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► **To cite this version:**

V. V. Kovtyukh, C. Soubiran, O. Bienaymé, T. V. Mishenina, S. I. Belik. High-precision effective temperatures of 215 FGK giants from line-depth ratios. *Monthly Notices of the Royal Astronomical Society*, 2006, 371, pp.879-884. 10.1111/j.1365-2966.2006.10719.x . hal-00109239

HAL Id: hal-00109239

<https://hal.science/hal-00109239>

Submitted on 13 Dec 2020

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High-precision effective temperatures of 215 FGK giants from line-depth ratios

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Accepted 2006 June 21. Received 2006 June 17; in original form 2006 May 12

ABSTRACT

We present precise effective temperatures (T_{eff}) of 215 FGK giants determined using the method of line-depth ratios. For each star, we have measured the line depths and equivalent widths of a large number of spectral lines of low and high excitation potentials and established ~ 100 relations between T_{eff} and their ratios. Starting with an initial value T_{eff} , the relations are then self-calibrated by an iterative process. Our final estimates have been compared with very accurate (1 per cent) published temperatures and show a good agreement. Using our calibrations, we derive precise temperatures for 215 giants with near-solar metallicity, from high-resolution ($R = 42\,000$) and high signal-to-noise ratio ($S/N = 100\text{--}250$) echelle spectra, obtained with the ELODIE spectrometer at the Observatoire de Haute Provence (OHP). The range of application of the method is 3500–5700 K (G0 III–K4 III). The internal error for a single calibration is less than 95 K, while the combination of all 100 calibrations reduces the uncertainty to only 5–20 K (1σ). A big advantage of the line ratio method is its independence of interstellar reddening, and its modest sensitivity to spectral resolution, abundance, macroturbulence and other factors.

Key words: stars: fundamental parameters.

1 INTRODUCTION

The method of line-depth ratios is based on the fact that low- and high-excitation spectral lines respond differently to changes of T_{eff} . Therefore, the ratio of their depths (or equivalent widths) is a very sensitive indicator of temperature. High-excitation lines vary much less with T_{eff} compared to low-excitation lines, so that pairing lines covering a large range of excitation potentials of the lower level and using a large number of pairs is a good way to increase the precision of the method. In general, the strength of a given line depends, besides the temperature, on a large number of other atmospheric factors, like chemical abundance (or metallicity, $[\text{Fe}/\text{H}]$), rotation, micro- and macroturbulence, surface gravity $\log g$, atomic constants, non-local thermodynamic equilibrium (non-LTE) conditions, etc. Measuring line ratios allows one to cancel those factors that affect all lines in the same way. The instrumental biases like telescope-dependent resolution are also removed. These advantages may not apply to the strong lines the strength of which is dominated by damping wings. Therefore, only sufficiently weak lines can be safely used with the line ratio technique.

The line-depth ratio method has a long history. Among the latest developments are the works by D. F. Gray and co-authors [main sequence (MS), giants, see Gray & Brown 2001 and references therein], Strassmeier & Schordan (2000, giants), Padgett (1996, T Tauri stars), etc. Despite its long history, the line ratio method has been only recently transformed into a form that is suitable for practical use, as for example in the investigation of the chemical abundance analysis of supergiant and MS stellar atmospheres. In a series of papers, our group has improved the method. In Kovtyukh, Gorlova & Klochkova (1998) and Kovtyukh & Gorlova (2000), 37 calibrations for T_{eff} were derived from high-dispersion spectra of supergiants with effective temperatures from 4500 to 7000 K. As a next step, we derived similar calibrations for 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 precision indicates that these calibrations are weakly sensitive to metallicity, surface gravity, micro- and macroturbulence, rotation and other individual stellar parameters. However, the precision of the derived temperature from a ‘single’ or a few (2 to 5) calibrations remains low compared to the results obtained with a large number of calibrations (80–105) applied to spectra with a moderate signal-to-noise ratio (S/N). The typical uncertainty for a given single calibration is about 60–100 K.

In our previous studies of MS stars, the zero-point of the calibrations has been adjusted to fit the Sun ($T_{\text{eff}} = 5777$ K). 11 solar

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spectra (obtained in the form of reflection spectra of the Moon and minor planets) allowed to establish the absolute calibration at a level of 1 K. In Kovtyukh et al. (2004), the discovery of a narrow gap (just 50 K wide, between 5560 and 5610 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. These MS stars can therefore serve as temperature standards.

The line ratio method has also been tested on giant stars. Among the most recent studies, Strassmeier & Schordan (2000) applied 12 calibrations for 224 giants with T_{eff} in the range 3200–7500 K, using $R = 38\,000$, $\lambda\lambda 6380\text{--}6460$ Å spectra. Gray & Brown (2001) derived temperatures for 92 giants using five calibrations with a typical 25-K error from $R = 100\,000$, 70-Å-wide Reticon spectra centred at 6250 Å. This latter work demonstrated how variations in T_{eff} at a 4-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 per cent (note that the absolute error may be appreciably larger; a discussion about the zero-point of the temperature scale for non-MS stars is beyond the scope of this paper).

The present work is based on the previous studies of the MS and supergiant stars and aims to expand the applicability of the line ratio method to giant stars. Our goal is to achieve a 5–20 K precision in T_{eff} , which in turn would improve the precision of metallicity and abundance determinations to 0.03–0.05 dex. For example, such a precision might suffice to disentangle the thick and thin disc components of the Galaxy, just on the base of chemical abundance criteria. Another field that can benefit from high-precision temperatures is the study of the planet host stars, from atmospheric properties to interactions between planets and protoplanetary discs.

2 OBSERVATIONS

The investigated spectra were obtained with the 193-cm telescope equipped with the ELODIE spectrometer ($R = 42\,000$). Most of them have been obtained for a probe of disc stars in the solar neighbourhood (Bienaymé et al. 2006; Mishenina et al. 2006). This sample has been increased by selecting giants in the ELODIE library compiled by Prugniel & Soubiran (2001, 2004).

The useful spectral range is 4400–6800 Å, and S/N are larger than 100. All the spectra have been reduced as described in Katz et al. (1998).

Further processing of spectra (continuum level location, the measuring of depths and equivalent widths, etc.) was carried out by us using the DECH20 software (Galazutdinov 1992). Depths R_λ and equivalent widths W_λ of lines were measured by means of a Gaussian fitting. The accuracy of depth determination was established by measuring the same lines in two or more spectra of the same star, when available. The rms obtained (0.01–0.02) reflects the typical error of R_λ and to a greater degree is caused by uncertainty in drawing the continuum. For more precise determination of the line depths, only the core is used. Noise is minimized as we approximate the core with the Gaussian curve. The typical observed error in a single line-depth ratio $r = R_{\lambda,1}/R_{\lambda,2}$ for the lines is 0.02–0.05. All sufficiently strong and very weak lines are rejected automatically (see next section). It is worth noting that looking at the FWHM of our spectra shows that no fast rotator is included in our sample.

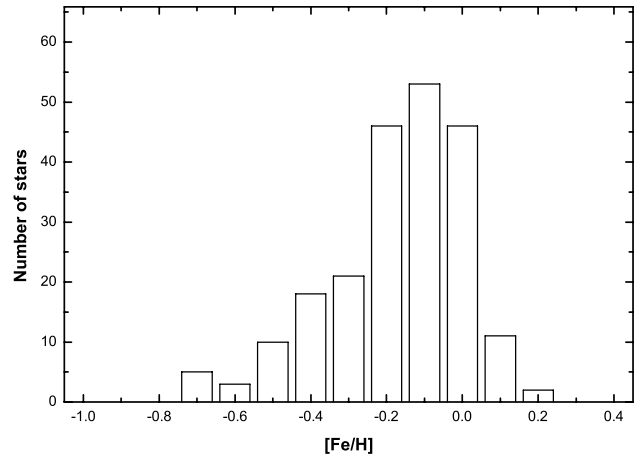


Figure 1. The metallicity distribution of our giant sample, according to TGMET determinations of $[\text{Fe}/\text{H}]$.

3 CONSTRUCTION OF THE TEMPERATURE CALIBRATIONS

3.1 The iterative process

All the spectra have been analysed with the TGMET software (Katz et al. 1998; Soubiran, Bienaymé & Siebert 2003) to have a first guess of their atmospheric parameters and absolute magnitudes. From the initial set, we have selected 215 giants with absolute magnitude $M_V < 3$ falling in the range $3500\text{ K} < T_{\text{eff}} < 5800\text{ K}$. Fig. 1 shows the histogram of metallicity of these giants ranging from $[\text{Fe}/\text{H}] = -0.70$ to $+0.25$, according to the TGMET determinations.

Based on our previous experience, we first conducted an analysis of all the possible atomic lines for the temperature calibrations. We excluded ion lines and high-excitation lines (such as C, N, O transitions), that are sensitive to $\log g$ and therefore ambiguous for temperature determination. We selected priority 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 was assigned to each star. A natural choice to initialize the line ratio method is to use the effective temperatures determined with TGMET because they are available for all stars and are homogeneous. According to Soubiran et al. (2003), TGMET gives very good results in the considered range of atmospheric parameters.

Using these temperatures, we constructed the first set of $R_{\lambda,1}/R_{\lambda,2}$ versus T_{eff} calibrations. Each calibration was built with lines that range over vastly different excitation energies of the lower level. We visually examined scatter plots for every ratio and retained only those that showed a clear tight correlation with T_{eff} . 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_{eff} approximation for each star. The random uncertainty has been reduced by 50–100 K. These improved values for T_{eff} have been iterated once again to produce the final calibrations. From the initial 500 calibrations, we choose 100 whose dispersion was smaller than 95 K.

The precision of a given calibration varies with T_{eff} . For example, the low-excitation lines weaken at large temperatures, which increases the measurement error for the line ratio and hence the error on the inferred T_{eff} . We therefore provide for each calibration an allowed range of temperatures where it should be used (thus the

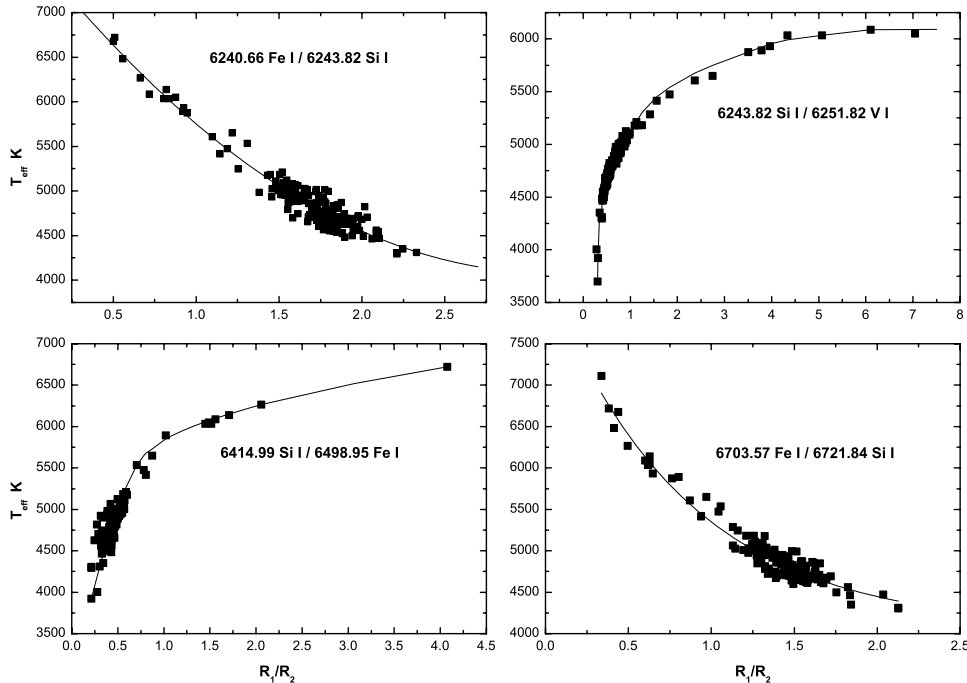


Figure 2. Examples of the typical temperature calibrations derived in this work. Each calibration is shown together with the corresponding wavelengths on whose line-depth ratio it relies (the x -axis). Each function is applied only in the temperature range where it provides a precision better than 100 K. The scatter is dominated by line-depth measuring errors and by real differences among stars, e.g. differing abundances, $\log g$, non-LTE effects, etc. The typical error in the line ratio is 0.02–0.05.

error remains smaller than 100 K). After this first temperature estimate obtained using 100 calibrations, the next estimate keeps only the calibrations that apply to the anticipated value of the temperature of the star.

The average internal accuracy of a single calibration (1σ) is 60–70 K (ranging from 40–45 K for the best and 90–95 K for the worst cases). Fig. 2 shows our typical calibrations. In many cases, the dependences could not be fitted with a continuous polynomial, therefore we tried other analytical functions as well, for example: $T_{\text{eff}} = ab^r r^c$, $T_{\text{eff}} = ab^{1/r} r^c$, $T_{\text{eff}} = ar^{1/b}$, $T_{\text{eff}} = ab^r$, $T_{\text{eff}} = a + b \ln(r)$. Here a , b , c are constants and r is the line ratio, $R_{\lambda_1}/R_{\lambda_2}$. The choice of the particular approximation was done according to the least-squares deviation. The accuracy of the fit is better than 5–10 K except the extremities and the bending points. The mean dispersion of ratio $r = R_{\lambda_1}/R_{\lambda_2}$ is about 0.02–0.05, implying a temperature error of 10–50 K.

In cases where $R_{\lambda_1}/R_{\lambda_2}$ was a non-monotonic function (i.e. a given value of $R_{\lambda_1}/R_{\lambda_2}$ corresponded to more than one value of T_{eff}), to exclude this ambiguity we have limited the range of temperatures in which the line ratio method is applied. More details about the line ratio techniques can be found in Kovtyukh et al. (2006).

The averaging of temperatures obtained from 70–100 line ratios significantly reduces the uncertainty from a single calibration. The final precision we achieve is 5–20 K (1σ), for the spectra of $R = 42\,000$, $S/N = 100$ –150. This can be further improved with higher resolution and larger S/N . For the vast majority of stars the errors are better than 10 K. We note that we only have a few stars below 4000 K, therefore a larger systematic error can be present there. For a number of giants, the temperature could be estimated independently from two or more spectra. For these stars with several estimations of T_{eff} , a repeat of the method agrees within individual errors of 1σ – 3σ .

All calibrations are available in electronic form and can be obtained from the first author on request.

In Table 1, we report T_{eff} for 215 giants derived from our calibrations. Each entry includes the name of the star, mean T_{eff} , number of calibrations used, and error of the mean (σ_{mean}).

3.2 Influence of stellar properties

Several stellar properties are supposed to affect the precision of the line-depth method, like rotation, macroturbulence, chemical abundance, gravity, magnetic field, etc. The scatter of the points in Fig. 2 mainly arises from the individual parameters of each star rather than from the measurement errors of line depths (which are mostly due to the uncertainty of continuum placement). However, both our sample and the iterative process that we apply minimize the effects of stellar properties, as discussed in this section.

The iterative process rejects about 400 line-depth ratio calibrations among 500, eliminating lines that are sensitive to non-LTE effects, metallicity or other factors. Moreover, each calibration is applied only in the temperature range where it provides uncertainties below 100 K. In this way, we automatically reject all strong (and also very weak) lines and lines sensitive to metallicity, $\log g$ and other effects for a given temperature (see Fig. 2).

Our sample occupies a quite narrow range of stellar properties. According to the FWHM of the spectra, only a very few targets exhibit moderate broadening, suggesting that our sample is made of giants that have a slow or negligible rotation ($v \sin i < 15 \text{ km s}^{-1}$). Our giants also occupy a compact region in the Hertzsprung–Russell (HR) diagram regarding luminosity, implying a restricted range of gravities. Finally, the metallicity distribution in Fig. 1 shows that all these giants are essentially in the disc, with $[\text{Fe}/\text{H}]$ ranging

Table 1. Effective temperatures of the programme stars.

HD	T_{eff} (K)	N^a	σ_{mean}^b (K)	HD	T_{eff} (K)	N^a	σ_{mean}^b (K)
HD 001227	5011	69	5.2	HD 050372	4830	63	12.3
HD 002910	4756	79	6.6	HD 050904	4953	74	5.0
HD 004188	4809	89	6.0	HD 053329	5012	77	12.2
HD 004482	4917	68	5.9	HD 054810	4669	80	9.7
HD 005395	4849	73	9.8	HD 055280	4654	72	8.7
HD 005857	4556	75	7.5	HD 056891	4707	79	6.0
HD 006319	4650	64	5.0	HD 058207	4799	75	5.0
HD 006482	4738	71	4.0	HD 059686	4654	66	9.0
HD 007106	4684	84	5.2	HD 060294	4569	71	7.7
HD 007578	4680	89	8.0	HD 060341	4634	86	6.3
HD 008207	4750	70	8.5	HD 061935	4780	86	5.9
HD 008599	4781	60	7.6	HD 062141	4971	70	4.6
HD 008733	4932	44	7.1	HD 062345	5032	85	6.1
HD 009408	4804	69	6.5	HD 063798	5004	86	4.8
HD 010975	4881	85	5.7	HD 064152	4977	85	6.0
HD 011559	4977	80	7.4	HD 064967	4684	77	10.8
HD 011749	4679	83	5.7	HD 065066	4868	76	6.1
HD 011949	4708	69	4.6	HD 065345	4963	84	4.0
HD 015453	4696	67	4.2	HD 068312	5090	78	4.6
HD 015755	4611	72	5.6	HD 068375	5071	74	5.5
HD 015779	4821	79	8.1	HD 070523	4642	79	8.5
HD 016247	4629	67	9.3	HD 071088	4900	70	5.2
HD 016400	4840	70	7.4	HD 071377	4465	75	9.7
HD 017361	4646	63	6.3	HD 071497	4816	82	6.3
HD 018885	4722	72	6.8	HD 072722	3700	34	15.8
HD 019270	4723	74	7.5	HD 073017	4693	70	15.7
HD 019787	4832	89	6.9	HD 074794	4701	75	8.0
HD 019845	4933	72	9.5	HD 075506	4876	85	6.7
HD 020123	5326	76	12.0	HD 075958	5030	71	6.1
HD 020791	4986	84	5.9	HD 076291	4495	83	9.7
HD 025602	4693	79	9.3	HD 076813	5060	73	5.5
HD 025604	4764	79	7.4	HD 078235	5070	79	6.1
HD 026546	4743	83	7.4	HD 079181	4867	80	9.8
HD 026659	5178	71	5.4	HD 079910	4521	76	7.2
HD 026755	4630	79	8.0	HD 080546	4601	82	6.5
HD 027348	5003	80	6.1	HD 081688	4789	83	7.4
HD 027371	4960	84	8.1	HD 082969	4948	77	6.2
HD 027697	4975	85	7.6	HD 083240	4682	70	4.5
HD 028292	4453	78	9.0	HD 083371	4861	78	8.1
HD 028305	4925	80	8.7	HD 084441	5483	84	11.5
HD 028307	4961	88	8.7	HD 085503	4567	81	12.6
HD 030557	4829	86	4.5	HD 086513	4755	75	4.7
HD 031444	5080	80	7.8	HD 089485	4306	71	12.0
HD 033419	4693	74	7.8	HD 090633	4596	80	7.1
HD 033618	4590	66	10.6	HD 093291	5061	87	6.1
HD 034200	4951	85	4.6	HD 093875	4590	71	7.8
HD 034559	5010	72	4.9	HD 094084	4787	75	7.8
HD 035369	4931	82	6.0	HD 094402	5004	89	7.2
HD 037638	5093	72	4.3	HD 094497	4702	80	5.9
HD 037984	4267	76	15.5	HD 094669	4494	74	8.3
HD 039070	5047	72	4.3	HD 095808	4946	71	5.2
HD 039910	4618	72	9.2	HD 098366	4702	74	8.2
HD 040020	4670	72	7.5	HD 100696	4862	83	9.8
HD 040801	4703	77	6.3	HD 101484	4891	70	5.0
HD 041079	4351	76	6.8	HD 102224	4311	77	12.7
HD 042341	4655	74	10.0	HD 102928	4654	74	5.6
HD 043023	4994	79	5.4	HD 103605	4611	82	6.8
HD 044418	4966	74	4.8	HD 103912	4870	79	14.0
HD 045415	4762	83	4.3	HD 104783	5247	71	17.6
HD 046374	4661	89	4.8	HD 104979	4915	79	10.2
HD 046758	5003	73	6.4	HD 106714	4935	77	5.7
HD 047138	5211	76	7.1	HD 108381	4680	73	9.6
HD 047366	4772	49	9.4	HD 109053	4921	58	16.0

Table 1 – continued

HD	T_{eff} (K)	N^a	σ_{mean}^b (K)	HD/BD	T_{eff} (K)	N^a	σ_{mean}^b (K)
HD 048432	4836	75	8.1	HD 110024	4921	77	6.1
HD 048433	4471	55	7.8	HD 113226	5079	82	8.1
HD 049063	4547	87	6.0	HD 113321	4739	84	8.7
HD 113997	4697	34	12.7	HD 184406	4485	65	10.5
HD 114357	4551	71	11.7	HD 185351	4949	81	5.5
HD 116292	4922	78	4.4	HD 185644	4591	73	6.0
HD 116515	4763	69	3.7	HD 187739	4649	86	5.3
HD 117304	4630	74	6.3	HD 188119	4995	62	12.5
HD 117566	5475	78	8.6	HD 192787	4987	84	4.7
HD 117876	4700	3	14.4	HD 192836	4772	88	7.1
HD 119126	4802	80	6.5	HD 195330	4792	84	5.9
HD 120084	4883	82	6.3	HD 195617	3921	52	9.0
HD 120164	4746	77	4.2	HD 196134	4741	80	6.4
HD 120420	4676	79	6.3	HD 197989	4710	78	6.6
HD 136138	4995	62	5.8	HD 198149	4858	78	8.1
HD 137759	4537	77	7.1	HD 198431	4524	74	7.4
HD 138852	4859	78	5.4	HD 199870	4940	76	8.5
HD 139254	4708	80	6.7	HD 200081	4969	83	4.3
HD 139329	4690	84	12.1	HD 204771	4904	80	7.1
HD 142091	4746	76	6.7	HD 205435	5070	86	5.1
HD 143553	4644	73	8.2	HD 205512	4685	76	6.8
HD 145742	4743	76	4.1	HD 206005	4709	81	7.6
HD 146388	4731	73	10.6	HD 207130	4783	65	8.7
HD 148604	5110	78	4.7	HD 208111	4592	73	10.2
HD 151796	4708	73	13.4	HD 211006	4553	73	10.0
HD 152224	4685	74	4.6	HD 212496	4646	73	10.1
HD 153956	4604	76	10.3	HD 212943	4543	82	9.8
HD 155970	4717	73	7.2	HD 214567	4981	81	7.1
HD 156874	4881	80	5.0	HD 215030	4723	78	10.1
HD 159353	4850	75	4.1	HD 215721	4890	84	9.9
HD 161074	4003	56	11.0	HD 216131	4978	77	8.9
HD 161178	4789	77	6.2	HD 216228	4711	62	6.2
HD 162076	4959	74	4.6	HD 218031	4692	76	5.4
HD 162652	4953	73	4.8	HD 219418	5281	81	9.1
HD 166578	4859	68	9.8	HD 219449	4651	73	5.9
HD 168653	4632	71	6.0	HD 219916	5038	75	4.8
HD 168723	4809	73	8.4	HD 221345	4664	78	10.0
HD 170527	4583	26	35.0	HD 221833	4603	84	8.3
HD 170693	4256	79	12.5	HD 225197	4734	82	6.4
HD 171994	5014	79	8.2	HD 225216	4720	74	7.5
HD 175743	4669	84	4.8	BD−01 1792	5183	73	19.1
HD 176408	4564	75	7.7	BD+22 2606	4680	62	10.1
HD 176598	5024	79	6.5	BD+25 2555	5014	46	16.6
HD 177463	4561	76	7.3	BD+28 2250	4630	39	17.6
HD 180711	4824	81	5.2				

^aThe number of calibrations used.^bThe error of the mean.

from -0.70 to $+0.25$. However, we cannot exclude that the stellar properties enlarge the scatter of the $T_{\text{eff}}-r$ relations.

Gray (1994) showed that the ratio of lines V I 6251.82 and Fe I 6252.55 depends strongly on metallicity. The reason is that the strong lines like Fe I 6252.55 ($R_{\lambda} = 0.52$ for the Sun) are already in the damping regime, were the linearity of W_{λ} on abundance breaks down. We therefore avoided using strong lines in our calibrations. However, one can not make conclusions based on a single (or even few) calibrations. It is clear that each line-depth ratio has an individual sensitivity to $[\text{Fe}/\text{H}]$ (and other effects). For example, a number of our calibrations (see below and Kovtyukh et al. 2003) show errors only 40–45 K within quite broad intervals of T_{eff} (4500–5700 K) and $[\text{Fe}/\text{H}]$ (-0.7 to $+0.4$). This can be explained entirely

by the errors in the continuum placement and the measurements of R_λ . [Note that with our resolution of $R = 42\,000$, we cannot reach the level of precision achieved by Gray & Brown (2001) who used $R = 100\,000$.] Therefore, these calibrations with a precision of 40–45 K are essentially independent of $[\text{Fe}/\text{H}]$, non-LTE and other effects (for our spectral resolution and S/N). Unfortunately, we have only about five to six such calibrations. Calibrations that have a slightly worse precision of 60–95 K must be only slightly sensitive to $[\text{Fe}/\text{H}]$ (and other effects). Thus one can judge the sensitivity to stellar parameters from the precision of the calibration. It is reasonable to assume that the use of all 100 calibrations that employ various atomic species mutually eliminates the influence of these other effects. Accounting for metallicity may further increase the precision.

Despite the fact that individual properties of stars, like abundance, V_{tur} , $v \sin i$, magnetic field, etc., are not taken into account, the line-depth method is extremely useful to follow-up stellar activity. When monitoring a given star, its individual properties remain fixed, which makes it possible to detect temperature ‘variations’ as small as 5 K (right up to 1–2 K for spectra with $R = 100\,000$ and $S/N > 300$). Such precision can be used to detect the passage of large spots and to study the activity cycle. Temperature variations at a level of a few degrees have been reported for σ Dra (K0V, Gray et al. 1992) and the G8 dwarf ξ Bootis A (Toner & Gray 1988).

The high precision of the T_{eff} determination provided by the line ratio method allows in turn to achieve a high accuracy in $[\text{Fe}/\text{H}]$ determination: at a level of precision of 0.02–0.05 dex.

4 ZERO-POINT AND COMPARISON WITH OTHER DETERMINATIONS

The zero-point of our temperature scale is that given by the TGMET method, for which an average of various temperature scales can be found in the literature. Unlike dwarfs, there is no such natural standard as the Sun to fix the zero-point of the temperature scale for giants. We find several giants in our sample that have been widely studied in the literature (e.g. HD 113226, BD–011792, HD 197989, HD 027371, HD 085503, HD 104979). By comparing their temperature determined by different authors, we find a typical rms uncertainty of 70 K, which reflects both the uncertainty of the zero-point and the measurement errors that affect these different studies. In this section, we compare our temperatures to several studies thanks to 15 to 57 stars that we have in common with them. We show that the zero-point of our temperature scale is in good agreement with most of them. Moreover, the rms of the comparisons gives an idea of the uncertainty of our method from an external source. Table 2 and Fig. 3 give the results of these comparisons.

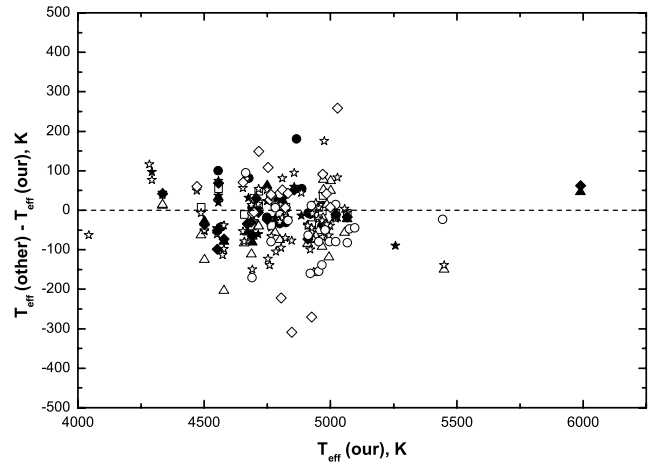


Figure 3. Comparison of our temperatures with estimates from the literature: filled squares, McWilliam (1990); open squares, Gray & Brown (2001); open circles, Strassmeier & Schordan (2000); filled triangles, Alonso et al. (1999); filled circles, Blackwell & Lynas-Gray (1998); filled stars, Di Benedetto (1998); open triangles, Luck (1991) and Luck & Challener (1995); and filled rhombus, Ramírez & Meléndez (2005).

Alonso, Arribas & Martínez-Roger (1999) determined T_{eff} based on the Infrared Flux Method (IRFM) for 500 giants, with a mean error of 1.5 per cent (i.e. 75–90 K) and the error in the zero-point of 0.9 per cent (40–50 K). From 15 common objects, their temperature scale is systematically lower than ours by 10 K. We measure an rms of 48 K, which shows that their estimate of errors was rather pessimistic and that our errors are small. Ramírez & Meléndez (2005) updated temperatures from the Alonso et al. (1999) sample and added 36 new giants.

Blackwell & Lynas-Gray (1998) used a similar technique based on the infrared (IR) flux to determine T_{eff} for 420 stars in the range A0–K3, luminosity types II–V. They achieved an accuracy of 0.9 per cent. We have 16 common stars with them. Their average temperatures are 22 K higher, with a 59-K rms. Di Benedetto (1998) derived T_{eff} for 537 dwarfs and giants by the empirical method of surface brightness and Johnson broad-band ($V - K$) colour: the claimed accuracy is 1 per cent. For the 17 stars in common, their temperatures are on average 2 K below ours and the mean error is 56 K. McWilliam (1990) determined T_{eff} for 671 G and K field giants, using the high-resolution spectra and calibrated broad-band Johnson colours in the range 3900–6000 K. Comparison to our determinations gives a mean difference of -19 K and a standard deviation of 69 K (57 common stars).

Table 2. Comparison of our temperatures with other determinations.

Source	Quoted error (K)	Number of common stars	The rms of comparison (K)	$T_{\text{eff}}(\text{other}) - T_{\text{eff}}(\text{ours})$ (K)
Alonso et al. (1999)	40–50	15	48	–10
Blackwell & Lynas-Gray (1998)	40–50	16	59	+22
Di Benedetto (1998)	40–55	17	56	–2
Gray & Brown (2001)	25	21	31	+2
Luck (1991), Luck & Challener (1995)	100–150	27	71	–54
McWilliam (1990)	–	57	69	–19
Ramírez & Meléndez (2005)	60	17	48	–12
Strassmeier & Schordan (2000)	33	20	69	–62
TGMET method	80	215	82	+3

Strassmeier & Schordan (2000) and Gray & Brown (2001) both used the line-depth ratio method (see Introduction for details). Note that the temperatures of Gray & Brown (2001) are in excellent agreement with ours, with a very low rms of 31 K. This is a nice confirmation of the precision of our determinations. We have however a significant offset, 62 K, with the temperature scale of Strassmeier & Schordan (2000) and the rms of the comparison is high, 69 K, compared to their mean uncertainty of 33 K.

Luck (1991) and Luck & Challener (1995) investigated 30 and 55 giants, respectively. For the determination of temperatures, they used spectroscopic and photometric methods. We obtain an rms of 71 K for the comparison, which is high but in agreement with their quoted internal error of about 100 K.

Finally, the mean difference between our initial temperatures, from TGMET, and the final ones is +3 K with a standard deviation of 82 K (215 stars).

To summarize, giant temperatures determined in this work using the line ratio technique are of high internal precision and agree well with the most accurate estimates from the literature. The zero-point of our scale falls within the range of published values.

5 DISCUSSION AND SUMMARY

Though giants in our sample are not known to be significantly variable, variability, especially among later-type giants, is one of the factors that has to be considered for further improvement of the proposed temperature scale.

Fig. 4 shows a histogram of giant distribution with T_{eff} . This histogram displays a bimodal distribution of the giants. Possible explanations of this bimodal distribution are:

- (i) selection effects;
- (ii) a bimodal distribution in the clump giants masses (see fig 4 of Girardi & Salaris 2001);
- (iii) it is the consequence of the ‘double peaked mass distribution’ predicted by Girardi (1999) within the clump (see paragraph 3.1 in Girardi 1999); and
- (iv) the stars with T_{eff} close to 4950 K are the result of a recent burst of star formation. We can remark that they have peculiar kinematics with low vertical velocities W and stay closer to the Galactic plane (Bienaymé et al. 2006).

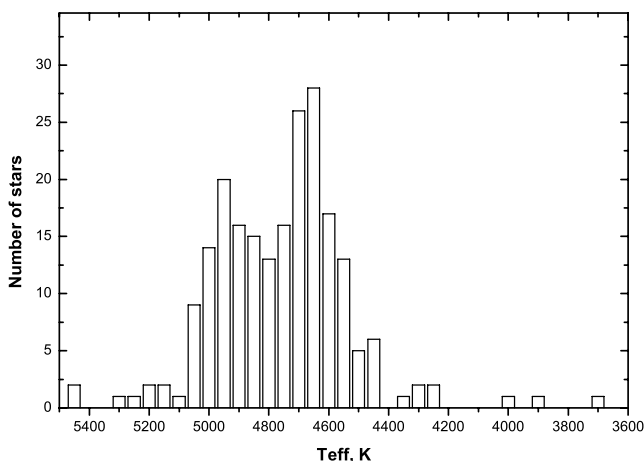


Figure 4. Effective temperature distribution of our giant sample.

Highly precise T_{eff} derived here for 215 giants can serve as T_{eff} standards within the 3500–5500 K range. For the majority of giants in the sample, the internal accuracy of these temperatures is 5–20 K and can be slightly worse at the edges of the range of temperatures, as well as for non-solar metallicities ($\Delta[\text{Fe}/\text{H}]$ larger than ± 0.5 dex). The zero-point is well established and is based on a large number of independent measurements from the literature; it would be unlikely that the error on the zero-point is larger than 20–50 K. The uncertainty can be further diminished by determining the T_{eff} of few giants by the direct method. The direct method to determine the T_{eff} of a star relies on the measurement of its angular diameter and bolometric flux.

For a given star, the line ratio technique allows to detect variations in T_{eff} as small as 5 K and even smaller. The spectral monitoring would allow the initiation of a study of the spots and activity cycles.

ACKNOWLEDGMENTS

This work is based on spectra collected with the 1.93-m telescope of the OHP (France). VVK and TVM want to thank the staff of the Observatoire de Bordeaux for their kind hospitality during their stay there. The authors are indebted to the anonymous referee for careful reading of the manuscript and numerous important remarks that helped to improve the paper.

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