Temperature and gravity calibration of $uvby\beta$ photometry for B, A and F stars

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We re-evaluate the fundamental values of $T_{\rm eff}$ determined by Code et al. (1976) with modern flux measurements and Kurucz (1991) model atmospheres. There are no significant changes. We also use eclipsing binaries to obtain fundamental values of $\log g$. Observed spectra of over 50 stars are used to calibrate a grid of synthetic β values. The new values of β are in remarkably good agreement with observed values for the fundamental stars.

These results are used to perform a completely new analysis of the calibration of $T_{\rm eff}$ and $\log g$ in terms of $uvby\beta$ photometry to produce new grids similar to those presented by Moon & Dworetsky (1985). The improvements place the calibrations on a much firmer basis, but the actual values of $T_{\rm eff}$ and $\log g$ are not very much different.

1 Introduction

The best possible determination of stellar atmospheric parameters is of intrinsic interest and is also a basic prerequisite for accurate determination of other quantities, such as elemental abundances, for example. A well–calibrated standard photometric system is an indispensible aid in such work.

Smalley & Dworetsky (1993) presented a detailed discussion of the atmospheric parameters of A and F stars. They resolved a long-running controversy over the atmospheric parameters of classical Am stars. The photometric calibrations for B-type stars have also received considerable attention (Castelli 1991; Napiwotzki et al. 1993). The Lester et al. (1986) $uvby\beta$ tables have been shown to be adversely affected by an error in their adopted $\log g$ for η UMa. However, it should be noted that η UMa is not a standard for $T_{\rm eff}$ and $\log g$ in the same sense as the Code et al. (1976) stars; it is only a secondary standard for flux calibrations. Napiwotzki et al. recommended the use of the Moon & Dworetsky (1985) grids, if corrected for slight gravity deviations.

Here we reconsider in detail the determination of fundamental values of $T_{\rm eff}$ and $\log g$ for several stars. A new comparison between theoretical and observed $uvby\beta$ photometry is presented, along with a set of newly calibrated $uvby\beta$ grids.

2 Fundamental Parameters

2.1 Temperatures

Fundamental values were obtained by Code et al. (1976). They obtained effective temperatures for 32 bright stars using angular diameter measurements and combined ultraviolet, optical and infrared fluxes. We have repeated the Code et al. analysis to see if modern observational data and newer model atmosphere fluxes have any significant effects.

A comparison with Code et al. indicates no significant differences; the largest differences are of the order a few percent. It is mostly the hottest stars that have the greatest differences, where the effects of the far-ultraviolet flux correction become important. The new fundamental $T_{\rm eff}$ values are in general slightly cooler than the Code et al. values, but hotter than given by Beeckmans (1977). Nevertheless, all three sets of effective temperatures are in agreement to within the uncertainties in the measurements.

2.2 Gravities

The stars in a binary system lend themselves to determinations of at least the mass and in the cases of eclipsing-binary systems the radii. Eclipsing binary stars listed by Popper (1980) and Andersen

(1991) have well-determined masses and radii, with both components on or near the main sequence.

Since we know the radii of the components in a binary system, we can determine the apparent angular diameters of the stars, provided we know the distance to the system. A few of the binary systems have parallax measurements in van Altena et al. (1991), hence angular diameters can be obtained. Fundamental values of $T_{\rm eff}$ can be obtained, provided we can determine the relative contributions to the observed flux by the two components.

These fundamental values of $T_{\rm eff}$ are of lower quality than the Code et al. stars. This is primarily due to the extra step involved in obtaining the angular diameters, *i.e.*, the use of parallax measurements. This uncertainty will eventually be reduced by the use of high-quality parallaxes from *HIPPARCOS*. Additionally, the fluxes of the stars have been less extensively observed. Nevertheless, we have shown that for certain binary systems we can obtain fundamental values of *both* $T_{\rm eff}$ and $\log g$.

3 Fits to Hβ profiles

Using the fundamental $T_{\rm eff}$ values for the Code et al. stars, fits were made to the Hβ profiles to determine the $\log g$ of the stars with $T_{\rm eff} > 8500$ K. Below this the Hβ profiles could only serve to check for agreement with the fundamental $T_{\rm eff}$ values. We find that the Hβ profiles give values of $\log g$ (and $T_{\rm eff}$ for the cooler stars) which are in very good agreement with the fundamental values. It was found that the supergiants in the list were very poorly fitted due to their low surfaces gravities. The best fits to the double-lined binary systems are illustrated in Figure 1.

4 $uvby\beta$ photometry

The Strömgren-Crawford $uvby\beta$ photometric system provides a quick and efficient means of estimating the atmospheric parameters of B, A and F stars, with several model atmosphere calibrations available (*e.g.*, Relyea & Kurucz 1978, Moon & Dworetsky 1985, Lester et al. 1986).

4.1 Synthetic β indices

Schmidt (1979) calculated a grid of β indices using Kurucz (1979) solar-composition model atmospheres. However, Schmidt did not allow for metal lines in his calculations, although the effect should only be significant for cool stars. Moon & Dworetsky (1985) found that the Schmidt β indices needed scaling to agree with photometric values of their fundamental stars, as they gave values of $\Delta\beta \simeq 0.04$ at $\beta = 2.9$.

We have used the Richardson-Brealey Spectrograph of the 1-m Kapteyn telescope on La Palma to obtain over 50 Hβ spectra and determine spectroscopic values of the β index, $\beta_{\rm RBS}$. Two Gaussian response functions with widths of 30Å and 150Å were used to mimic the narrow and wide filters respectively. The values of $\beta_{\rm RBS}$ were transformed onto the standard system, $\beta_{\rm STD}$, using the method of Crawford & Mander (1966). The photometric values of β for these stars were taken from Hauck & Mermilliod (1990) and the transformation could then be readily obtained:

$$\beta_{\rm STD} = 1.0094\ \beta_{\rm RBS} + 0.6634$$

The correlation was very tight with a typical scatter of $\sim$0.01 in β. Figure 2 shows the correlation and one can see that there is no evidence for bifurcation.

Using synthetic spectra, we have calculated a new grid of theoretical β indices. These were transformed onto the standard system using the above equation. A similar calculation was performed using just the Kurucz (1979) profiles (with no other absorption lines). The result was essentially the same, except for $T_{\rm eff} < 6500$ K where blanketing effects become significant. Neglecting the line-blanketing produced in that domain yielded values of β that were too small.

5 A new set of grids

Using the values of $T_{\rm eff}$ and $\log g$ for the fundamental stars (Table 1), we have generated a new set of $uvby\beta$ grids based on the methods employed by Moon & Dworetsky (1985). Full details of the calibration procedures will be given in Dworetsky & Smalley (1994). The calibrations of the individual grids are based on the following precepts:

Cool (β, c_0) grid. 5500 – 8500 K

Our synthetic β indices are based on Kurucz (1979) model atmospheres with lines included in the synthetic spectra. These were renormalised using Code et al. standards plus β Aur and AR Aur. A total of 11 stars was used. The Moon & Dworetsky scaling of Relyea & Kurucz (1978) colours was used, the main point being the continuation of their adoption of the semi-empirical corrections to the [Fe/H]=0.0 grid of Philip & Relyea (1979) for c_0.

Gravities obtained from the grid for "cool" stars should be corrected for metallicity by the method given by Dworetsky & Moon (1986), because c_0 is affected by line–blanketing.

Intermediate (a_0, r^*) grid. 8000 – 11000 K

Again, we used β indices and colours normalised as above. This grid is intended mainly for stars in the range 8500 – 10000 K, but the extensions allow the program to stay in the same grid if the bounds are exceeded slightly during iteration to a solution. The β values are slightly different from the Moon & Dworetsky values at the high $T_{\rm eff}$ end, but not by much, and $\log g$ is only affected by a few hundredths at most. The general trend is to improve agreement with Napiwotzki et al., though not all the differences are eliminated. We regard this agreement as remarkable confirmation of the accuracy of that earlier work.

Hot (β, c_0) grid. 10000 – 30000 K

For this grid we have, after comparisons with colours of the fundamental stars in Table 1, adopted Kurucz (1991) colours with no corrections, and synthetic β indices (calculated using Kurucz (1991) models) normalised to bring the gravities into agreement with our Hβ profile fits for 7 stars, Napiwotzki et al.'s Hγ fits for 5 stars, and a further 3 fundamental stars in the range $T_{\rm eff}$ = 9500 – 11000 K. The new grid virtually eliminates any disagreements with Napiwotzki et al.'s gravities for $T_{\rm eff} > 10000$ K, which is not surprising in view of the fact that all three gravity criteria are based on the same set of model atmospheres.

5.1 Evaluation of new β indices

Our new synthetic β indices are more firmly based on detailed synthesis of the β index when compared to those used by Moon & Dworetsky (1985). There are only small differences between the photometric β values and the model values for the fundamental $T_{\rm eff}$ and $\log g$ values. As can been seen in Figure 3, there is a slight slope with β and the two slopes for the hot and cool stars are very similar. The small differences between raw synthetic indices and those for fundamental stars are probably due to the fact that the RBS transformation was based on a set of completely different non-fundamental stars, most of which were not in themselves β-index standards.

The final adopted sets of β-indices are based on the transformations to the fundamental stars, given below.

Cool and intermediate grid

The linear adjustment to the fundamental stars is given by:

$$\Delta\beta = -0.076 \times \ \beta_{\rm syn} + 0.212$$

This correction has been applied to the cool and intermediate grids in order to match the temperatures (cool grid) and gravities (mainly) for the (a_0, r^*) grid. The new cool grid uses the Philip & Relyea (1979) corrections to c_0, and the +0.008 shift used elsewhere by Moon & Dworetsky.

The scatter is $\sigma = 0.0055$, a bit tighter than might be expected from observational errors in β. The correlation coefficient $r = -0.881$, which corresponds to $P < 0.001$.

Hot grid fit, $T_{\rm eff}$ 10000–30000 K

The linear adjustment to the fundamental stars in this region is given by:

$$\Delta\beta = -0.042 \times \ \beta_{\rm syn} + 0.111$$

The standards used have $T_{\rm eff}$ from 11000 to 25000 K and 9 of the 15 are Code et al. stars; the rest are Napiwotzki et al. Hγ stars or the binary AR Aur. 7 stars have $\log g$ from our Hβ fits, 5 have $\log g$ from Napiwotzki et al. Hγ fits, and 3 are binary stars; some have $\log g$ from more than one source, but these agree closely in those few cases.

The scatter is $\sigma = 0.0089$, which is about what we would expect for errors due mainly to observational uncertainty in β. The correlation coefficient $r = -0.5100$, which gives $P = 0.05$. This is not nearly as significant as the result for the cool grids. However, the slope and intercept are within a range one might expect by comparison with the cool and intermediate grid fit.

6 Conclusion

We have used fundamental values of $T_{\rm eff}$ and $\log g$ to calibrate synthetic $uvby\beta$ values. The new grids (see Figures 4 – 6) are slightly different from those originally presented by Moon & Dworetsky (1985), but the differences are in all cases remarkably small. A full discussion of this work is given in Smalley & Dworetsky (1994) and Dworetsky & Smalley (1994).

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Table 1: Dereddened $uvby\beta$ photometry for the fundamental stars.

	$(b-y)_0$	m_0	c_0	β	$E(b-y)$	$T_{\rm eff}$	$\log g$
HR				*Code et al. stars*			
472				2.606		14370 ± 470	2.3 ± 0.3
1713	−0.087	0.092	0.268	2.541	0.113	11600 ± 260	<2
1790	−0.103	0.080	0.109	2.613	0.012	20930 ± 950	3.6 ± 0.1
1903	−0.127	0.054	−0.112	2.548	0.093	23930 ± 1130	<3.0
2004	−0.126	0.056	−0.101	2.568	0.090	25580 ± 1290	<3.3
2294	−0.117	0.061	−0.007	2.593	0.027	24020 ± 1150	3.6 ± 0.1
2326	0.110	0.128	1.512	2.732	0.	7520 ± 460	<1.5
2421	−0.008	0.154	1.183	2.869	0.015	9220 ± 330	3.5 ± 0.15
2491	−0.004	0.158	0.982	2.906	0.	9940 ± 210	4.33 ± 0.05
2618	−0.112	0.088	−0.008	2.577	0.031	20210 ± 950	3.1 ± 0.1
2693	0.326	0.338	0.920	2.661	0.049	6170 ± 430	<1.0
2827	−0.096	0.089	0.170	2.538	0.111	13500 ± 630	<2.0
2943	0.272	0.167	0.532	2.671	0.	6560 ± 130	4.06 ± 0.06
3685	−0.015	0.146	1.269	2.836	0.019	9150 ± 240	3.5 ± 0.5
3982	−0.047	0.104	0.711	2.723	0.006	12090 ± 370	3.6 ± 0.1
4534	0.044	0.210	0.975	2.900	0.	8870 ± 350	4.0 ± 0.25
4662	−0.046	0.113	0.749	2.717	0.	12510 ± 580	3.7 ± 0.1
4853	−0.119	0.066	−0.044	2.596	0.016	26150 ± 1110	4.2 ± 0.5
5056	−0.114	0.080	0.018	2.607	0.	23070 ± 1000	3.65 ± 0.17
5132	−0.112	0.064	0.040	2.608	0.018	24740 ± 1210	4.5 ± 0.5
6556	0.093	0.168	1.039	2.832	0.	7960 ± 330	3.8 ± 0.3
6879	−0.007	0.109	1.172	2.778	0.023	9420 ± 240	4.5 ± 0.3
7001	−0.003	0.159	1.088	2.903	0.007	9600 ± 180	4.0 ± 0.1
7557	0.116	0.185	0.876	2.824	0.021	7990 ± 210	4.0 ± 0.3
7790	−0.092	0.087	0.271	2.662	0.	17640 ± 790	3.5 ± 0.5
8425	−0.061	0.105	0.576	2.728	0.	13910 ± 590	4.0 ± 0.5
8728	0.036	0.206	0.991	2.906	0.	8760 ± 310	4.2 ± 0.3
HD				*Binary stars*			
16739	0.345	0.206	0.396	2.633	0.023	6200 ± 200	4.26 ± 0.12
34335	0.320	0.159	0.454	2.627	0.	6500 ± 100	4.10 ± 0.04
34364	−0.035	0.156	0.872	2.862	0.	11000 ± 300	4.30 ± 0.03
40183	0.017	0.174	1.091	2.888	0.	9000 ± 500	4.00 ± 0.01
46052	0.081	0.231	0.944	2.862	0.	8500 ± 300	4.15 ± 0.02
62863	0.198	0.172	0.634	2.723	0.	7200 ± 100	4.25 ± 0.01
71581	−0.010	0.173	1.007	2.881	0.038	10200 ± 500	4.10 ± 0.01
90242	0.287	0.160	0.397	2.648	0.	6700 ± 100	4.30 ± 0.10
110379	0.235	0.154	0.521	2.708	0.007	7000 ± 100	4.21 ± 0.17
156247	−0.077	0.101	0.373	2.694	0.157	16500 ± 500	4.10 ± 0.02
185912	0.290	0.166	0.450	2.663	0.004	6700 ± 100	4.30 ± 0.02
202275	0.327	0.161	0.411	2.629	0.004	6290 ± 300	4.34 ± 0.02

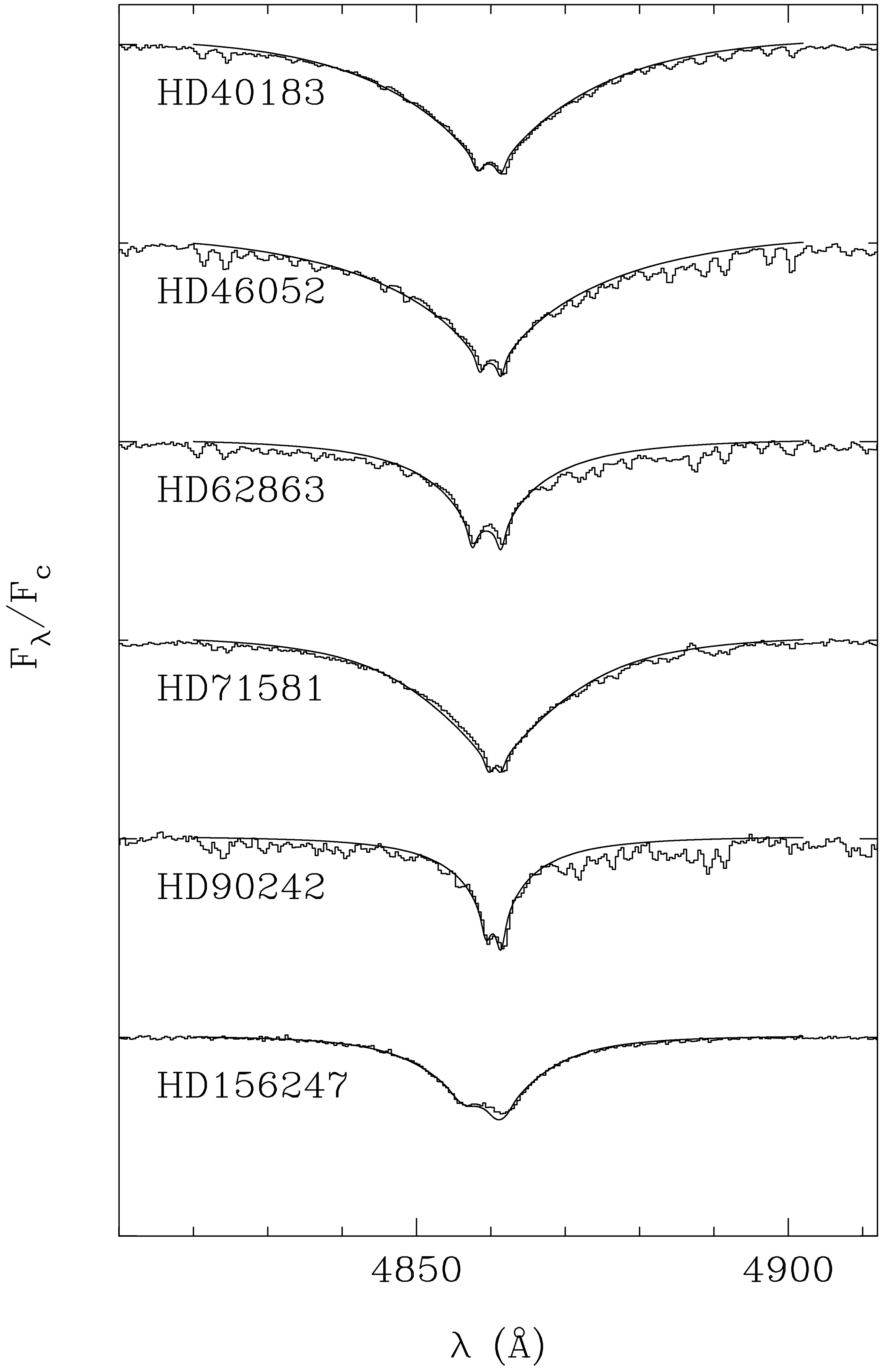

Figure 1: Fits to binary-star spectra. The spectra are given as histograms and the best fitting hydrogen-line profiles as the continuous lines.

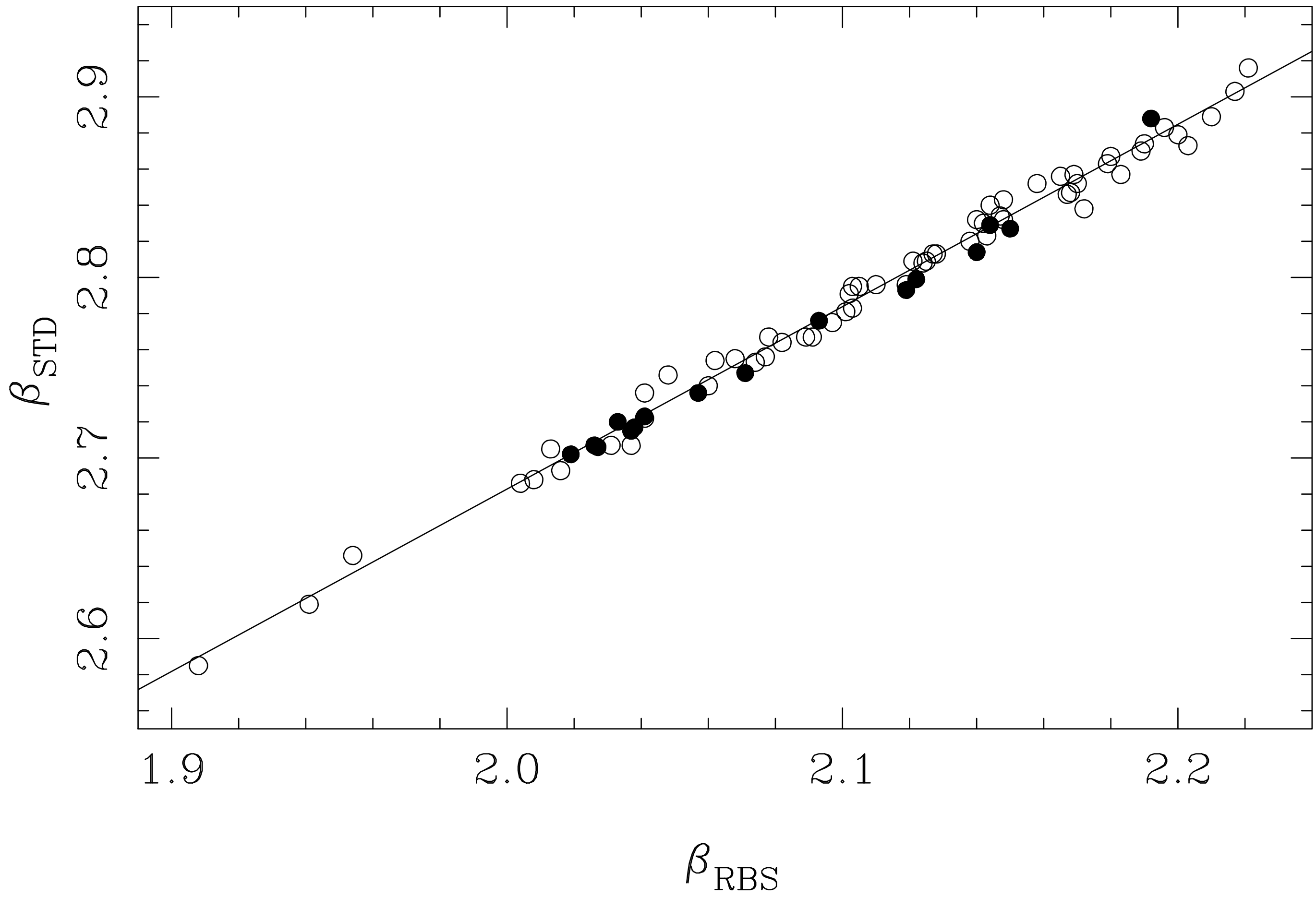

Figure 2: Comparison between the spectroscopic β indices ($\beta_{\rm RBS}$) and the photometric values ($\beta_{\rm STD}$). The open circles indicate stars with $T_{\rm eff} < 10000$ K and the filled circles are the hotter stars. There is no evidence for bifurcation; the hot stars follow the same trend as the cooler stars.

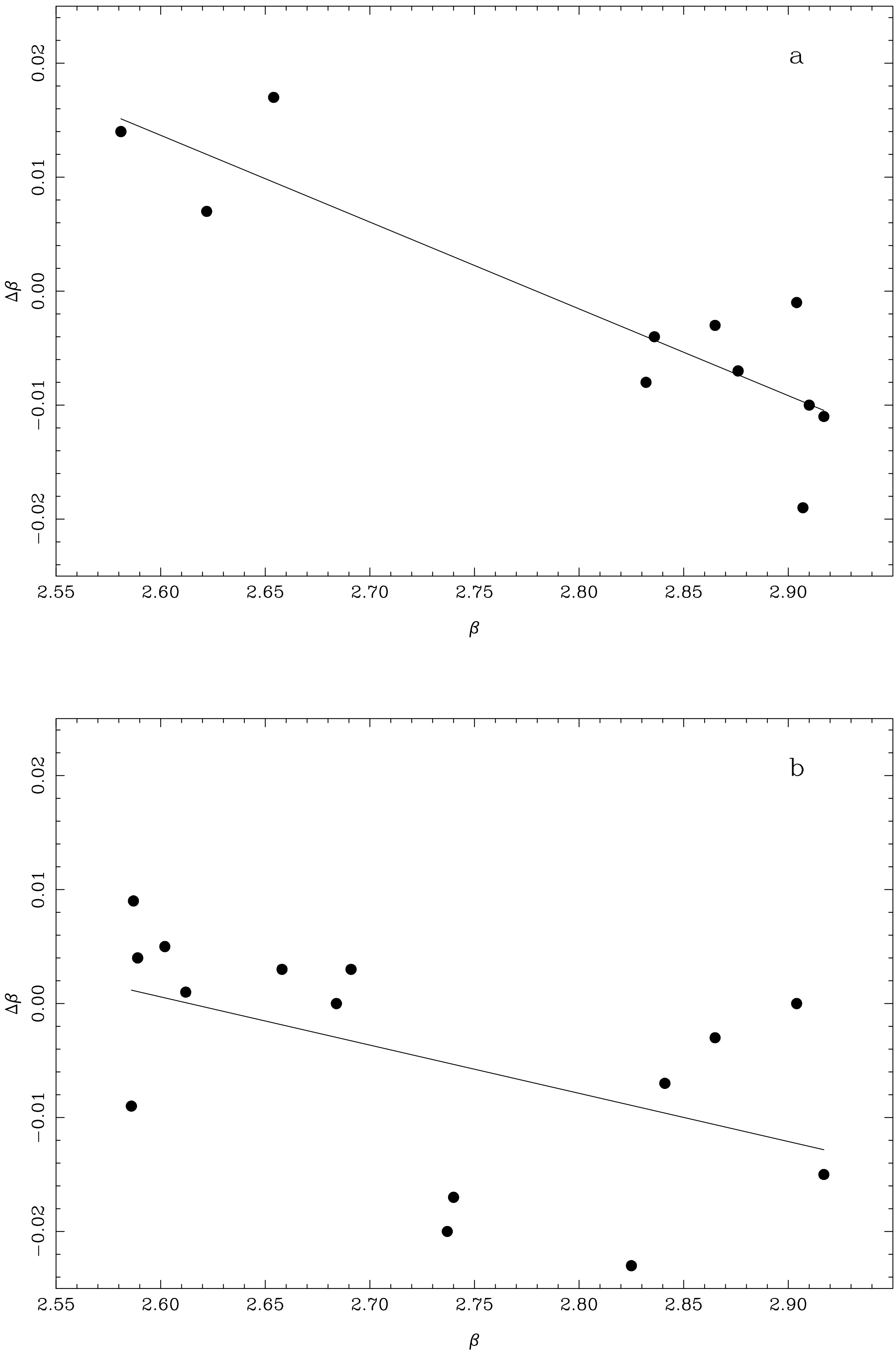

Figure 3: Variation of $\Delta\beta = \beta_{\rm phot} - \beta_{\rm calc}$ versus $\beta_{\rm calc}$ for **(a)** the cool grid and **(b)** the hot grid. The solid lines are least-squares fits to the points (see Text).

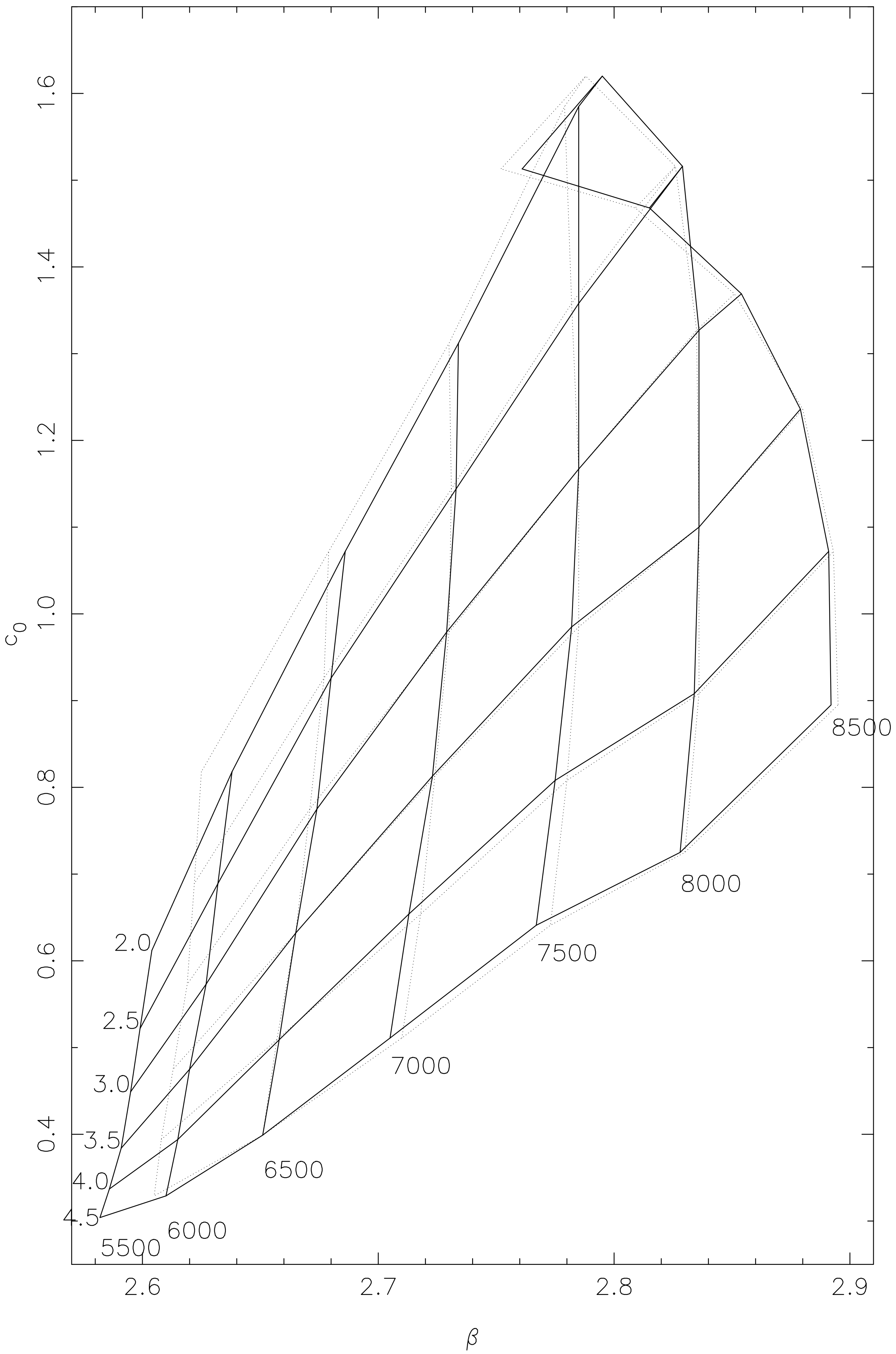

Figure 4: The new Cool (β, c_0) grid. The fainter dotted lines indicate the Moon & Dworetsky (1985) grid.

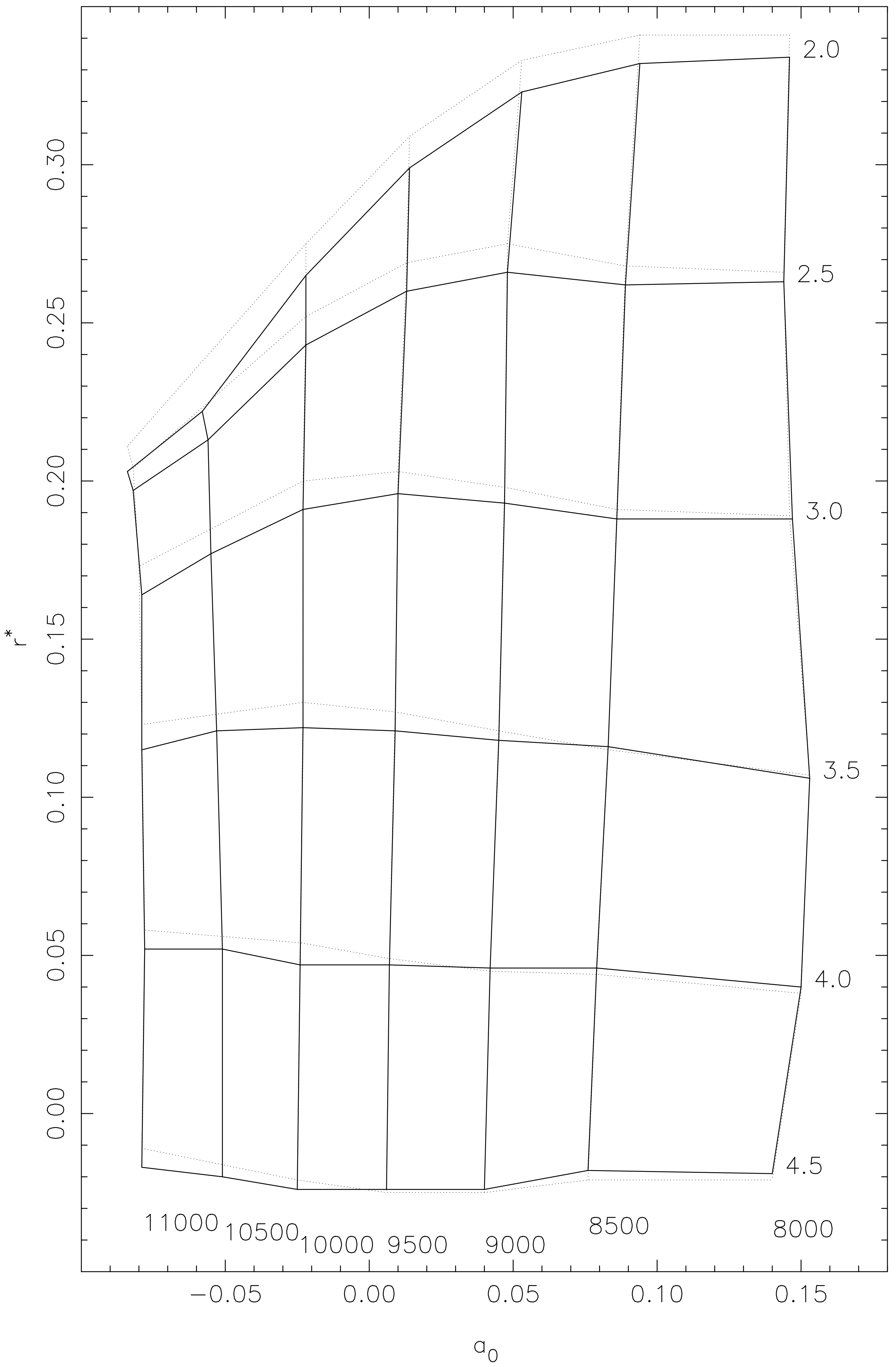

Figure 5: The new Intermediate (a_0, r^*) grid. The fainter dotted lines indicate the Moon & Dworetsky (1985) grid.

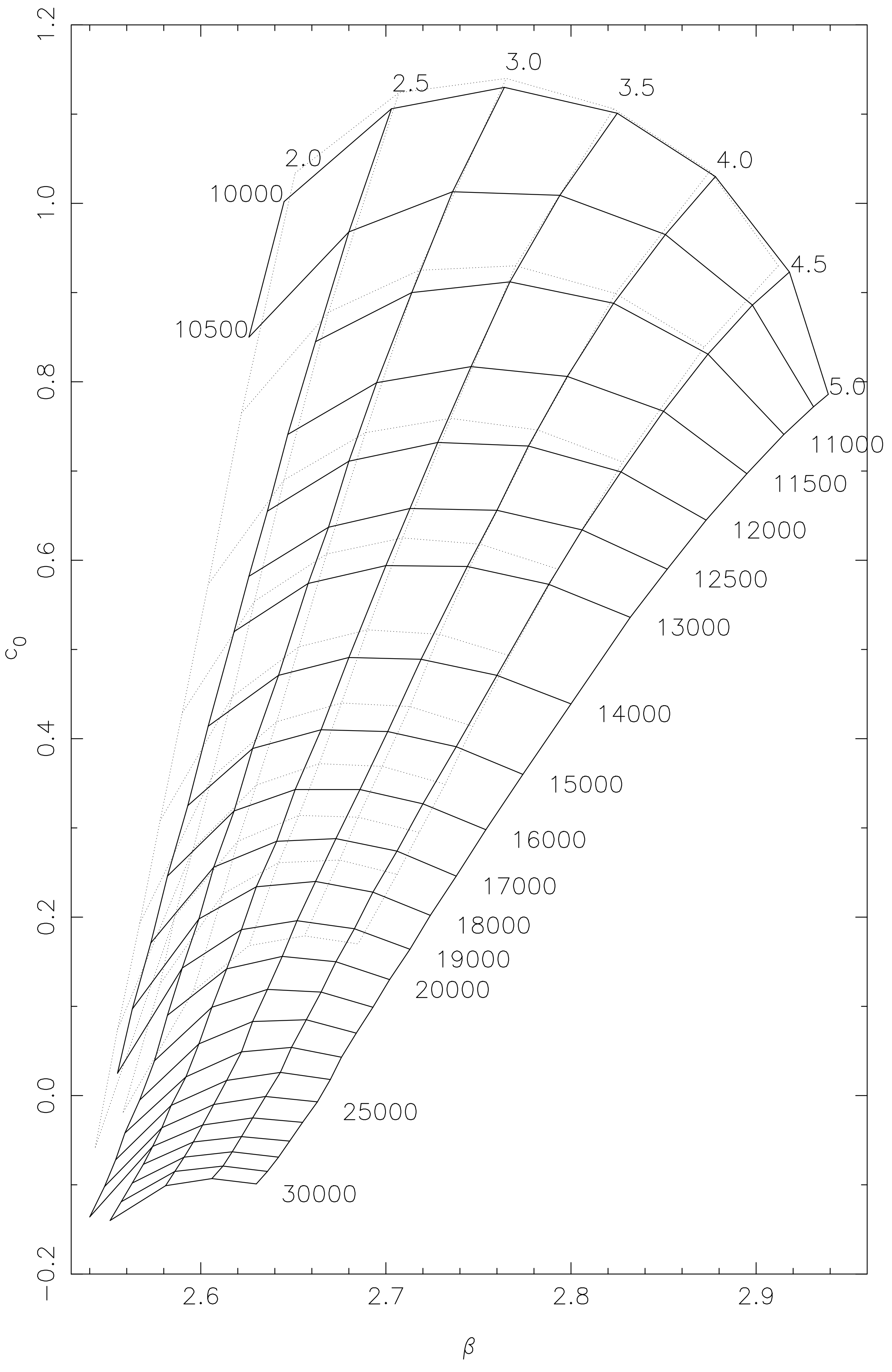

Figure 6: The new Hot (β, c_0) grid. The fainter dotted lines indicate the Moon & Dworetsky (1985) grid.