HIGH PRECISION EFFECTIVE TEMPERATURES OF F-K SUPERGIANTS AND CLASSICAL CEPHEIDS

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ABSTRACT. We present precise effective temperatures ($T_{\rm eff}$) of 110 F-K supergiants determined from the method of line depth ratios. For each star, we have measured the line depths a large number of spectral lines of low and high excitation potentials and established $\sim$ 100 relations between $T_{\rm eff}$ and their ratios. These relations have been calibrated against previously published accurate temperature estimates. The range of application of the method is 4000–7000 K (F2–K4). The internal error for a single calibration is less than 110 K, while the combination of all 100 calibrations reduces the uncertainty to only 5–35 K (1 sigma). A big advantage of the line ratio method is its independence on interstellar reddening, spectral resolution, and line broadening due to rotation or microturbulence.

Key words: Stars: fundamental parameters; stars: effective temperatures; stars: supergiants; stars: classical cepheids.

1. Introduction

The method of the line depth ratios (R1/R2) is based on the use of a large number of paired spectral lines. The lines are paired to cover a large range of excitation potentials of the lower level. The low and high-excitation lines respond differently to the change of $T_{\rm eff}$, therefore the ratio of their depths (or equivalent widths) should be a very sensitive indicator of the temperature. The high-excitation lines vary much less with $T_{\rm eff}$ compared to the low-excitation lines.

In general, the strength of a given line depends, beside the temperature, on the large number of other atmospheric factors, like chemical abundance (or metallicity, [Fe/H]), rotation, micro- and macroturbulence, surface gravity log g, atomic constants, non-LTE conditions, etc. The rationing of lines allows to cancel those factors that affect all lines in the same way. These advantages may not apply to the strong lines which strength is dominated by the damping wings. Therefore only weak lines can be safely used with the line ratio technique.

The line depth ratio method has a long history. Among latest developments are the works by Gray and co-authors (Main Sequence, giants), Strassmeier & Schordan (2000, giants), Padgett (1996, T Tauri stars), etc. Despite the long history, the line ratio method has been only recently transformed into a form that is suitable for the practical use, as for example in the investigation of the chemical abundance analysis of supergiant, giants and Main Sequence (MS) stellar atmospheres. In a serie of papers, our group has improved the method. In Kovtyukh et al. (1998) and Kovtyukh & Gorlova (2000), 37 calibrations for $T_{\rm eff}$ were derived from high-dispersion spectra of supergiants and classical cepheids with effective temperatures from 4500 to 7000 K. The original Kovtyukh & Gorlova (2000) calibration depend upon the excitation temperature analysis of Fry & Carney (1997) combined with the photometric results of Kiss & Szatmary (1998). The current calibration uses the previous information combined with the excitation analysis results for supergiants of Luck & Bond (1989) and the 13-color photometry results of Bravo Alfaro, Arellano Ferro & Schuster (1997). Luck & Bond showed that their effective temperatures were consistent with the V–K calibration of Ridgway et al. (1980) and agreed well with J–K calibration especially at temperatures above 4600 K. This method is not totally dependent upon previous excitation analyses. More importantly, it has been demonstrated to yield consistent results as a function of phase for numerous Cepheids spanning periods from 3 to 47 days (Luck & Andrievsky 2004; Kovtyukh et al. 2005; Andrievsky, Luck & Kovtyukh 2005).

As a next step we derived similar calibrations for the MS stars, with temperatures 4000–6150 K (Kovtyukh et al. 2003; Kovtyukh, Soubiran & Belik 2004). From 600 line pairs we selected 105 with the smallest dispersions (less than 100 K each). This high precision indicates that these calibrations are largely insensitive to metallicity, surface gravity, micro- and macroturbulence, rotation and other individual stellar parameters. In Kovtyukh, Soubiran & Belik (2004), the discovery of a narrow gap (just 50 K wide, between 5560 and 5610

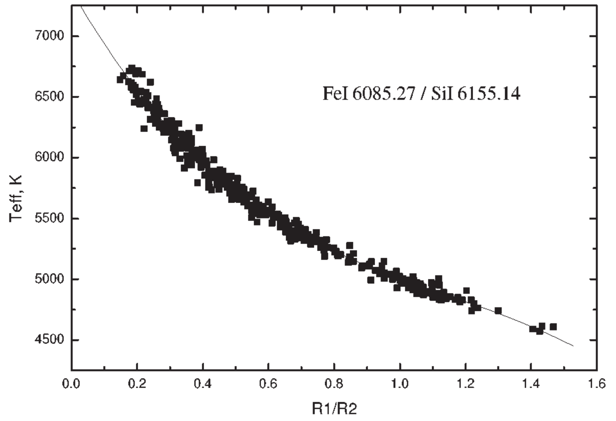

Figure 1: Example of the typical temperature calibrations derived in this work.

K) in the distribution of effective temperatures for 248 MS stars was a nice confirmation of the precision of the method. This gap is attributed to the jump in the penetration depth of the convective zone. The line ratio method has also been tested on giant stars (Kovtyukh et al. 2006). This latter work demonstrated how variations in $T_{\rm eff}$ at a 5–10 K level can be detected for a given star.

The effective temperature obtained from this new technique gives currently one of the most precisely determined fundamental stellar parameters – the relative precision is of the order of 0.1 percent.

2. Observations

The investigated spectra are part of the library collected at the Haute Provence Observatory (Soubiran et al. 1998) and they were obtained with the 193 cm telescope equipped with the ELODIE spectrometer (R=42000). The useful spectral range is 4400–6800 ÅÅ, signal-to-noise ratios are larger than 100. All the spectra have been reduced as described in Katz et al. (1998).

Also we used the spectra obtained with UVES at the VLT unit Kueyen (=VLT2). All supergiants are observed with two instrument modes Dichroic 1 and Dichroic 2, in order to cover almost completely the wavelength interval from 3000 to 10000 Å. The spectral resolution is about 80000, and for most of the spectra, the typical S/N ratio is 300–500 in the V band.

The further processing of spectra (continuum level location, measuring of line depths and equivalent widths) was carried out by us using the DECH20 software (Galazutdinov 1992). Line depths R_λ were measured by means of a Gaussian fitting.

3. Construction of the temperature calibrations

Based on our previous experience, we first conducted an analysis of the potential atomic lines used for the temperature calibrations. We excluded ion lines and the high excitation lines (such as C, N, O transitions), that are sensitive to log g and therefore ambiguous for temperature determination (see Caccin, Penza & Gomez 2002). We primarily used lines belonging to the iron-peak elements (such as Si, Ti, V, Cr, Fe, Ni) because they have a negligible response to changes in log g, and a negligible star to star variation in element abundances.

Then, to begin the iteration process, an initial temperature has been assigned to each star. These temperatures will be a source of systematic uncertainties in the zero-point and in the slope of the final calibrations. They will also affect the internal precision of the calibrations. The choice of the initial temperature scale is therefore very important. Unlike dwarfs, there is no for the supergiants such a natural standard as the Sun. Many recent studies can be found in the literature with temperature scales for supergiants (Luck & Bond 1989; Luck & Wepfer 1995; Fry & Carney 1997; Bravo Alfaro, Arellano Ferro & Schuster 1997, Gray, Graham & Hoyt 2001, Yong et al. 2006). Using these temperatures, we constructed the first set of R1/R2 vs. $T_{\rm eff}$ calibrations. Each calibration was composed of the the lines with vastly different excitation energies of the lower level. We visually examined scattered plots for every ratio and retained only those that showed a clear tight correlation with $T_{\rm eff}$ (see Fig.1). An analytic fit was performed for these selected ratios to produce the first calibrations. By averaging temperatures calculated from these fits, we obtained a second $T_{\rm eff}$ approximation for each star. The random uncertainty has been reduced by 50–100 K. These improved values for $T_{\rm eff}$ have been iterated once again to produced the final calibrations.

The precision of a given calibration varies with $T_{\rm eff}$. We therefore provide for each calibration an allowed range of temperatures where it should be used.

The average internal accuracy of a single calibration (1 sigma) is 60–110 K (ranging from 60–65 K for the best and 100–110 K for the worst cases). Fig. 1 shows our typical calibration. In many cases the dependences could not be fitted with a continuous polynomial, therefore we tried other analytical functions: $T_{\rm eff} = ab^r r^c$, $T_{\rm eff} = ab^{1/r} r^c$, $T_{\rm eff} = ar^b$, $T_{\rm eff} = ab^r$, $T_{\rm eff} = a + b * ln(r)$. Here a, b, c are constants and r is the line ratio, r=R1/R2. The choice of the particular approximation was done according to the least square deviation.

In cases where R1/R2 was a non-monotonic function (i.e., a given value of R1/R2 corresponded to more

Table 1: High precise temperatures of the supergiants

HD	$T_{\rm eff}$	σ, K	N	error, K	HD	$T_{\rm eff}$	σ, K	N	error, K
000371	5083	52	34	9.0	147266	5078	123	34	21.1
000611	5405	117	78	13.2	151237	5808	140	43	21.3
003421	5300	84	80	9.4	152830	6754	159	36	26.5
004362	5301	103	83	11.3	159181	5181	61	72	7.2
004482	4935	122	51	17.0	164136	6797	134	25	26.9
005747	5044	137	35	23.1	171635	6151	87	79	9.8
008992	6331	81	73	9.5	172365	6018	222	36	36.9
009900	4620	53	27	10.3	172588	6803	258	71	30.6
009973	6836	124	73	14.6	174383	5713	99	88	10.6
010806	5049	89	34	15.3	176155	6474	85	38	13.7
011544	5145	60	34	10.3	179784	4975	35	34	6.0
015784	6606	118	36	19.7	180028	6307	115	72	13.6
016901	5509	70	89	7.4	180583	5986	71	35	12.0
017905	6476	165	24	33.7	182296	5054	47	33	8.1
018391	5756	142	66	17.5	185018	5398	89	34	15.3
020123	5160	54	61	6.9	185758	5367	91	67	11.1
020902	6705	84	68	10.2	186155	6839	148	7	56.0
026630	5309	58	67	7.1	187203	5750	113	26	22.1
031910	5401	103	86	11.1	188650	5649	186	69	22.4
032655	6755	144	53	19.7	189671	4919	59	32	10.5
034248	6077	171	70	20.5	190323	6133	122	35	20.6
036891	5089	59	70	7.1	190403	4978	102	31	18.4
042456	4821	86	62	10.9	190405	6071	251	30	45.8
044812	4931	80	67	9.8	193370	6467	85	31	15.3
045416	4826	74	58	9.7	194069	4916	48	30	8.7
045829	4547	59	36	9.8	194093	6227	70	32	12.3
048329	4583	46	40	7.3	195295	6780	71	75	8.2
048616	6528	93	64	11.7	195432	5907	132	38	21.4
050372	4860	72	53	9.8	195593	6567	95	31	17.1
052220	5605	67	90	7.1	198726	6097	81	86	8.8
053003	5499	113	81	12.5	199394	5082	125	34	21.5
054605	6564	83	69	10.0	200102	5312	93	33	16.2
057146	5126	48	68	5.9	201078	6338	73	64	9.2
062345	5004	85	62	10.8	202109	5060	113	33	19.7
067523	6558	137	76	15.8	202314	4996	75	33	13.0
074395	5247	64	75	7.4	204075	5262	91	71	10.8
077020	4911	68	59	8.9	204867	5431	65	76	7.5
079698	5241	105	72	12.3	205603	4989	59	29	10.9
084441	5281	92	66	11.3	206731	5037	63	32	11.1
090452	6890	99	68	12.0	206859	4912	37	63	4.7
092125	5336	99	84	10.8	208606	4766	60	31	10.8
097082	5557	48	87	5.2	209750	5199	57	65	7.1
099648	4967	75	63	9.5	210848	6238	160	82	17.6
101947	6578	188	65	23.4	211153	5132	132	34	22.6
104452	5663	248	32	43.8	214567	4950	84	57	11.1
109379	5124	99	69	11.9	214714	5416	178	66	21.9
114988	4972	173	25	34.5	215665	4900	70	54	9.6
117440	4736	62	50	8.7	216206	5029	39	32	6.8
125728	5009	99	34	17.0	216219	5758	184	78	20.8
125809	4861	57	59	7.4	217754	6860	172	72	20.2
134852	6650	197	37	32.3	218043	6625	128	29	23.9
136537	4978	56	62	7.1	221661	5034	116	33	20.2
139862	5086	106	35	17.8	223047	4864	39	54	5.3
142357	6397	123	24	25.2	224165	4857	34	32	6.1
146143	6072	92	89	9.8	225292	4974	74	34	12.7

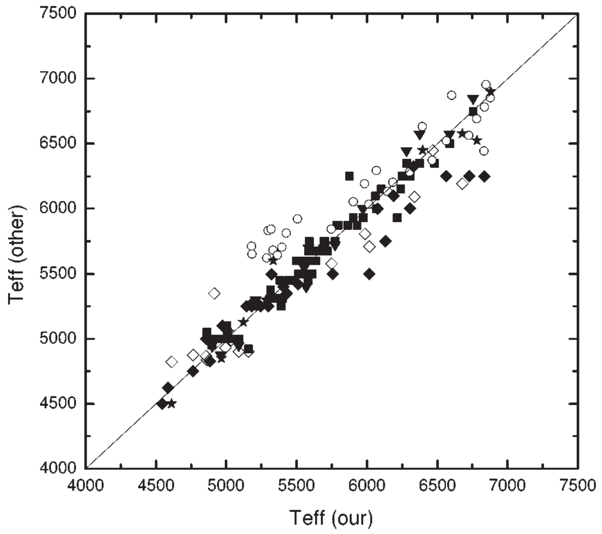

Figure 2: Comparison of our temperatures with estimates from the literature: filled squares – Fry & Carney 1997; open rhombuses – Bravo Alfaro, Arellano Ferro & Schuster 1997; open circles – Gray, Graham, Hoyt 2001; filled triangles – Yong et al. 2006; filled rhombuses – Luck & Bond 1989; stars – Luck & Wepfer 1995.

than one value of $T_{\rm eff}$), we have limited the range of application for temperatures to exclude this ambiguity. More details about the line ratio techniques can be found in Kovtyukh et al. (2006).

4. Results and summary

In Table 1 we report $T_{\rm eff}$ for 110 supergiants derived from our calibrations. Each entry includes the name of the star, mean $T_{\rm eff}$, standard deviation of the mean temperature, number of calibrations used, and 1 sigma error. Fig. 2 compares for 110 objects our temperatures with estimates from the literature.

The final precision we achieve is 5–35 K (1 sigma), for the spectra of R=42000, S/N=100–150. This can be further improved with higher resolution and larger S/N. We note that this error budget does not include the possible uncertainties that arise from the individual properties of stars, like magnetic field, metallicity, V_{tur}, v*sini*, etc. When monitoring a given star however, these individual parameters remain fixed, which allows to detect temperature "variations" as small as 4–10 K.

The high accuracy of $T_{\rm eff}$ determination provided by the line ratio method allows in turn to achieve a high accuracy in [Fe/H] determination – down to 0.02–0.05 dex. The scatter of the points in Fig.1 arises mainly from the individual parameters of each star (like rotation, chemical composition, convection, binarity, etc.) rather than from the measurements errors of line depths (which are mostly due to the uncertainty of continuum placement). The averaging of temperatures obtained from 70–100 line ratios significantly reduces the uncertainty from a single calibration.

Summarizing, supergiant temperatures determined in this work using line ratio technique, are of high internal precision and agree well with the most accurate estimates from the literature.

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