2.591 ± 0.005 determined by Saxner & Hammarback (1985). The model adopted for the Sun is a new-ODF ATLAS9 model

[1] Program beta.forcd in
`http://kurucz.harvard.edu/programs/COLORS`

[2] `http://kurucz.harvard.edu/programs/SYNTHECD/synthe.for`

[3] `http://kurucz.harvard.edu/OPACITIES/DFBETA`

[4] `http://kurucz.harvard.edu/LINELISTS/GF100`

[5] `http://kurucz.harvard.edu/molecules.html`

Table 1. Example of table with computed H_β indices.

$T_{\rm eff}$	log g	$[M]$	$V_{\rm turb}$	l/H	Small	Big	Beta
3500	0.00	0.00	2.00	1.25	−12.354	−12.505	2.713
3500	0.50	0.00	2.00	1.25	−12.321	−12.493	2.742
3500	1.00	0.00	2.00	1.25	−12.286	−12.477	2.768
3500	1.50	0.00	2.00	1.25	−12.269	−12.476	2.789
3500	2.00	0.00	2.00	1.25	−12.281	−12.498	2.803
3500	2.50	0.00	2.00	1.25	−12.327	−12.549	2.810
3500	3.00	0.00	2.00	1.25	−12.414	−12.634	2.807
3500	3.50	0.00	2.00	1.25	−12.551	−12.757	2.788
3500	4.00	0.00	2.00	1.25	−12.744	−12.919	2.746
3500	4.50	0.00	2.00	1.25	−12.932	−13.069	2.693
3500	5.00	0.00	2.00	1.25	−13.074	−13.175	2.644
3750	0.00	0.00	2.00	1.25	−13.602	−13.660	2.586
3750	0.50	0.00	2.00	1.25	−13.633	−13.689	2.583
3750	1.00	0.00	2.00	1.25	−13.637	−13.693	2.583
3750	1.50	0.00	2.00	1.25	−13.623	−13.683	2.588
3750	2.00	0.00	2.00	1.25	−13.600	−13.666	2.596
3750	2.50	0.00	2.00	1.25	−13.577	−13.649	2.606
3750	3.00	0.00	2.00	1.25	−13.566	−13.645	2.614
3750	3.50	0.00	2.00	1.25	−13.577	−13.659	2.618
3750	4.00	0.00	2.00	1.25	−13.625	−13.700	2.609
3750	4.50	0.00	2.00	1.25	−13.706	−13.766	2.588
3750	5.00	0.00	2.00	1.25	−13.794	−13.837	2.564
4000	0.00	0.00	2.00	1.25	−14.350	−14.405	2.581

(Castelli & Kurucz 2003) with parameters $T_{\rm eff}$ = 5777 K, log g = 4.44377, ξ = 1.0 km s^{-1}, and [M/H] = 0.0. The SD95 grid gives H_β = 2.581 for the Sun.

For η UMa (B3 V), Napiwotzki et al. (1993) found that the log g which best fits both H_β and H_γ profiles for $T_{\rm eff}$ = 17 000 K is log g = 4.24. Interpolating for the same temperature and gravity in our H_β grid computed for [M/H] = 0.0 and ξ = 2 km s^{-1} we obtain H_β = 2.689 which differs by −0.05 dex from the observed value 2.694 ± 0.001 (Hauck & Mermilliod 1998)[6]. SD95 obtained H_β = 2.698, which differs by +0.04 dex from the observed value. Vice versa, for $T_{\rm eff}$ = 17 000 K we derived log g = 4.31 from the observed H_β index, while SD95 yield log g = 4.18.

3. The computed grids of H_β index

H_β indices were computed as a function of $T_{\rm eff}$ and log g for the microturbulent velocity ξ = 2.0 km s^{-1} for the following metallicities: [+0.5], [+0.5a], [+0.2], [0.0], [0.0a], [−0.5], [−0.5a], [−1.0], [−1.0a], [−1.5], [−1.5a], [−2.0], [−2.0a], [−2.5], [−2.5a], [−4.0a]. A further table of H_β indices was computed for [M/H] = 0.0 and ξ = 0.0 km s^{-1}. The suffix "a" means that the abundances of the α elements, O, Ne, Mg, Si, S, Ar, Ca, and Ti are enhanced by +0.4 dex over the solar or scaled-solar abundances. The new-ODFs grids of model atmospheres (Castelli & Kurucz 2003) were used as input models for the computations. There are 476 models for each metallicity. The model parameters of the grids are given in Table 1 of Castelli & Kurucz (2003). These models differ from the Kurucz (1979) model atmospheres for the atomic line blanketing which was computed with a much larger number of lines in the new models and with the addition of the molecular line opacity which was completely left out in the 1979 models. Furthermore, updated solar abundances (Grevesse & Sauval 1998), updated continuous opacities, and 72 atmospheric layers instead of 64, were adopted.

[6] http://obswww.unige.ch/gcpd/gcpd.html

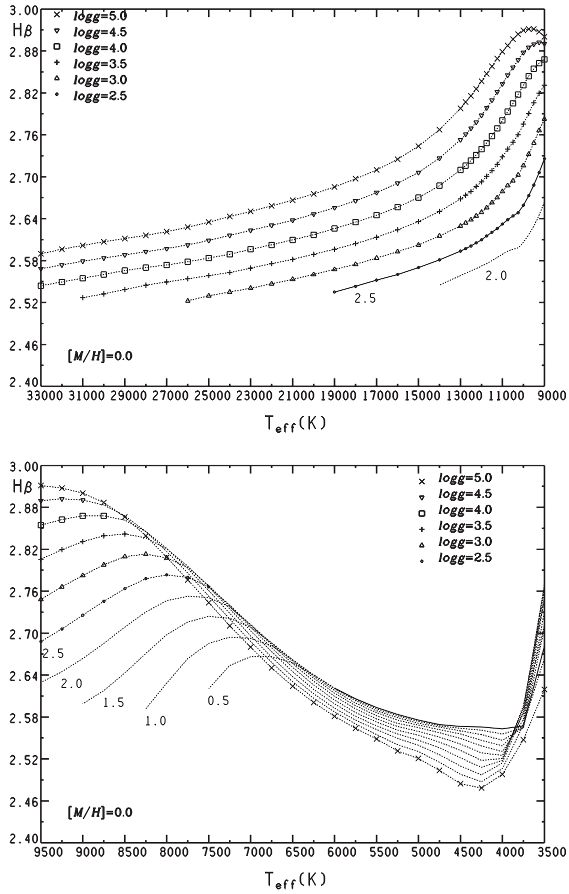

Fig. 2. The dependence of the H_β index on $T_{\rm eff}$ for different gravities, [M/H] = 0.0 and ξ = 2 km s^{-1}.

A total of 17 Tables of H_β indices for all the above quoted metallicities is available at the CDS. They are also available on our web[7]. They have the form shown in Table 1, where the Cols. 6 and 7 give the magnitude through the small and big filter, respectively, at the star surface. The last column lists the final H_β indices after normalization to Vega. The full table available on the website extends from $T_{\rm eff}$ = 3500 K to $T_{\rm eff}$ = 50 000 K.

4. Dependence of H_β on $T_{\rm eff}$, log g, and metallicity

The dependence of H_β on $T_{\rm eff}$ for several different gravities is shown in Fig. 2 for [M/H] = 0.0 and ξ = 2 km s^{-1}. H_β is a good gravity index for both giants and dwarfs for $T_{\rm eff}$ ≥ 9250 K provided that $T_{\rm eff}$ is known rather well in advance. The lower limit of 9250 K can be progressively shifted toward lower temperatures as the gravity lowers.

The two different normalizations of the indices for $T_{\rm eff}$ ≤ 10 500 K and $T_{\rm eff}$ > 10 500 K give rise to a small discontinuity of the index at 10 500 K for gravities lower than 3.5 dex. The discontinuity was reduced by smoothing H_β over $T_{\rm eff}$ from 10 250 K to 11 000 K. For [M/H] = 0.0 and log g = 2.0 the indices at 10 500 K and 10 750 K are respectively 2.611 and 2.618 without any smoothing and 2.618 and 2.615 after smoothing. At $T_{\rm eff}$ = 10 500 K the difference between the indices obtained with and without smoothing decreases from 0.007 dex for log g = 2.0 to 0.001 dex for log g = 5.0. We note that the only effect of a

[7] http://wwwuser.oat.ts.astro.it/castelli/colors/hbeta.html

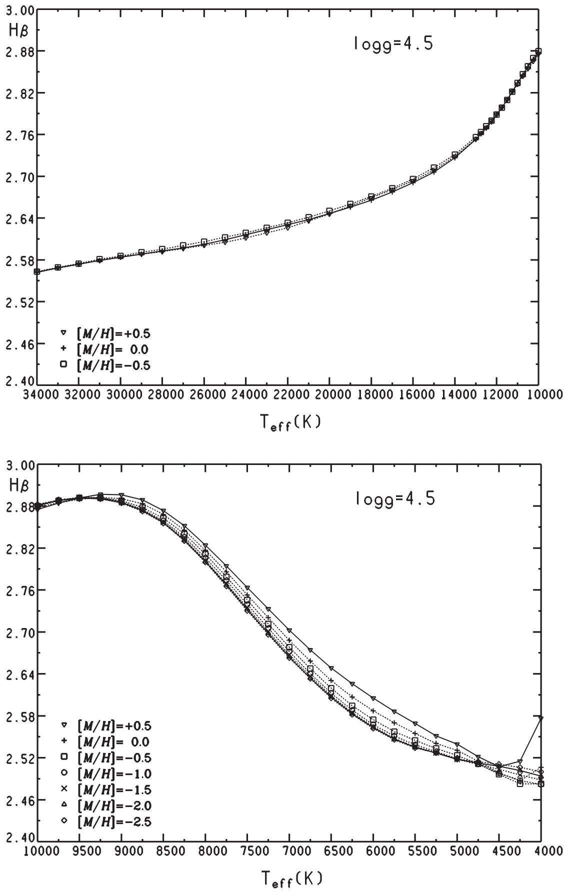

Fig. 3. The dependence of the H_β index on $T_{\rm eff}$ for different metallicities for log g = 4.5.

different choice for the temperature limit between the two different calibrations is a shift of the discontinuity to the position of the new $T_{\rm eff}$. This problem, affecting the indices computed for low gravities, is possibly related with the very small number of giants that were used by Crawford & Mander (1966) to fix the two transformation equations from the natural system to the standard system for B and A, F stars.

H_β can be used as a temperature index for dwarfs (log $g \geq$ 3.0) having $T_{\rm eff}$ between 8000 K and 4500 K and for giants (log g < 3.0) with $T_{\rm eff} \geq 4750$ K, but with a decreasing of the upper limit from 7500 K for log g = 2.5 to 6500 K for log g = 0.5. As noted by Alonso et al. (1996), H_β is a poorer temperature indicator than most of the other photometric colours, but because it is almost independent from interstellar extinction it may be useful to derive temperatures for reddened stars, although below about $T_{\rm eff}$ = 4500 K it is meaningless because rather than indicate the Hβ strength it measures the line blanketing due the numerous lines lying in the Hβ region, which may be also stronger than the Hβ line itself.

Figure 3 shows the dependence of H_β on metallicity for log g = 4.5. The effect of the metallicity is fully negligible for $T_{\rm eff} \geq 9250$ K, while there is some spread for cooler temperatures; but the spread decreases with decreasing metallicity and disappears when [M/H] ≤ -1.0. We checked that this behaviour is similar also for other gravities.

The comparison between H_β indices computed for [M/H] = 0.0 and different microturbulent velocities ξ = 2 km s^{-1} and ξ = 0.0 km s^{-1} has shown fully negligible differences.

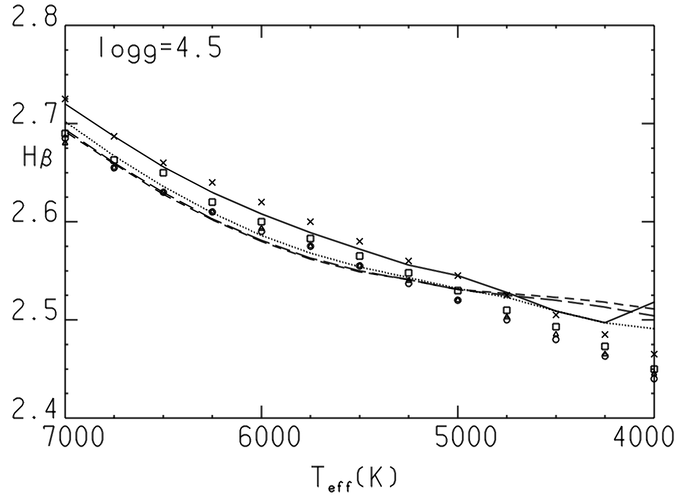

Fig. 4. Empirical relations $T_{\rm eff}$–H_β from Alonso et al. (1996) for F0V-K5V stars for [M/H] = 0.0 (crosses), −1.0 (squares), −2.0 (triangles), and −2.5 (circles)) are compared with the computed relations for log g = 4.5 and [M/H] = 0.0 (full line), −1.0 (dotted line), −2.0 (long-dashed line), −2.5 (dashed line).

5. Comparison with other H_β determinations

Alonso et al. (1996) calibrated $T_{\rm eff}$ versus the H_β index for main sequence stars with temperatures between 4000 K and 7000 K and for metallicities from [+0.5] to [−3.5]. Figure 4 compares the empirical $T_{\rm eff}$–H_β relations taken from Table 3 of Alonso et al. (1996) for [M/H] = 0.0, −1.0, −2.0, and −2.5 with the corresponding computed relations for log g = 4.5. Both the empirical relations for [M/H] = −2.0 and [M/H] = −2.5 and the two corresponding computed relations are undistinguishable for $T_{\rm eff}$ > 5000 K. Figure 4 shows agreement between computed and empirical relations for $T_{\rm eff} \leq 4250$ K for [M/H] = 0.0, while the computed indices are larger by several magnitudes than the observed indices for the lower metallicities when $T_{\rm eff}$ < 5000 K. We note that both observed and computed indices have to be taken with caution at these temperatures.

For $T_{\rm eff} \geq 4750$ K, the largest discrepancy between the computed and empirical relations occurs at 5750 K, where for [M/H] = 0.0, the difference $T_{\rm eff}$(empirical)-$T_{\rm eff}$(this paper) is −145 K. This behaviour is similar for the other metallicities. This maximum temperature difference of −145 K is very close to the uncertainty ΔT = 141 K assigned by Alonso et al. (1996) to the $T_{\rm eff}$–H_β empirical relation.

Figure 5 compares the computed $T_{\rm eff}$–H_β relations from this paper for [M/H] = 0.0, ξ = 2 km s^{-1} and both log g = 4.5 and log g = 2.5 with those inferred from the SD95 and the LGK86 computed indices. There is a close agreement with the SD95 relation, especially for hot stars. For cool stars, for a given H_β, the SD95 temperatures are a little bit higher than those from this paper. The difference $T_{\rm eff}$(SD95)−$T_{\rm eff}$(this paper) increases from 94 K at 5500 K to 228 K at 8000 K. As a consequence, the discrepancy between $T_{\rm eff}$–H_β relation from SD95 and the empirical relation from Alonso et al. (1996) is still larger than that we obtained.

For hot stars the difference in H_β for a given temperature corresponds to a difference in log g not larger than 0.12 dex which occurs at 15 000−16 000 K for log g = 4.5. Our indices predict higher gravities than SD95.

For a given H_β the LGK indices give lower temperatures for cool stars than those from both our indices and the SD95 indices

Table 2. T_{eff} (Col. 7) from the observed H_β index (Col. 6) is compared with T_{eff} (Col. 4) of stars having either T_{eff} (Col. 4) or log g (Col. 5) or both determined as fundamental values and taken from the literature (sources in Col. 9). Last column indicates which are the fundamental parameters.

HR	Star	HD	T_{eff}	log g[1]	H^2_β(obs)	$T_{eff}(H_\beta)$	ΔT_{eff}	Source[3]	Fundamental
788	12 Per	16739	6220 ± 168	4.20 ± 0.03	2.633	6237	17	1	T_{eff}, log g
	UX Men	37513	6151 ± 293	4.29 ± 0.01	2.615	6050	−101	1	T_{eff}, log g
2326	α Car	45348	7520 ± 460	1.0 (<1.5ph)	2.732	7533	13	2	T_{eff}
2373	WW Aur	46052	7827 ± 419	4.17 ± 0.02	2.862	7967	140	1	T_{eff}, log g
2693	δ CMa	54605	6170 ± 430	1.0 (<1.00ph)	2.660 ± 0.001	6170	0	2	T_{eff}
2943	α CMi	61421	6560 ± 130	4.06 ± 0.06	2.671 ± 0.000	6564	4	3	T_{eff}, log g
3524	RS Cha	75747	7342 ± 266	4.00 ± 0.21	2.791 ± 0.002	7431	89	1	T_{eff}, log g
	HS Hya	90242	5985 ± 282	4.34 ± 0.006	2.648 ± 0.003	6400	415	1	T_{eff}, log g
4534	β Leo	102647	8870 ± 350	4.1 (4.0 ± 0.25b, 4.1 ± 0.3ph)	2.899 ± 0.002	8302	−568	2	T_{eff}
4825	γ Vir	110379	7143 ± 450	4.21 ± 0.017	2.809	7582	439	1	T_{eff}, log g
6556	α Oph	159561	7960 ± 330	3.80 ± 0.3ph	2.832	7709	−251	3	T_{eff}
6611	V624 Her	161321	8222 ± 489	3.93 ± 0.014	2.870 ± 0.003	8021	−201	1	T_{eff}, log g
7484	V1143 Cyg	185912	6418 ± 184	4.32 ± 0.02	2.663	6533	115	1	T_{eff}, log g
7557	α Aql	187642	7990 ± 210	4.00 ± 0.3ph	2.821 ± 0.011	7643	−347	4	T_{eff}
	MY Cyg	193637	7437 ± 877	4.01 ± 0.02	2.756 ± 0.002	7189	−248	1	T_{eff}, log g
8123	δ Equ	202275	6393 ± 147	4.34 ± 0.02	2.629 ± 0.006	6214	−179	1	T_{eff}, log g
8728	α PsA	216956	8760 ± 310	4.20 ± 0.3ph	2.906 ± 0.004	8382	−378	3	T_{eff}

[1] "ph" indicates gravities derived from the spectrophotometry; "b" indicates gravities derived from Balmer profiles. [2] Hauck & Mermilliod (1998; see also footnote 6 in the text). [3] Sources for T_{eff} and log g in Cols. 4 and 5: (1) Smalley et al. (2002, Setal02); (2) Smalley & Dworetsky (1995, SD95); (3) Gardiner et al. (1999, GKS99); (4) Moon & Dworetsky (1985, MD85).

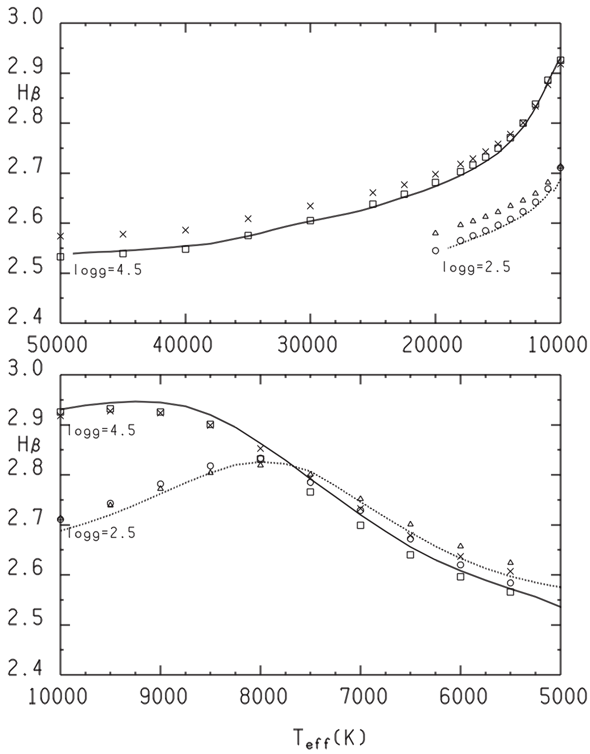

Fig. 5. Comparison of H_β indices from this paper (full line for log g = 4.5, dotted line for log g = 2.5) with H_β indices from LGK86 (crosses for log g = 4.5, triangles for log g = 2.5) and SD95 (squares for log g = 4.5, circles for log g = 2.5).

and give higher gravities for hot stars. This discrepancy increases with increasing temperature, so confirming the trend shown by Castelli (1991).

6. Stellar parameters from the computed H_β indices

We compared T_{eff} and log g that we derived from the computed H_β index with the parameters obtained by SD95 (and further improvements) for a set of stars called fundamental stars according to Hayes (1978), in that their model parameters were fixed by means of model-independent methods (fundamental methods) (see also Smalley 2005).

Among the stars studied by SD95 there are only four stars (HD 16739, HD 40183, HD 110379, and HD 202275) with both T_{eff} and log g given as fundamental parameters, while for all the other stars only either T_{eff} or log g is a fundamental value. For these stars the other non-fundamental parameter was derived spectroscopically by SD95 from Hβ profiles and/or from the spectrophotometry. Stars with fundamental T_{eff} are the Code et al. (1976) stars reanalyzed by SD95. Stars with fundamental log g are binary stars. Successively, for a few stars the parameters were improved by Gardiner et al. (1999) and especially by Smalley et al. (2002), who derived fundamental values of T_{eff} for several binary stars of the SD95 sample. We adopted for our comparisons the last values for the parameters that we found in the above quoted series of papers. The sources are listed in Col. 9 of Tables 2 and 3. The fundamental parameter is indicated in the last column of the tables.

Table 2 compares T_{eff} that we derived from the H_β index with T_{eff} taken from the above quoted literature for stars cooler than 9000 K. Figure 6 shows that for most of the stars with $T_{eff} \leq$ 8000 K the temperatures inferred from H_β agree with the literature values, within the error limits (actually, very large for some stars). Exceptions are HD 90242 and HD 187642 which lie outside the error limits. We can note the excellent agreement for Procyon (HD 61421) which has the most tightly constrained value of T_{eff} due to the accuracy of the direct measurement of angular diameter. The poor agreement for the two hottest stars with T_{eff} > 8000 K, HD 102647 (T_{eff}(fundamental) = 8870 K) and HD 216956 (T_{eff}(fundamental) = 8760 K) can be explained with the overcoming of the validity limits for H_β as temperature index (Fig. 2).

Table 3 compares log g that we derived from the H_β index with log g of the MD95 sample for stars hotter than 9000 K. There is only a star with an exceptionally large disagreement. It is HD 169022 for which Δlog g is −1.61. Other stars with large Δlog g are those with the gravity derived by MD95 from

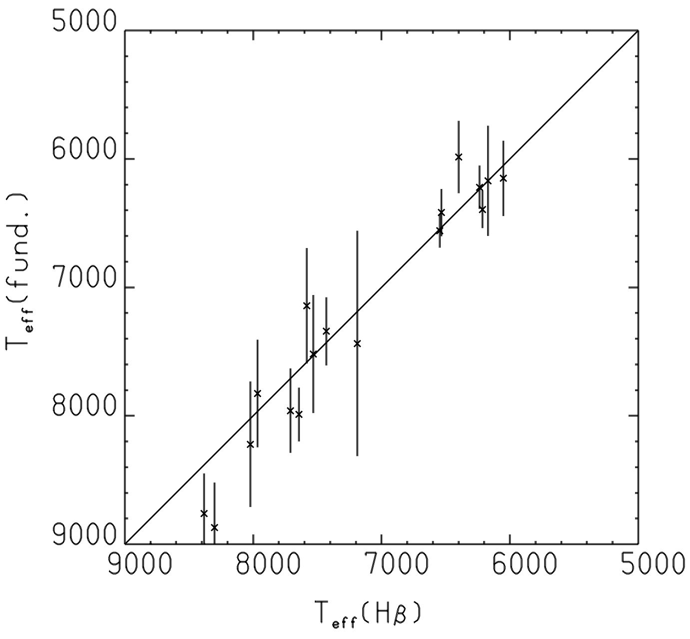

Fig. 6. $T_{\rm eff}$ computed from the H_β index is compared with $T_{\rm eff}$ taken from the SD95 sample of stars having either one or both parameters given as fundamental (see Table 2). The error bars are the errors in $T_{\rm eff}$ as taken from the literature sources listed in Table 2, Col. 9.

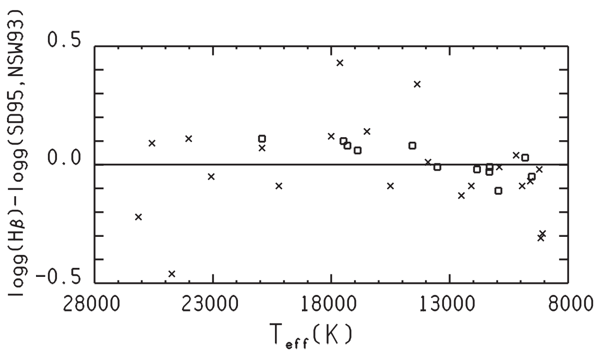

Fig. 7. Δlog g differences between the gravities derived from the H_β index and those taken from the literature (see Table 3) are plotted as a function of $T_{\rm eff}$. Squares indicate log $g(H_\beta)$ − log g(NSW93) from Table 3. Crosses indicate all the others Δlog g from Table 3, Col. 8.

the spectrophotometry, a method giving values affected by errors of the order of 0.5−0.3 dex. We added in Table 3 the comparison of log g from H_β with log g determined from Balmer profiles by Napiwotzki et al. (1993, hereafter NSW93) for 12 B-type stars. These are not fundamental stars having $T_{\rm eff}$ derived from observed Strömgren indices by using the TEFFLOGG code of Moon (1985). We adopted the temperatures from NSW93. Note that Napiwotzki et al. (1993) adopted for η UMa both $T_{\rm eff}$ = 17 000 K and $T_{\rm eff}$ = 17 320 K to derive log g from the Balmer profiles (their Fig. 18 and Table 4). For comparison purposes we used the two different $T_{\rm eff}$ values here and in Sect. 2.3. The agreement is within 0.11 dex for all the stars. Excluding HD 169022, Fig. 7 shows that the gravity derived from the H_β index agrees, on average, with the literature gravity obtained from other methods.

Figure 8 shows a comparison between the observed H_β indices given Tables 2 and 3 (Hauck & Mermilliod 1998 and footnote 6) and those interpolated in the grid computed for [M/H] = 0.0, ξ = 2.0 Km s^{-1}, by assuming for each star $T_{\rm eff}$ and log g given in Cols. 4 and 5 of Table 2 and Cols. 4 and 6 of Table 3.

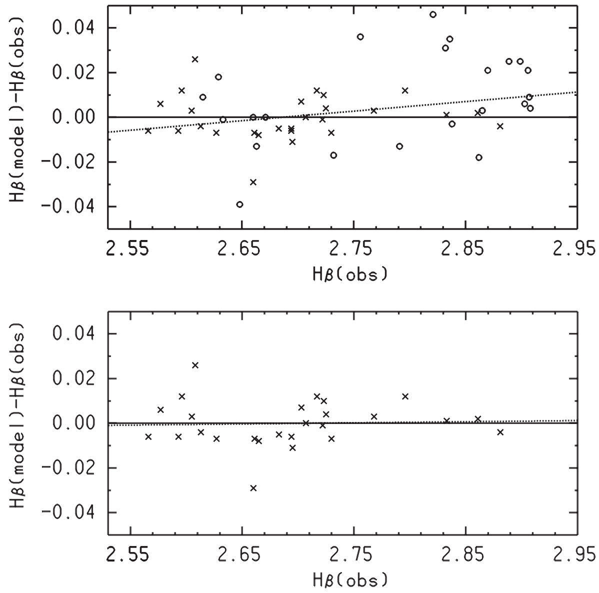

Fig. 8. Comparison between the observed H_β indices and those predicted for the stars listed in Tables 2 and 3 as a function of the observed H_β. In the upper plot all the stars (except ϵ Sgr) are plotted. Stars hotter than 10 000 K are shown as crosses, the cooler ones as open circles. The dashed line is the least squares fit to all the points. In the lower plot only stars with $T_{\rm eff}$ > 10 000 K are plotted. The trend disappears almost completely.

On average, the differences are larger for the stars cooler than $T_{\rm eff}$ = 10 000 K than for the hotter stars. This is due to the large uncertainties in $T_{\rm eff}$ that affect the fundamental determination of this parameter. There is a small trend mostly due to the cooler stars. In fact, the trend disappears almost completely if only stars hotter than 10 000 K are considered. In this case the difference between computed and observed indices averages to zero.

7. Conclusions

We have presented synthetic H_β indices based on new-ODF ATLAS9 model atmospheres (Castelli & Kurucz 2003). The comparison with other determinations and with the observed indices of fundamental stars has shown that they are comparable or even superior to those computed by Smalley & Dworetsky (1995), which were the best ones from ATLAS9 available up to now.

For cool main sequence stars, the computed $T_{\rm eff}$–H_β relation agrees better with the empirical relation from Alonso et al. (1996) than the SD95 indices do. In fact, for a given H_β and $T_{\rm eff} \geq$ 5000 K, our indices are the same or a little bit bluer (with a maximum difference of 146 K at 6000 K) than those from Alonso et al. (1996), but the SD95 indices are still more bluer. We note that our indices (except at 6000 K) are within the uncertainty of 141 K of the $T_{\rm eff}$–H_β empirical relation. For $T_{\rm eff}$ < 5000 K, the agreement between the computed and the empirical relations extends up to $T_{\rm eff}$ = 4250 K for solar metallicity, but it is remarkably reduced for lower metallicities. Because $T_{\rm eff}$–H_β empirical relations are only estimates for sub solar metallicities when $T_{\rm eff} \leq$ 4500 K and because the utility of the H_β index is very scarce in this region of the HR diagram we did not worry to further investigate about these discrepancies.

We showed in Sect. 2.3 that for the Sun the observed H_β is better reproduced by our computations than by those of SD95. Also the computed index for Procyon (α CMi) for $T_{\rm eff}$ = 6560 K,

Table 3. Upper table: log g (Col. 7) from the observed H_β index (Col. 5) is compared with log g (Col. 6) of stars having either T_{eff} (Col. 4) or log g (Col. 6) or both determined as fundamental values and taken from the literature (sources in Col. 9). Last column indicates which are the fundamental parameters. Lower table: log g (Col. 7) from the observed H_β index (Col. 5) is compared with log g (Col. 6) derived by Napiwotzki et al. (1993, NSW93) from Hβ profiles. The temperature T_{eff} given in Col. 4 was derived by NSW93 from the Strömgren photometry.

HR	Star	HD	T_{eff}(K)	$H^1{}_\beta$(obs)	log g^2	log $g(H_\beta)$	Δlog g	Source[3]	Fundamental
472	α Eri	10144	14 370 ± 470	2.607 ± 0.003	2.30 ± 0.30ph	2.64	0.34	2	T_{eff}
1728	AR Aur A+B	34364	10 900 ± 250	2.861 ± 0.001	4.29 ± 0.03	4.28	−0.01	2	log g
1790	γ Ori	35468	20 930 ± 950	2.613 ± 0.001	3.60 (3.60 ± 0.1b, 4.0 ± 0.5ph)	3.67	0.07	2	T_{eff}
2004	κ Ori	38771	25 580 ± 1290	2.566 ± 0.022	3.30 (<3.30b,<3.5ph)	3.39	0.09	2	T_{eff}
2088	β Aur A+B	40183	9077 ± 217	2.889 ± 0.006	3.95 ± 0.010	3.66	−0.29	1	T_{eff}, log g
2294	β CMa	44743	24 020 ± 1150	2.593 ± 0.004	3.60 (3.60 ± 0.1b,4.0 ± 0.5ph)	3.71	0.11	2	T_{eff}
2421	γ Gem	47105	9220 ± 330	2.865 ± 0.009	3.50 (3.5 ± 0.15b,3.5 ± 0.5ph)	3.48	−0.02	3	T_{eff}
2491	α CMa A	48915	9940 ± 210	2.907 ± 0.003	4.33 ± 0.05	4.24	−0.09	3	T_{eff}, log g
2618	ϵ CMa	52089	20 210 ± 950	2.577	3.10 (3.1 ± 0.1b,<3.0ph)	3.01	−0.09	2	T_{eff}
3335	VV Pyx A+B	71581	10 200 ± 500	2.881	4.09 ± 0.01	4.13	0.04	2	log g
3685	β Car	80007	9150 ± 240	2.836	3.50 ± 0.5ph	3.19	−0.31	2	T_{eff}
3982	α Leo	87901	12 090 ± 370	2.723 ± 0.006	3.60 (3.6 ± 0.1b,3.2 ± 0.3ph)	3.51	−0.09	2	T_{eff}
4662	γ Crv	106625	12 510 ± 580	2.717 ± 0.004	3.70 (3.7 ± 0.1b,4.0 ± 0.5ph)	3.57	−0.13	2	T_{eff}
4853	β Cru	111123	26 150 ± 1110	2.596 ± 0.002	4.20 ± 0.5ph	3.98	−0.22	2	T_{eff}
5056	α Vir A+B	116658	23 070 ± 1000	2.605 ± 0.004	3.84 ± 0.17	3.79	−0.05	2	T_{eff}, log g
5132	ϵ Cen	118716	24 740 ± 1210	2.608 ± 0.001	4.50 ± 0.5ph	4.04	−0.46	2	T_{eff}
	V 760 Sco A+B	147683	15 500	2.703 ± 0.007	4.22 ± 0.02	4.13	−0.09	4,2	log g
6414	U Oph A	156247	16 500 ± 500	2.695 ± 0.001	4.08 ± 0.02	4.22	0.14	2	log g
6622	V 539 Ara A	161783	18 000	2.665 ± 0.003	3.941 ± 0.017	4.06	0.12	4,2	log g
6879	ϵ Sgr	169022	9420 ± 240	2.778	4.50 ± 0.3ph	2.89	−1.61	2	T_{eff}
7001	α Lyr	172167	9600 ± 180	2.903	4.10 (4.00 ± 0.1b,3.8 ± 0.3ph)	4.03	−0.07	3	T_{eff}
7790	α Pav	193924	17 640 ± 790	2.660 ± 0.007	3.50 ± 0.5ph	3.93	0.43	2	T_{eff}
8425	α Gru	209925	13 910 ± 590	2.722	4.00 ± 0.5ph	4.01	0.01	2	T_{eff}
153	ζ Cas	3360	20 930	2.627 ± 0.005	3.78	3.89	0.11	5	
1641	η Aur	32630	16 890	2.683 ± 0.002	4.07	4.13	0.06	5	
4119	β Sex	90994	14 570	2.730 ± 0.003	4.18	4.26	0.08	5	
5191	η UMa	120315	17 320	2.694 ± 0.001	4.28	4.36	0.08	5	
6588	ι Her	160762	17 480	2.661 ± 0.001	3.82	3.92	0.10	5	
7447	ι Aql	184930	13 520	2.707 ± 0.004	3.73	3.72	−0.01	5	
7906	α Del	196867	10 950	2.796 ± 0.005	3.85	3.74	−0.11	5	
8585	α Lac	213558	9530	2.908 ± 0.003	4.11	4.06	−0.05	5	
8634	ζ Peg	214923	11 330	2.768 ± 0.003	3.69	3.66	−0.03	5	
8781	α Peg	218045	9810	2.838 ± 0.003	3.54	3.57	0.03	5	
8965	ι And	222173	11 850	2.725 ± 0.005	3.47	3.45	−0.02	5	
8976	κ And	222439	11 310	2.833 ± 0.002	4.23	4.22	−0.01	5	

[1] Hauck & Mermilliod (1998; see also footnote 6 in the text). [2] "ph" indicates gravities derived from the spectrophotometry; "b" indicates gravities derived from Balmer profiles. [3] Sources for T_{eff} and log g in Cols. 4 and 6: (1) Smalley et al. (2002, Setal02); (2) Smalley & Dworetsky (1995, SD95); (3) Gardiner et al. (1999, GKS99); (4) Moon & Dworetsky (1985, MD85); (5) Napiwotzki et al. (1993, NSW93).

log g = 4.06 is the same as the observed one, H_β = 2.671 ± 0.000, while SD95 derived H_β = 2.654. The large differences in T_{eff} for some fundamental cool stars obtained by us from the comparison of the computed and observed indices are very probably related with the low accuracy of the fundamental T_{eff} which is affected by large errors (Table 2).

For hot stars (T_{eff} > 9000 K), the trend of the differences ΔH_β between the computed and observed indices as a function of H_β(obs) is fully negligible. The comparison of our indices with the SD95 ones has shown a close agreement, although the latter ones would generally give a little bit lower gravity. An example is η UMa that we discussed in Sect. 2.3.

In this paper we have performed several tests on the reliability of the computed H_β indices which have given encouraging results. For stars with well known stellar parameters, as is the case of Procyon and the Sun, the predicted indices are within the observational errors. For cool dwarfs the accuracy of the computed indices is within the error limits of the empirical relations. For stars hotter than 10 000 K the difference between observed and computed indices is of the order of 2.0%. It becomes less than 0.2% when averaged over all the considered stars. It has to be stressed that the uncertainties in the computed indices deduced from our analysis are strongly related to the accuracy of the stellar parameters adopted from the literature, but also with the capability of the ATLAS9 model atmospheres to predict the observations. A discussion on the physical, numerical, and computational limits of the ATLAS9 models can be found in Kurucz (2005). In particular, the treatment of convection in cool stars, the treatment of rotation in hotter stars and the use of the LTE hypothesis for all the stars may affect some computational results for the different spectral types.

Appendix A: Data for computing response functions for H_β indices

All the data used for computing the response functions needed to obtain the synthetic H_β index are collected in Table A.1. Columns 1–4 list the transmission curve for the narrow filter 212 and the transmission curve for the wide filter 214 both reproducing the filter set from Crawford & Mander (1966); Cols. 5, 6 list the 1P21 photomultiplier sensitivity; Cols. 7, 8 list the

Table A.1. Data used for computing the response function for the H_β indices calculations.

λ_{212}(Å)	S_{212}	λ_{214}(Å)	S_{214}	λ_{1P21}	S_{1P21}	$\lambda_{\rm Al}$	$S_{\rm Al}$	$\lambda_{\rm air}$	$a_{\rm air}$
4760	0.000	4640	0.000	3000	0.08	3000	0.82	3000	4.50
4765	0.000	4650	0.000	3100	0.22	3500	0.83	3200	1.30
4770	0.000	4660	0.002	3200	0.45	3800	0.84	3400	0.84
4775	0.001	4670	0.005	3300	0.68	4000	0.85	3600	0.68
4780	0.002	4680	0.007	3400	0.81	4500	0.86	3800	0.55
4785	0.003	4690	0.009	3500	0.90	5000	0.97	4000	0.46
4790	0.004	4700	0.011	3600	0.95	5550	0.88	4500	0.31
4795	0.006	4710	0.014	3700	0.97	6000	0.89	5000	0.23
4800	0.006	4720	0.019	3800	0.99			5500	0.195
4805	0.010	4730	0.026	3900	1.00			6000	0.170
4810	0.014	4740	0.036	4000	1.00				
4815	0.019	4750	0.049	4100	0.99				
4820	0.032	4760	0.064	4200	0.98				
4825	0.056	4770	0.098	4300	0.95				
4830	0.113	4780	0.138	4400	0.91				
4835	0.173	4790	0.195	4500	0.87				
4840	0.263	4800	0.274	4600	0.83				
4845	0.315	4810	0.368	4700	0.77				
4850	0.480	4820	0.473	4800	0.71				
4855	0.578	4830	0.551	4900	0.65				
4860	0.623	4840	0.604	5000	0.58				
4865	0.525	4850	0.640	5100	0.52				
4970	0.453	4860	0.664	5200	0.46				
4875	0.285	4870	0.683	5300	0.40				
4880	0.139	4880	0.698	5400	0.34				
4885	0.086	4890	0.701	5500	0.29				
4890	0.053	4900	0.701	5600	0.24				
4895	0.032	4910	0.683	5700	0.20				
4900	0.019	4920	0.645	5800	0.16				
4905	0.016	4930	0.563	5900	0.13				
4910	0.014	4940	0.428	6000	0.10				
4915	0.011	4950	0.325						
4920	0.009	4960	0.244						
4925	0.007	4970	0.197						
4930	0.005	4980	0.150						
4935	0.002	4990	0.109						
4940	0.000	5000	0.086						
4945	0.000	5010	0.066						
4950	0.000	5020	0.056						
		5030	0.051						
		5040	0.046						
		5050	0.041						
		5060	0.035						
		5070	0.030						
		5080	0.025						
		5090	0.020						
		5100	0.015						
		5110	0.010						
		5120	0.005						
		5130	0.000						
		5140	0.000						

reflectivity of aluminium; Cols. 9, 10 list the atmospheric transmission. We took all these data from the Kurucz code beta.forcd (see footnote 1).

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