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Precise temperatures of classical Cepheids and yellow supergiants from line-depth ratios

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Abstract. The ratios of spectral line-depths are powerful indicators of the effective temperature. Thirty-two functional formulas to estimate the effective temperatures from line-depth ratios for Cepheids and F–G supergiants are offered. For high-quality spectra we find errors in the temperature as small as 10–15 K. These calibrations are only little sensitive to other stellar parameters and allow to derive highly precise T_{eff} for supergiants in the range 4700–6700 K.

Key words: line: formation – stars: fundamental parameters – stars: variables: Cepheids

1. Introduction

Precise temperatures should provide reliable localization of variable and nonvariable supergiants in the Cepheid instability strip, considerable increase in the accuracy of abundances determination that affects period – luminosity relation, help to trace cyclic temperature changes in Cepheids, and to study other subtle effects that may occur in the atmospheres of stars.

Temperature is one of the basic stellar parameters and numerous methods have been developed for its determination. The simplest one is the use of colors, either broad or intermediate band. A variety of calibrations of colors has been published defining T_{eff} for supergiants in terms of $B-V, V-R, b-y$ or $R-I$. The disadvantage of color–temperature calibrations is that the result is never independent of the other stellar parameters such as gravity, microturbulent velocity and chemical composition. Another factor is the uncertainty in interstellar reddening that results in 60–150 K error. At best these calibrations provide only a first estimate of a star's effective temperature.

Blackwell & Shallis (1977) have proposed the so–called integrated flux method, which compares the integrated flux measured in the wavelength interval (λ_1, λ_2) with the flux predicted from an atmospheric model. Unfortunately, being applied to pulsating objects the method causes errors as large as 200–250 K and it is also sensitive to reddening (Fernley et al., 1989).

For dwarfs one may use the hydrogen line profiles as a temperature indicator (equivalent to the β–color). However, in case of supergiants this technique fails because of great uncertainties arising from the profile strong dependence on gravity.

Evans & Teays (1996) used energy distribution to trace temperature variations in Cepheid δ Cep. They estimate the accuracy to be $\pm$ 120 K.

An alternative to the color calibrations is the analysis of temperature–sensitive spectral lines.

Gray (1989, 1994) showed that in giants and dwarfs there are many elements such as Fe, V and Ti whose lines in the visible part of spectrum are very sensitive to variations of temperature. But the line strength itself cannot serve as a temperature indicator, being strongly dependent on abundance. To eliminate the problem he proposed to use line ratios instead, taking either lines of the same or similar elements (Gray 1989, 1994; Gray & Johanson 1991). Based on the weak lines (to exclude line broadening effects) this method in principle allows to resolve temperature differences as small as 1-10 K provided of the high spectral resolution and the absence of stellar surface peculiarities. The additional advantage of using line-depths or equivalent widths ratios is that they do not depend upon the interstellar reddening and the effects of metallicity as is the case for the integrated flux method or colors calibrations (Gray 1994).

Gray & Johanson (1991) developed temperature calibration for $F5-K7$ dwarfs using VI λ 6251 Å and FeI λ 6253 Å ratio versus temperature converted from $B-V$ value. They attained 10 K precision for spectra of G–stars with S/N = 400 $\div$ 600.

The approach proved to be especially effective for the Sun. Long-term monitoring of CI λ 5380 Å, FeI λ 5379 Å and $TiII$ λ 5381 Å line-depth ratios revealed their systematical variation during the activity cycle. This corresponds to variation in solar effective temperature with the amplitude of 1.5 K $\pm$ 0.2 K being in accordance with the range implied by the variations of the sunspot-corrected irradiation (Gray & Livingston 1997a, 1997b).

Sasselov & Lester (1990) found that the ratio of CI and SiI lines near λ 1.07 mkm with widely differing excitation potentials may serve as a good thermometer for Cepheids providing a 30 K precision.

The method of determining T_{eff} for $F-G$ supergiants from the ratio of line equivalent widths in the visible was first developed by Klochkova & Topil'skaya (1996). Having shown that the spectroscopic criteria were only slightly sensitive to variations in $\log\ g$, V_t , $[Fe/H]$, they developed the method of T_{eff} determination by reconciling theoretically calculated and observed ratios of the equivalent widths (W_λ) of selected pairs of lines. Nineteen CI, OI, FeI, and $FeII$ lines in the wavelength range $\lambda\lambda$ 5000-9000 ÅÅ were used to reach an accuracy in T_{eff} of about 100–150 K.

According to Krockenberg et al. (1998) report, they derived temperatures of Cepheids and non-variable supergiants in a similar way by comparison of line-depth ratios in program star spectrum and in synthetic spectrum calculated with Kurucz's model atmospheres. They found that the uncertainty in the temperature for a single point of a Cepheid like star γ Cyg is about 150 K and errors in the mean T_{eff} are as small as 10 K for the best sampled Cepheids.

The approach of Klochkova & Topil'skaya (1996) was further developed in the work of Kovtyukh et al., (1998), who examined the dependence of observed depth ratios upon the photometrical temperatures. The purpose was to increase substantially the accuracy and reliability of the temperatures. The authors derived 23 analytical relations for determining T_{eff} from spectroscopic criteria in the visible spectral range ($\lambda\lambda$ 5000-7000 ÅÅ) which is commonly used to determine the chemical composition. In this range, unblended Si, Ti, V, Cr, Fe and Ni lines have been studied to check if they were suitable for T_{eff} determination. The accuracy reached is of the order of 50-80 K. However in practice the number of criteria appeared small for obtaining reliable T_{eff} , especially in the case of weak objects with low S/N. Here we propose an improved version of the calibration based upon more qualitative observational material.

2. Observations

For establishing very precise calibrations we used 64 high-resolution low-noise spectra of 10 bright classical Cepheids.

Cepheids have been chosen because for them there is a strict test of the derived temperatures: metallicity should not vary with pulsational phase (Fry & Carney 1997). This requirement helps to avoid systematical errors of the scale in a wide temperature range while using a great number of spectra allows to set quite precise zero-point.

The question is whether we may apply hydrostatic model atmosphere to the pulsating objects like Cepheids. To investigate this point, we carried out a detailed abundance analysis of δ Cep in seven phases (Kovtyukh & Andrievsky 1999).

As one can judge from this paper, there are no noticeable differences between the results from spectra exposed on different phases. We paid special attention to possible abundance variations determined from individual lines. With the exception of several lines (probably blended), the abundance derived proved to be independent upon pulsation phase. This indicated both the high quality of the spectral material and absence of errors in the adopted atmospheric parameters (T_{eff} , $\log\ g$, V_t).

It should be noted that near the phase of maximum light the lines become asymmetrical, but this does not affect abundances either. Consequently, such line parameters as W_λ and R_λ, especially their ratios, remain practically unaltered by asymmetry.

We may therefore conclude that employment of static models in the analysis of Cepheid spectra should not be a source of great concern. From the P-L relation we can infer luminosities of calibrating Cepheids which enables us to outline the region on the H-R diagram where the proposed calibrations may be used (see below).

Observations were carried out at Kitt Peak National Observatory coudé feed telescope during 21–27 September 1995. The spectrograph was equipped with a 3070×1024 CCD camera. An automatic reduction pipeline was associated with the spectrograph and images were reduced a few minutes after the exposure (bias and flat-field correction, order extraction, cosmic hits removal). High-resolution spectra of bright Galactic Cepheids (each of which is three spectra co-added, resolving power 80000 (30000 for four phases), S/N $\approx$ 150–200) were taken in the spectral region 5600-7800 ÅÅ (19–25 orders).

Detailed descriptions of the telescope and spectrograph can be found in Fry & Carney (1997). They derived spectroscopic temperatures and abundance for 23 Cepheids. These temperatures were used by Fry & Carney (1999) for specification of $(B-V)_0 \sim T_{eff}$ and $(V-R)_0 \sim T_{eff}$ relations. All calibrating Cepheids were from open clusters with reliably determined reddening; metallicity has been allowed for. They find that $B-V$ and $V-R$ are the best colors to use to determine T_{eff} .

Further work with the spectra (continuum level, wavelength calibration, line-depths measurements, etc) was performed using the DECH20 package (Galazutdinov 1992). For the number of lines we had two estimates of the line-depths R_λ from adjacent orders. In all cases, the differences between independent estimates did not exceed 0.01, being usually less than this value. It indicates the high quality of the spectra and high precision of the line-depth determination, even for the lines located near the order edges.

3. Search for relationships

As was shown by Sheminova (1993), weak metal lines with low excitation potentials are most temperature-dependent. They grow with temperature decrease. High potential and ionic lines make up most of the insensitive lines. However, there is no possibility to use ionic lines in case of supergiants since their strengths depend on surface gravity.

To eliminate a possible dependence on microturbulent velocity, weak lines are more preferable, but they are more difficult to measure. That is why at high temperatures, when many lines weaken, the number and accuracy of calibrations decrease. Using weak lines is also recommended to avoid the effects of metallicity, since two lines on different parts of their curves of growth respond differently to changes in metallicity. Needless to say, the reliable line-depth can be had if only the continuum and the core of the line are unblended.

Using ratios rather than absolute line-depths alleviates if it does not remove completely the uncertainty arising from differences in chemical abundance, micro- and macroturbulent velocities and $vsini$ (Gray 1989, 1994). We refer the reader to these works where an exhaustive all-round analysis of all possible errors of the method (instrumentation, resolution ones, errors caused by individual differences among stars and others) can

Table 1. Calibrations for determining T_{eff} using line-depth ratios r = $R_{\lambda 1}$ / $R_{\lambda 2}$.
T_{eff} = a + b r + c r^2 + d r^3

N	λ_1	El	$\chi(eV)$	λ_2	El	$\chi(eV)$	$\Delta\ T_{eff}$ (K)	σ (K)	a	b	c	d
1	5670.86	VI	1.08	5690.43	SiI	4.93	4900–6400	82	7024	-6235	6045	-1986
2	5754.68	NiI	1.93	5772.15	SiI	5.08	4700–6700	131	7474	-751	-424.5	...
3	5772.15	SiI	5.08	5778.46	FeI	2.59	4700–6200	92	3853	1038	-157.9	8.17
4	5793.08	SiI	4.93	5793.93	FeI	4.22	4700–6600	105	1975	3618	-943.9	80.9
5	6056.00	FeI	4.73	6062.89	FeI	2.18	4700–6600	52	3998	810	-111.4	6.1
6	6062.89	FeI	2.18	6078.50	FeI	4.79	4800–6600	65	7052	-6461	6658	-2559
7	6078.50	FeI	4.79	6082.72	FeI	2.22	4700–6500	66	3518	1652	-350.6	26.7
8	6078.50	FeI	4.79	6085.27	FeI	2.76	4700–6500	70	3056	2227	-532.3	44.5
9	6085.27	FeI	2.76	6091.92	SiI	5.87	4700–6700	58	7206	-1611	224.9	...
10	6090.21	VI	1.08	6091.92	SiI	5.87	4700–6700	70	7227	-2166	474.1	...
11	6125.03	SiI	5.61	6126.22	TiI	1.06	4700–6600	52	3825	1909	-511.7	50.5
12	6145.02	SiI	5.62	6151.62	FeI	2.18	4700–6600	45	2631	6566	-4162	969.9
13	6151.62	FeI	2.18	6155.14	SiI	5.62	4700–6700	32	7116	-2393	482.6	...
14	6155.14	SiI	5.62	6180.21	FeI	2.73	4700–6600	36	2197	4664	-1867.2	272.1
15	6170.49	FeI	4.79	6180.21	FeI	2.73	4700–6600	56	-1824	11611	-5746.5	992.1
16	6176.81	NiI	4.08	6258.10	TiI	1.44	4700–6500	56	2238	3580	-755.7	...
17	6176.81	NiI	4.08	6261.10	TiI	1.42	4700–6700	128	2011	3758	-753.8	...
18	6237.33	SiI	5.61	6240.65	FeI	2.22	4700–6500	48	2737	4310	-1810	272.9
19	6243.11	VI	0.30	6243.81	SiI	5.61	4800–6300	39	6524	-2028	606.1	...
20	6243.11	VI	0.30	6244.47	SiI	5.61	4800–6300	67	6589	-2013	575.36	...
21	6244.47	SiI	5.61	6258.10	TiI	1.44	4700–6600	85	2199	6096	-3216	634.3
22	6327.60	NiI	1.67	6414.99	SiI	5.87	4700–6600	49	6950	-1762	323.65	...
23	6330.13	CrI	0.94	6330.86	FeI	4.73	4700–6700	101	7190	-2042	307.6	...
24	6330.13	CrI	0.94	6414.99	SiI	5.87	4900–6600	67	6947	-2710	862.9	...
25	6355.04	FeI	2.84	6419.98	FeI	4.73	4700–6600	61	6793	238	-1608.7	...
26	6414.99	SiI	5.87	6498.95	FeI	0.95	4700–6500	46	3476	4233	-2552	576.5
27	6498.95	FeI	0.95	6597.61	FeI	4.79	4800–6700	52	7137	-1478	218.45	...
28	6597.61	FeI	4.79	6608.04	FeI	2.28	4700–6500	52	3853	1195	-225	15.9
29	6680.15	CrI	4.16	6703.58	FeI	2.76	4800–6500	79	3635	2633	-967	130.6
30	6710.31	FeI	1.48	6713.76	FeI	4.79	4800–6300	80	6674	-1353	233.29	...
31	6710.31	FeI	1.48	6721.85	SiI	5.86	4800–6200	49	6614	-3424	2593	-763.9
32	6806.85	FeI	2.73	6848.57	SiI	5.86	4700–6700	101	7116	-790.9	...	...

be found. The conclusion made is that all these factors are not of great importance and on the whole considerably compensate each other. We therefore will not discuss in detail this problem again, but will only concentrate on the most important factors.

Errors in continuum placement and field errors across the spectrum can be reduced by making ratios of close lines. Unfortunately, we found only few such pairs and had to be content with rather wide ones.

The accuracy of depth determination was established from measuring the same lines in two adjacent orders. Despite the fact that at edges where these lines are situated the S/N ratio is lower, the typical error of R_λ (residual intensity) makes only 0.006–0.01 and to the greater degree is caused by uncertainty in drawing continuum. Noise is minimized as we approximate the whole profile with Gaussian curve. The procedure gives very exact R_λ. The typical observed error in a single line-depth ratio r=$R_{\lambda_1}/R_{\lambda_2}$ for the lines is 0.01-0.02.

Of course, increasing the S/N ratio of spectra would reduce error of temperature determination and consequently the limit of detectable temperature variations. In a few cases some line-depths were missing in calibrating spectra because of a CCD flaw, cosmic particle and such like.

In accordance with all the above, the following criteria for the line-depth ratios have been adopted:

(1) the excitation potentials of the lines must differ as much as possible;

(2) the lines must be close, if possible, to eliminate errors in continuum placement;

(3) the lines must be weak enough to eliminate a possible dependence on V_t ;

(4) since ionic lines are quite sensitive to $\log\ g$, they were excluded from the analysis;

(5) excluded were also lines of carbon, nitrogen and oxygen, as well as of other elements whose abundances change with supergiant evolution;

(6) a spectral regions with a large number of telluric lines were not used either.

The search for line combinations was carried out by direct comparison of spectra taken during phases of maximum and minimum light (and temperature). Potentially useful pairs were to consist of temperature sensitive and insensitive close lines. In this way we selected practically all (45) most suitable lines within the wavelength interval 5600-6850 ÅÅ. Twenty-two of them are sensitive to temperature and the remainder insensitive. Then the ratios were tested and only those giving small scattering in T_{eff} have been retained. In all, 32 ratios of line-depths were selected as temperature indices (see Table 1).

4. Temperatures

The main source of initial temperatures was Fry & Carney (1997) work (T_{eff} (F&C), see Table 2), who derived T_{eff} using the independence of iron abundance on excitation potential of FeI lines. In case of high quality spectra, this method provides no more than 100–150 K error and does not depend on reddening. The authors found good agreement with the results obtained by other methods, such as the infrared flux method (Fernley et al., 1989) or detailed analysis of energy distribution over a wide spectral range carried out for δ Cep and nonvariable supergiants (Evans & Teays 1996).

Another source was photometry. There are several investigations of temperature variations during pulsational cycle of Cepheids where $B-V, R-I, b-y$ colors have been considered. We chose Kiss (1998) observations because they were carried out nearly simultaneously with our observations and there is no need to take possible changes of periods into account. Phases were calculated according to the same paper. These latter temperatures, derived from $T_{eff} \sim (b-y)_0$ calibrations of Kiss & Szatmary (1998), were reduced to a system common with T_{eff} Fry & Carney (1997), because of probable reddening errors.

Using weighted least-square method, we calibrated our ratios with mean values of temperatures determined for each phase as described above. Greater weight was assigned to better exposures. For approximation we employed polynomial fit. Thirty-two calibration curves gave 20–32 estimates of temperature for each spectrum (extremely weak and strong lines had been omitted). Being averaged, they were plotted again and new, final, calibrations have been obtained. In this way we smooth individual errors of the input temperatures.

Temperatures for 64 Cepheid phases derived in the way just described are given in Table 2 (averaged values from calibrations from Table 1), as well as T_{eff} by Fry and Carney (1997), mean errors of a single measurement (σ), the number of calibrations used (N) and the errors of the mean (σ_{mean}). Mean square deviation of our temperatures from Fry & Carney's is only 78 K, which may be considered the error of their single temperature determination.

The statistical error fixing the fitting curve's position is known more precisely than the scatter of the individual points ($\approx$ 80–100 K), because all of the points are used to determine the curve.

Further, while the use of the mean out of 32 estimates allows to eliminate random errors, a systematical error remains, which corresponds to the uncertainty of the zero-point of T_{eff} scale and may achieve several tens of degrees. But we are not concerned with absolute temperatures as such in this study. The purpose was to establish a temperature scale that would permit to consider the relative position of nonvariable supergiants on the temperature axis compared to Cepheids.

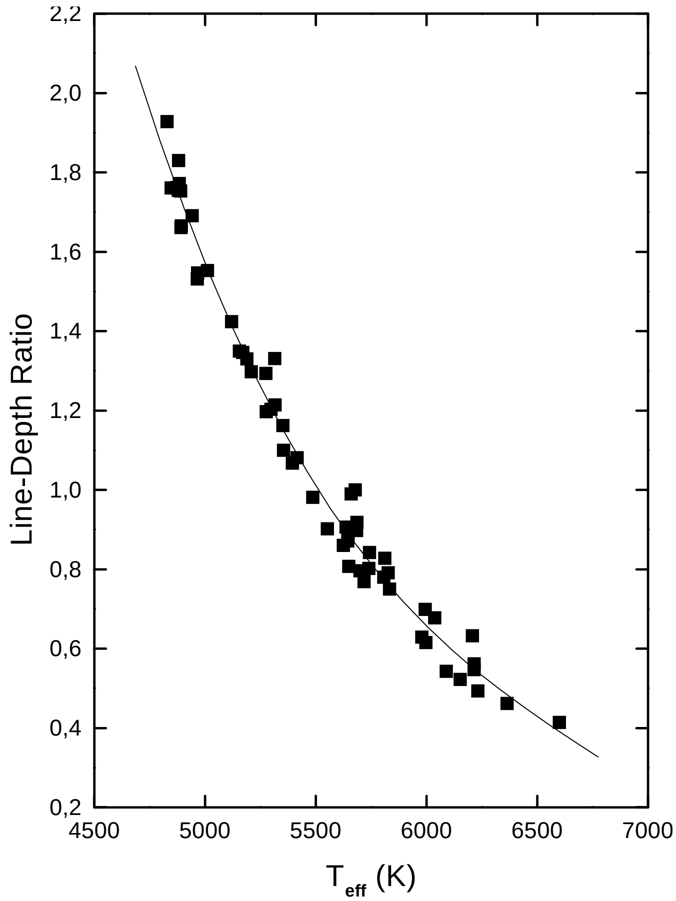

Fig. 1. A typical calibration curve. The ratio of spectral line-depths, λ 6090.21 Å VI to λ 6091.92 Å SiI (calibration No.10 from Table 1), is shown as a function of effective temperature.

In Figs. 1–2 we show typical calibration relations. The scatter is dominated by line-depth measuring errors and by real differences among stars, e.g., differing abundances, luminosity, $\log\ g$, V_t , $vsini$, non–LTE effects etc.

Mathematical expressions for the calibrations are given in Table 1. This table contains wavelengths (λ_1, λ_2) and excitation potentials (in eV) of lines for each criterion, working temperature range, *mean* square deviation for each curve σ and the calibration expressions themselves (r = $R_{\lambda_1}/R_{\lambda_2}$).

It is clear that the ratios have different precision. The accuracy of temperature determination decreases at higher and lower temperatures. Especially at higher temperatures, where the error of line-depth measuring grows because of line weakening. Let us estimate the error of T_{eff} caused by the uncertainty of line-depth measurements. The mean dispersion of ratios r = $R_{\lambda_1}/R_{\lambda_2}$ measured on several orders is 0.01–0.02. We may translate this dispersion into the temperature error by using the slope of a typical curve in Fig. 1. Near the center of the figure this slope is about -1060 K per unit ratio, implying a temperature error of $\approx \pm$ 10-20 K. That is, provided the good quality of

Table 2. Temperatures from individual spectra

Star	ϕ	T_{eff} (F&C)	T_{eff}	σ	N	σ_{mean}	Star	ϕ	T_{eff} (F&C)	T_{eff}	σ	N	σ_{mean}
η Aql	0.387	5750	5644	51	32	9.0	S Sge	0.480	5450	5416	53	32	9.3
	0.525	5450	5394	45	32	8.0		0.599	5300	5276	56	32	9.9
	0.664	5375	5298	67	32	11.8		0.720	5500	5354	67	32	11.8
	0.803	5875	5649	111	29	20.7		0.838	5750	5826	100	32	17.7
	0.944	6350	6214	97	31	17.4		0.957	6400	6215	69	22	14.6
	0.221	5875	5806	57	32	10.0	U Sgr	0.842	5675	5740	97	25	19.3
	0.359	5750	5718	64	32	11.2		0.989	6350	6254	106	28	20.0
	0.707	5400	5351	90	26	17.6		0.137	6100	6021	77	28	14.6
δ Cep	0.443	5675	5624	71	32	12.6		0.285	5750	5754	81	32	14.4
	0.628	5450	5486	51	32	8.9		0.439	5600	5595	67	32	11.8
	0.809	5675	5678	78	31	14.0	SZ Tau	0.963	6250	6207	78	21	17.1
	0.002	6750	6648	62	31	11.2		0.279	5930	5994	54	29	10.0
	0.190	6150	6089	56	32	9.8		0.924	6250	6170	67	22	14.3
	0.364	5675	5699	71	32	12.5		0.237	6000	6037	54	28	10.3
	0.551	5500	5552	71	32	12.5		0.549	5750	5811	82	32	14.5
X Cyg	0.417	5000	4964	66	25	13.3	T Vul	0.045	6500	6399	77	18	18.1
	0.477	5000	4890	55	21	12.0		0.271	5875	5978	53	29	9.8
	0.600	5050	4836	50	20	11.2		0.490	5600	5684	62	31	11.2
	0.661	4950	4828	59	25	11.7		0.718	5500	5659	87	32	15.4
	0.720	5050	4942	78	25	15.7		0.945	6350	6363	48	19	11.0
ζ Gem	0.495	5250	5171	42	29	7.8		0.162	6150	6152	67	29	12.4
	0.592	5310	5316	57	32	10.0		0.123	6250	6232	104	19	20.1
	0.792	5675	5685	57	31	10.3		0.572	5600	5637	70	24	14.2
	0.891	5750	5743	41	32	7.3	SV Vul	0.292	5310	5314	64	30	11.7
	0.988	5875	5833	50	32	8.8		0.315	5310	5274	61	31	11.0
T Mon	0.344	5000	5011	75	27	14.4		0.337	5310	5209	44	29	8.3
	0.380	5000	4967	82	25	16.4		0.359	5200	5188	61	30	11.2
	0.418	5100	4891	64	20	14.2		0.382	5200	5155	57	30	10.3
	0.456	5000	4889	77	21	16.8		0.403	5200	5120	58	30	10.6
	0.493	5000	4879	89	23	18.5		0.721	4925	4880	61	28	11.5
	0.529	5000	4871	110	32	19.5		0.769	4825	4883	53	30	9.6
S Sge	0.243	5930	5997	54	32	9.6							
	0.362	5675	5645	65	32	11.5							

spectra and employment of large number of criteria, the error in T_{eff} induced by uncertainties in continuum placement and line-depth measurements proves to be quite small.

Taking into consideration that the errors in calibration stars' temperatures are 40–130 K (Table 1), we infer that the mean uncertainty in the temperature determination arises from the real differences between individual stars: in chemical composition, luminosity, macro- and microturbulence, rotation and non-LTE effects. It is rather difficult to establish exactly which factors besides temperature affect genuine ratio $R_{\lambda_1}/R_{\lambda_2}$ and what their relative contribution into resulting error is. However, judging from the small value of latter, we may assert that the influence of these differences upon line-ratios, even in the wide luminosity range, remains of minor importance.

Are there any fundamental limitations on the precision with which the calibration curves can be determined? For Cepheids, such limitation will likely be set by intrinsic variation of temperature of Cepheid during time exposure. To reduce the effect we took bright Cepheids with minimal exposure time. In this case the variations did not exceed 5–10 K. Speaking more correctly, we derive temperatures averaged over exposure time. For stationary stars, apparent temperature changes of several degrees may be produced by some surface features and rotational modulation, as for example, documented for the G8 dwarf ξ Bootis A (Toner & Gray 1988) and σ Dra (K0V, Gray et al., 1992).

The high precision of the technique may be demonstrated on the long-period Cepheids from our observational set: T Mon (P=27.^{d}025) and SV Vul (P=44.^{d}994). Spectra of these stars, taken during several successive nights, show very smooth decreasing of T_{eff} by 10–70 degrees, which is in accordance with the fact that these phases are phases of light falling.

Taking into account the large period range of our Cepheids (from 3.15 to 44.99 days) and small errors of the derived calibrations, we may conclude that these calibrations are valid in a wide region of H–R diagram: (M$_v$ = –2^m ÷ –6^m, T_{eff} = 4700–6700 K), where most $F-G$ supergiants reside.

All the spectra except four (last two phases of T Vul and SV Vul) were of very high resolution (R=80000), which allowed to a large extent to escape errors in line-depth measurement. But even in the case of the four mentioned spectra having

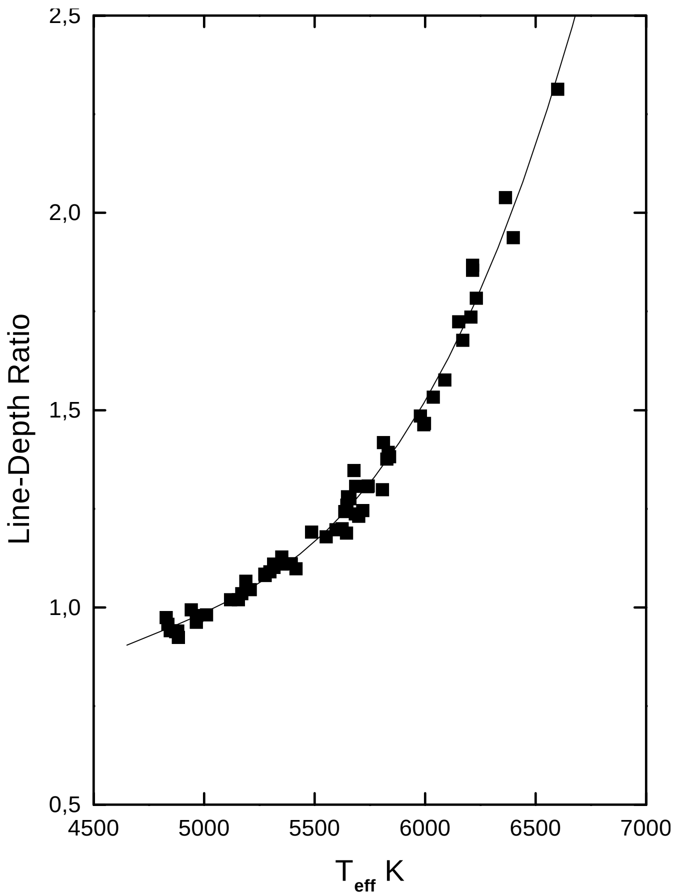

Fig. 2. Same as Fig. 1, but for spectral lines λ 6170.49 Å FeI and λ 6180.21 Å FeI. Calibration No.15.

R=30000, the resulting temperatures are practically of the same precision. This is because the orders of these spectra overlap strongly which permits to diminish observational error by measuring each line two to three times.

Still lower resolution reduces the accuracy of measurement leading to increasing of sigma, but the value of T_{eff} itself remains practically unaffected. Gray (1989, 1994) arrives at a similar conclusion.

5. Conclusion

The line-depth ratio method proved to be a precise method of the effective temperature estimation for various types of stars. On the basis of specially selected pairs of lines 32 calibration ratios have been obtained yielding relative temperatures for Cepheids and yellow supergiants with 10–15 K error.

The authors have a simple BASIC program for calculating T_{eff} and can send it at request.

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