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Spectroscopic criteria of the effective temperature for F–supergiants

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Abstract. 26 spectroscopic criteria in the form of the ratio of equivalent widths of weak absorptions in the red spectral region are selected for determination of the effective temperature for F–supergiants. The grid of these criteria was calculated in the LTE approach. The selected criteria, being very sensitive to the effective temperature, are practically independent upon the surface gravity, microturbulent velocity and chemical element abundances.
Using the calculated criteria and high resolution CCD–spectra for some F–supergiants we obtained the values of the effective temperature, which are in good agreement with the data determined by other methods.

Key words: stars: supergiants – stars: post-AGB – stars: fundamental parameters

1. Introduction

The determination of the fundamental parameter, the effective temperature of a star T_e, is the first step in solving most problems of astrophysics. Despite the great attention given to this question it has remained so far complicated and open to argument since the only method that allows accurate determination of T_e from a star total flux is rather a complicated one and therefore applicable to a small number of the brightest stars as yet. The numerous developed photometric and spectroscopic calibrations differ from one another to a greater degree than their intrinsic errors. That is why the choice of T_e turns out frequently to be subjective. The situation is especially aggravated when studying peculiar and evolved stars since in this case one has to use particular calibrations for each class of objects.

For the last few years the 6 m telescope has been used to carry out a number of programs of high resolution spectroscopy of F, G–supergiants at different stages of evolution: classical cepheids (Klochkova, 1991; Klochkova, Panchuk, 1991), peculiar supergiants of UU Her type at high galactic latitudes, which apparently belong to the halo population (Klochkova, Panchuk, 1989), supergiants with large IR excesses at the short–time transitional stage from post–AGB to planetary nebula (Klochkova, 1995). Let us enumerate the distinctions of these type stars which impede the determination of effective temperatures based on the traditional approaches.

1. All supergiants have unstable atmospheres (de Jager, 1980), their pulsations, but for the cepheids being of irregular character, which requires that the effective temperature should be determined for each particular moment of observations.

2. It is not infrequent that the energy distribution in their spectra is distorted by the presence of circumstellar dust matter ejected at the previous phase of evolution.

3. The abundance of a number of chemical elements in the atmospheres of late supergiants is changed in the course of their own evolution as a result of dredge-up to the surface of products of nuclear reactions in their interiors.

4. The determination of T_e for stars of high luminosity from some spectral details is complicated by the compound structure of the atmospheres of supergiants and by the failure to describe their spectra in the approach of plane–parallel, stationary model atmospheres computed for the approach of local thermodynamic equilibrium (LTE). At the present time there is no wide grid of model atmospheres of supergiants, although work is being done in this direction (Fieldus et al., 1990; Sellmaier et al., 1993).

For analysis of the spectra of F–supergiants the grid of Kurucz (1979) or Bell et al. (1976) model atmospheres are mainly used. To decrease the influence of non–LTE and atmosphere instability effects, only weak spectral lines formed in deep atmospheric layers have to be used. The most common spectroscopic method of determining T_e is the use of the Boltzmann equilibrium for the lines of neutral iron. However this procedure is rather labour consuming since it requires accurate measurements of a great number of weak lines. Besides, it is necessary to determine other model atmosphere parameters at the same time: the surface gravity $\log g$ and microturbulent velocity ξ_t. To estimate $\log g$ the ionization equilibrium for the lines SiI and SiII, FeI and FeII, CrI and CrII, TiI and TiII is used. The microturbulent velocity is found from the condition of independence of the element abundance (most frequently neutral iron) on the equivalent width of lines. Thus we have to calculate chemical element abundances from a great number of lines for the grid of models with different T_e, $\log g$ and different ξ_t.

Remaining in the frame of plane–parallel, stationary model atmospheres in the LTE approximation, we seek to promote the determination of T_e by applying the method of spectral criteria. Earlier this technique in combination with model atmosphere method was advanced in the series of papers by Kopylov et al. (1989a, b), Gvozd' et al. (1991) for normal MS stars of spectral classes B0–A0. Later the method of spectral criteria was used for analysis of chemically peculiar He–weak and He–rich stars (Gvozd', Topilskaya, 1992; Topilskaya, 1993). In what follows we investigate the applicability of this method to the atmospheres of F–supergiants.

2. Selection and calculation of spectral criteria of T_e

When selecting criteria for determining T_e of distant poorly studied stars we aimed at that the criteria, sensitive to T_e, were slightly dependent upon others early unknown atmosphere parameters: chemical composition, surface gravity, and microturbulent velocity. It is well known that lines of low excitation potential are most sensitive to temperature variations. A detailed analysis of sensitivity of different absorption lines to the main parameters of the atmosphere: temperature, pressure and microturbulent velocity is made in the paper by Sheminova (1993), which was aimed at selecting lines to study local variations of the physical conditions in the atmosphere of the Sun.

As distinct from the criteria for B–stars, in the case of F–supergiants we have used weak lines with equivalent widths W_λ in the interval $5 - 200\,$mÅ. This restriction reduced the influence of non–LTE effects, however it places stringent requirements upon observational data, therefore originally we were guided by high S/N spectra obtained on the spectrometers with CCDs.

In order to rule out the dependence of the criteria on the chemical composition, we have used as the T_e criteria the ratios of the equivalent widths of lines of one element, as has been suggested in the early paper by Kopylov (1958). It is important here that the lines included into one criterion should lie on one part of the curve of growth, i.e. be equally dependent on the element abundance. By using the lines of close and small intensities we rule out simultaneously the dependence of the criteria on ξ_t.

It has been shown in the paper by Sheminova (1993) that for stars of solar chemical composition most temperature sensitive are the lines with a low level excitation potential of $\epsilon \approx (0-2)\,$eV with depths $R_0 < 0.35$ and $W_\lambda < 30\,$mÅ. However, since for stars whose chemical composition is unknown we are forced to use the ratios W_λ of two lines, one of them must be only slightly sensitive to T_e. Sheminova (1993) has shown that such are the lines with $\epsilon \approx (5.5 - 7.5)\,$eV. However the situation is aggravated by the fact that the high excitation potential lines become sensitive to $\log g$. In order to find a sufficient number of weak isolated lines, candidates for the criteria, we have computed synthetic spectra in a wide region of $\lambda\lambda 5000 - 8000\,$ÅÅ for two model atmospheres with the parameters $T_e = 5700\,$K, $\log g = 2.0$ and $T_e = 6400\,$K, $\log g = 1.6$ of solar chemical composition from the grid of Kurucz (1979). The lists of lines BELLLIGHT, BELLHEAVY, GFRION (Ryabchikova, 1994) have been used. As in forming the criteria we calculate only the equivalent widths, the part played by rotation is inessential. It is clear from the said above that the final choice of the criteria can be made only after these are calculated in the region of three parameters: T_e, $\log g$ and the chemical element abundance. To this end a three–dimensional net of W_λ of the selected lines and their ratios for the following grid of parameters T_e and $\log g$ and the chemical element abundance with respect to the Sun $[\alpha]$ is as follows

T_e = 5500, 5700, 6000, 6250, 6500, 7000, 7500 K
$\log g$ = 0.5, 1.0, 1.5, 2.0
$[\alpha]$ = -0.3, 0.0, 0.3.

The calculations of W_λ of the absorption lines were performed using the programs KONTUR (Leushin, Topilskaya, 1986) and Kurucz (1979) model atmospheres. For selecting the criteria to meet the above conditions private derivatives with respect to T_e, $\log g$ and $[\alpha]$ were calculated for every candidate for the criteria at each point of the grid. After that the most sensitive criteria were selected, for which the derivative with respect to T_e was about an order larger than the derivatives with respect to $\log g$ and $[\alpha]$ at all points of the grid. To check the dependence of the criteria on ξ_t of individual points the calculations were accomplished with $\xi_t = 0$ and 5 km/s. In the calculations of the final grid of the criteria the micro–turbulent velocity $\xi_t = 5\,$km/s, typical of F–supergiants, was taken.

As a result of analysis of the computations, 26 criteria have been selected, which include 19 lines of C, O, Fe from the red region of the spectrum

Table 1: *Spectral criteria of* T_e

CI 7483.44/CI 8727.13
CI 6587.62/CI 8727.13
CI 7884.49/CI 8727.13
CI 8018.57/CI 8727.13
CI 8045.34/CI 8727.13
OI 7002.23/OI 5577.34
OI 7002.23/OI 6300.30
OI 7982.40/OI 5577.34
OI 7982.40/OI 6300.30
OI 7987.33/OI 5577.34
OI 7987.33/OI 6300.30
FeI 5650.02/FeI 5175.71
FeI 5650.02/FeI 6498.94
FeI 5650.02/FeI 6609.68
FeI 5650.70/FeI 5175.71
FeI 5650.70/FeI 6498.94
FeI 5650.70/FeI 6609.68
FeI 5805.76/FeI 5175.71
FeI 5805.76/FeI 6498.94
FeI 5805.76/FeI 6609.68
FeII 5813.68/FeI 5175.71
FeII 5813.68/FeI 6498.94
FeII 5813.68/FeI 6609.68
FeII 7515.09/FeI 5175.71
FeII 7515.09/FeI 6498.94
FeII 7515.09/FeI 6609.68

Table 2: *Parameters of the lines included in the criteria*

Species	λ, Å	log gf	ϵ, ev
CI	6587.62	-1.60	8.54
CI	7483.45	-1.59	8.77
CI	7884.49	-1.58	8.85
CI	8018.57	-1.93	8.85
CI	8045.34	-1.81	8.85
CI	8727.13	-8.21	1.26
OI	5577.34	-8.20	1.97
OI	6300.30	-9.82	0.00
OI	7002.23	-0.78	10.99
OI	7982.40	-0.34	10.99
OI	7987.33	-0.47	10.99
FeI	5175.71	-6.19	0.09
FeI	5650.02	-0.85	5.10
FeI	5650.70	-0.89	5.09
FeI	5805.76	-1.52	5.03
FeII	5813.68	-2.90	5.57
FeI	6498.94	-4.70	0.96
FeI	6609.68	-5.50	0.99
FeII	7515.09	-2.36	5.82

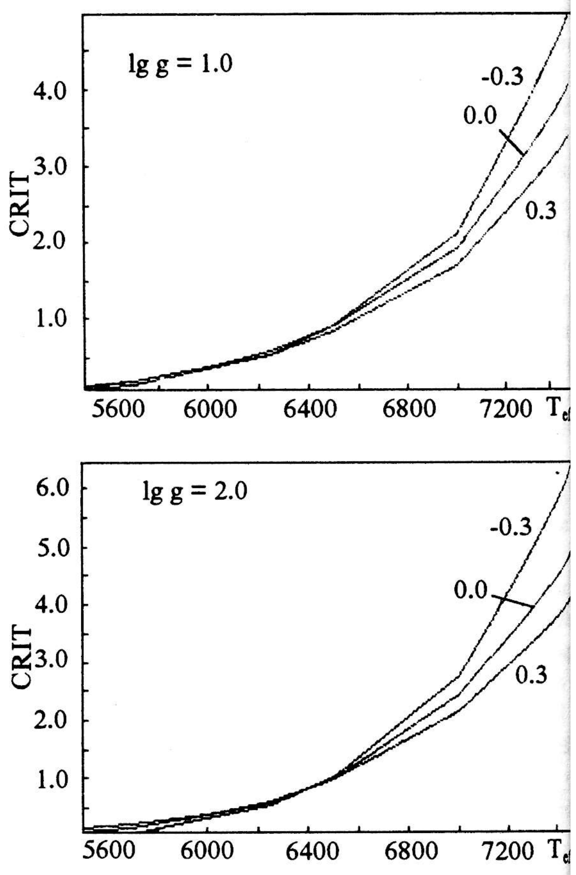

Figure 1: *Ctiterion* W(OI, λ7002)/W(OI, λ5577) *function of* T_e. *Numbers near lines indicate the v* [α].

5000 – 9000 ÅÅ. The list of the criteria is give Table 1, while the parameters of the lines involve the criteria are listed in Table 2. As an example, of the criteria is shown in Fig.1 as a function o for different values of log g and [α].

3. Application of the method to lected supergiants

The grid of the calculated theoretical effective t perature criteria was used to determine T_e of a n ber of F–supergiants, for which T_e had already b found using other techniques. For the practical plication of the criteria a program has been writ which determines T_e of a star from specified obser W_λ of the lines included in the criteria. The lis stars, their spectral classes are presented in Tabl These stars are at different stages of evolution: α ρ Cas and HD 10494 are young massive supergiant the galactic disk; FN Aql – is a classical cepheid a period P = $9^d.481614$ (Moffet and Barnes, 19 IRAS17436+1005 and IRAS18095+2704 are, ap

Table 3: *Temperatures of F–supergiants determined from the spectral criteria (the upper line for each object corresponds to* $[\alpha] = -0.3$*, middle – for* $[\alpha] = 0.0$*, bottom – for* $[\alpha] = 0.3$*).*

Star	T_e				N
	logg = 0.5	logg = 1.0	logg = 1.5	logg = 2.0	
α Per	6250 ± 140	6260 ± 100	6420 ± 120	6400 ± 100	15
(F5Ib)	6140 ± 90	6320 ± 110	6480 ± 110	6450 ± 100	
	6345 ± 130	6390 ± 110	6460 ± 120	6420 ± 60	
ρ Cas	6030 ± 190	5945 ± 120	5960 ± 70	6040 ± 40	11
(F8Iab)	5875 ± 150	5925 ± 110	5950 ± 70	6030 ± 80	
	5860 ± 130	5920 ± 100	5860 ± 100	6050 ± 100	
HD 10494	6540 ± 70	6480 ± 70	6460 ± 60	6400 ± 35	15
(F5Ia)	6520 ± 80	6460 ± 65	6520 ± 60	6440 ± 50	
	6660 ± 90	6530 ± 75	6450 ± 75	6470 ± 45	
FN Aql	5800 ± 95	5730 ± 75	5750 ± 50	5870 ± 75	21
(F8-G2)	5785 ± 110	5710 ± 70	5740 ± 60	5730 ± 75	
$\phi = 0.06$	5730 ± 80	5710 ± 80	5695 ± 60	5670 ± 70	
FN Aql	5950 ± 220	6090 ± 230	6080 ± 225	6230 ± 90	12
$\phi = 0.84$	5880 ± 220	5970 ± 240	6030 ± 230	6290 ± 140	
	5920 ± 230	6000 ± 230	6010 ± 220	6115 ± 210	
IRAS17436+1005	6210 ± 80	6340 ± 70	6400 ± 100	6260 ± 130	11
(F3Ib)	6240 ± 80	6290 ± 80	6415 ± 100	6450 ± 85	
	6280 ± 90	6450 ± 50	6445 ± 100	6490 ± 100	
IRAS18095+2704	6320 ± 120	6460 ± 130	6460 ± 125	6320 ± 100	12
(F3Ib)	6360 ± 120	6410 ± 120	6525 ± 130	6400 ± 120	
	6320 ± 75	6370 ± 100	6540 ± 160	6390 ± 120	

ently, post–AGB stars (Volk and Kwok, 1989; Trams et al., 1991). Equivalent widths of the desired lines were measured from the spectra taken by Klochkova V.G. and Panchuk V.E. with the high resolution echelle spectrometer LYNX of the 6 m telescope of the SAO RAS (Panchuk et al., 1993). The spectra with a spectral resolution R = 25000 in the wavelength range 5000 – 8700 ÅÅ have the S/N ratio higher than 100. For each star Table 3 presents a set of T_e values obtained at the grid points of theoretical criteria and the mean–square errors of the temperatures.

It is seen that the T_e mean–square error determined from all the criteria at each point of the grid is 100 K, while the temperature scatter for individual star from all values of parameters log g and $[\alpha]$ is 200–300 K. The last column of Table 3 gives the number of criteria used in temperature determination. For FN Aql in Table 3 are presented the results for both phases separately.

Inasmuch as only weak lines are used in the criteria, the results appear quite sensitive to the errors in W_λ measurement. That is why an evident condition that should be met in determination of reliable T_e from our criteria is the use of highly accurate spectrophotometric data. The application of as many criteria as possible requires observations in a wide wavelength range.

Correct identification of lines is also of great importance. To test the identification we have used synthetic spectra.

For comparison in Table 4 are presented T_e and log g determined by other methods for the stars investigated. For both phases of FN Aql, the parameters T_e and log g have been determined by us. In addition to T_e determined for FN Aql from the condition of Boltzmann equilibrium, we have also estimated T_e from the colour index (B–V) from Moffet and Barnes (1984), taking into account the calibration by McWilliam (1991) and colour excesses E(B–V) from Dean et al. (1977).

Taking into consideration the variability of all supergiants and imperfection of all the techniques used,

Table 4: *Parameters of F–supergiants determined by different methods*

Star	T_e	logg	Reference	Method
α Per	6250 ± 150	1.8	Parsons 1967	H_γ, H_δ – profiles
	6400	1.6	Parsons 1970	Energy distribution
	6250 ± 200	0.9–0.3	Luck, Lambert 1985	Boltzmann equilibrium condition for FeI
	6500	1.5	Klochkova, Panchuk 1988a	Boltzmann equilibrium condition for FeI
	6500	—	Mc William 1991	Total flux
ρ Cas	6000	0.25	Boyarchuk, Lyubimkov 1983	H_γ, H_β – profiles
	5500	0.2	This paper	Boltzmann equilibrium condition for FeI
HD 10494	6700	0.0	Klochkova, Panchuk 1988b	$W_\lambda(H_\gamma)$, $W_\lambda(H_\alpha)$
FN Aql $\phi = 0.06$	5700	1.75	This paper	Boltzmann equilibrium condition for FeI
	5875		This paper	(B-V)
FN Aql $\phi = 0.84$	5700	2.00	This paper	Boltzmann equilibrium condition for FeI
	5870	—	This paper	(B-V)
IRAS17436 +1005	6500 ± 200	0.7-0.5	Luck et al., 1990	(b–y), m_1, c_1
	6600	0.0–0.5	Klochkova, 1995	Boltzmann equilibrium condition for FeI
IRAS18095+2704	6000	—	Van den Veen 1989	IR–flux
	6700 ± 300	1.1–0.5	Klochkova 1995	Boltzmann equilibrium condition for FeI

it can be concluded from a comparison of the data of Tables 3 and 4 that T_e determined by the method of theoretical spectral criteria are not contradict to other estimates of this parameter.

It is also seen from Table 4 that some stars from the list, ρ Cas, HD 10494, and, possibly, IRAS17436+1005, are beyond the scope of the calculations in their log g values. However T_e estimated from the spectral criteria show good agreement with T_e determined by other methods for these stars too. Due to low sensitivity of the theoretical criterium of the grid calculated herein to the parameter log g it can be used to determine T_e for F–supergiants even of the highest luminosity.

4. Conclusions

Let us enumerate in brief the principles of the above described method of theoretical spectral criteria proposed for determination of the effective temperature of F–supergiants.

1. When determining the temperature we use as criteria the ratios of the equivalent widths of weak isolated lines of one chemical element in the red region of the spectrum. This region is not beneficial fro[m] point of view of energy for observation of cool st[...]

2. Effective temperatures are estimated fro[m] calculated dependences of the criteria on T_e. S[...] weak lines were taken, in the calculations were [...] plane–parallel, stationary model atmospheres in [...] approximation.

3. The criteria of T_e that have been found very slightly dependent on other parameters of star atmospheres: surface gravity, chemical elem[...] abundance, and microturbulent velocity.

The grid of the calculated spectral criteria [...] the program for determination of the effective te[...]perature with the use of these criteria can be m[...] available to people interested in.

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