COLOUR EXCESSES OF 74 SUPERGIANTS AND 30 CLASSICAL CEPHEIDS

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ABSTRACT. We derive accurate, homogeneous atmospheric parameters ($T_{\rm eff}$, log g, V_t, [Fe/H]) for 74 FGK non-variable supergiants and for 30 classical cepheids in 302 pulsation phases based on the high-resolution, high signal-to-noise echelle spectra. The extremely high precision of the effective temperature determination (10–30 K) is achieved by using the line-depth ratio method. These parameters are correlated with unreddened B–V colour index compiled from the literature for investigated stars to obtain an empirical relationship of the form

$$(B-V)_0 = 57.984 - 10.3587(logT_{\rm eff})^2 +$$
$$+1.67572(logT_{\rm eff})^3 - 3.356logg + 0.0321V_t +$$
$$+0.2615[Fe/H] + 0.8833(logg)(logT_{\rm eff})$$

This expression have been used for the estimation of the colour excesses E(B–V) of individual supergiants and classical cepheids with an error 0.05 mag, which matches precision of the most sophisticated photometric techniques. The application range is F0–K0, luminosity classes I and II. Considering the large distances of supergiants, this method opens up a possibility for the large-scale extinction mapping of the Galaxy, with sensitivity down to 0.1–0.2 mag.

Key words: Stars: fundamental parameters; stars: colour excesses; stars: supergiants; stars: classical cepheids.

1. Introduction

The Cepheid period-luminosity (P–L) relation has played a key role in the determination of distances within Local Group and to nearby galaxies. The absolute calibration of the P–L relation requires not only accurate distance measurements but also appropriate accounting for the effects of interstellar extinction and reddening because Galactic Cepheids are heavily obscured with an average E(B–V) of order 0.5 mag. We propose a new method of an accurate E(B–V) determination which relies on the spectroscopically determined stellar parameters.

2. Observations

The spectra of the supergiants were obtained using facilities of the 1.93 m telescope of the Haute-Provence Observatoire (France) equipped with échelle-spectrograph ELODIE (Soubiran et al. 1998). The resolving power was R =42 000, wavelengths range 4400–6800 ÅÅ, and S/N>100 (at 5500 Å). The initial processing of the spectra (image extraction, cosmic ray removal, flatfielding, etc) was carried out as described in Katz et al. (1998).

In addition we employed spectra obtained with UVES at the VLT unit Kueyen (Bagnulo et al. 2003). All supergiants were observed with two instrumental modes *Dichroic*1 and *Dichroic*2, in order to cover almost completely the wavelength interval from 3000 to 10 000 Å. The spectral resolution is about 80 000, and for most of the spectra, the typical S/N ratio is 300–500 in the V band.

For Classical Cepheids we have used our published results (Andrievsky, Luck & Kovtyukh 2005, Kovtyukh et al. 2005).

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. Atmosphere parameters of supergiants and Classical Cepheids

We used Kurucz's WIDTH9 code with an atmospheric model for each star interpolated from a grid

Table 1: The computed colour excesses for Classical Cepheids

Name	P, day	E(B–V)	error	N	$E(B–V)_{LC}$	Name	P, day	E(B–V)	error	N	$E(B–V)_{LC}$
η Aql	7.177	0.103	0.010	13	0.138	SV Mon	15.233	0.203	0.036	11	0.214
SZ Aql	17.141	0.590	0.024	9	0.531	Y Oph	17.127	0.694	0.011	14	0.668
TT Aql	13.755	0.473	0.025	7	0.432	VX Per	10.889	0.503	0.030	8	0.477
YZ Aur	18.193	0.648	0.030	3	–	X Pup	25.961	0.463	0.015	6	0.399
RW Cam	16.415	0.449	0.083	14	0.659	S Sge	8.382	0.111	0.014	9	0.099
RX Cam	7.912	0.545	0.034	9	0.553	U Sgr	6.745	0.402	0.020	9	0.421
SU Cas	1.949	0.299	0.019	12	0.282	W Sgr	7.595	0.087	0.017	8	0.108
DL Cas	8.001	0.500	0.024	14	0.499	Y Sgr	5.773	0.192	0.020	12	0.195
δ Cep	5.366	0.046	0.015	16	0.087	WZ Sgr	21.850	0.435	0.023	10	0.467
X Cyg	16.386	0.242	0.027	24	0.208	YZ Sgr	9.554	0.288	0.014	8	0.298
SU Cyg	3.845	0.085	0.020	12	0.091	S Vul	68.464	0.972	0.054	6	0.674
CD Cyg	17.074	0.454	0.024	14	0.513	T Vul	4.435	0.076	0.014	20	0.054
Y Lac	4.324	0.152	0.012	9	0.195	U Vul	7.991	0.665	0.016	7	0.640
Z Lac	10.886	0.426	0.032	7	0.368	X Vul	6.320	0.800	0.021	6	0.702
T Mon	27.025	0.175	0.023	18	0.188	SV Vul	44.995	0.528	0.020	23	0.412

Remark: $E(B–V)_{LC}$ values are from Laney & Caldwell (2007, BELRED values).

of models calculated with microturbulent velocity of 4 km s^{-1}. At some phases Cepheids can have microturbulent velocities significantly deviating from this model value; however, our previous test calculations showed that changes in the model microturbulence over a range of several kilometers per second have an insignificant impact on the resulting elemental abundances.

The effective temperature for each Cepheid at each pulsational phase and for supergiants has been determined using the calibrating relations from Kovtyukh (2007). These relations combine the effective temperature with a set of spectral line depth ratios. The internal accuracy of the effective temperature determined in this way is rather high in the temperature range 5000 K to 6500 K: typically 150 K or less (standard deviation or 10 to 20 K for the standard error). Another very important advantage of this method (or any spectroscopic method) is that it produces the reddening-free $T_{\rm eff}$estimates. 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.

The method used for gravity and microturbulent velocity determination in a supergiant star such as these Cepheids is described in detail by Kovtyukh & Andrievsky (1999). This method determines the microturbulent velocity using Fe II lines: the dominant ionization species of iron and hence less susceptible to any NLTE effects which might be in play in supergiant atmospheres. The gravity value is found by enforcing the ionization balance condition (the mean iron abundance from Fe II lines equals the iron abundance which results from the Fe I – EW relation extrapolated to zero equivalent width). This method resolves some previous problems within the abundance analysis of supergiant stars. Note that in these analyses we have used no lines stronger than 175 mÅ.

The uncertainty in the microturbulent velocity and the gravity is more difficult to assess. For the microturbulence a variation of 0.5 km s^{-1} from the adopted velocity causes a significant slope in the relation between Fe II line abundance and equivalent width. We therefore adopt 0.5 km s^{-1} as the uncertainty in the microturbulence. For log gwe adopt 0.1 dex as the formal uncertainty based on the numerical result that a change in gravity at that level will result in a difference of 0.05 dex between the total iron abundance as computed from the Fe I and Fe II lines. Since we have forced an ionization balance we do not allow a spread larger than 0.05 dex in the total abundance of iron as derived from the two ions and thus our uncertainty estimate (Andrievsky, Luck & Kovtyukh 2005, Kovtyukh et al. 2005).

The final results of the determinations of $T_{\rm eff}$, log g, V_t and [Fe/H] for supergiants are given in Table 2.

4. Colours excesses

The $T_{\rm eff}$, log g, V_t and [Fe/H] obtained in the manner described above can be used for determining the intrinsic colours of the target Cepheids and FGK supergiants. From Bersier (1996) and from Laney & Caldwell (2007) we take the unreddened B–V colour index for these stars. With the lack of simultaneous photometry, the instantaneous "observed" B–V color index is determined from Berdnikov's (2007) extensive data set of Cepheids. The latter contains multicolour photoelectric observations for all of our 30 Cepheids. The light curves were subjected to Fourier analysis and the coefficients determined up to the third to fifth order. Thus a pair of reddened and unreddened B–V values

Table 2: The computed colour excesses for supergiants. The negative E(B–V) have been set to zero.

HD	$T_{\rm eff}$	log g	$\rm V_t$	[Fe/H]	E(B–V)	HD/BD	$T_{\rm eff}$	log g	$\rm V_t$	[Fe/H]	E(B–V)
000725	7053	2.1	6.3	–0.04	0.271	171635	6151	2.15	5.2	–0.04	0.051
001457	7636	2.3	4.8	–0.04	0.394	172365	6196	2.5	7.5	–0.07	0.180
004362	5301	1.6	4.4	–0.15	0.219	173638	7444	2.4	4.7	0.11	0.302
007927	7341	1.0	8.7	–0.24	0.425	174104	5657	3.1	4.8	–0.02	0.045
008890	6008	2.2	4.35	0.07	–0.007	179784	4956	2.0	2.5	0.08	0.394
008906	6710	2.2	4.8	–0.07	0.350	180028	6307	1.9	4.0	0.10	0.320
009900	4529	1.7:	2.7	0.10	0.073	182296	5072	2.1	3.6	0.17	0.321
009973	6654	2.0	5.7	–0.05	0.434	182835	6969	1.6	4.9	0.00	0.268
010494	6672	1.25	7.5	–0.20	0.813	183864	5323	1.8	3.5	–0.02	0.425
011544	5126	1.4	3.5	0.01	0.174	185758	5367	2.4	2.1	–0.03	0.037
016901	5505	1.7	4.3	–0.03	0.110	187203	5710	2.2	5.1	0.05	0.222
017971	6822	1.3	8.7	–0.20	0.644	187299	4566	1.2	3.5	0.03	0.257
018391	5756	1.2	11.5	0.02	0.991	187428	5892	2.4:	2.9	0.02	0.177
020902	6541	2.0	4.8	–0.01	0.039	190113	4784	1.9	3.5	0.05	0.360
025056	5752	2.1	5.6	0.15	0.437	190403	4894	2.0	2.5	0.09	0.133
025291	7497	2.65	4.1	0.00	0.241	191010	5253	2.1:	1.9	0.05	0.171
026630	5309	1.8	3.7	0.02	0.085	194093	6244	1.7	6.1	0.05	0.087
032655	6755	2.7	5.0	–0.12	0.059	195295	6572	2.4	3.5	0.01	0.001
032655	6653	2.5	5.0	–0.13	0.044	200102	5364	1.6	3.3	–0.13	0.250
036673	7500	2.3	4.4	0.07	–0.046	200805	6865	2.2	4.6	–0.03	0.455
036891	5089	1.7	3.3	–0.06	0.081	202314	5004	2.1	3.2	0.12	0.082
039949	5239	2.0:	3.3	–0.05	0.233	202618	6541	2.8	4.0	–0.16	0.053
044391	4599	1.6	3.4	0.03	0.119	204022	5337	1.5:	3.9	0.01	0.602
045348	7557	2.2	2.7	–0.10	0.016	204075	5262	2.0	2.6	–0.08	0.186
047731	4989	2.0	3.2	0.02	0.092	204867	5431	1.6	4.15	–0.04	0.006
048329	4583	1.2	3.7	0.16	0.021	206859	4912	1.2	2.5	0.04	0.065
052497	5090	2.45	3.6	–0.02	0.033	207489	6350	2.85	5.6	0.13	0.119
054605	6364	1.5	10.2	–0.03	0.085	208606	4702	1.4	4.0	0.11	0.323
057146	5126	1.9	3.6	0.17	–0.019	209750	5199	1.4	3.55	0.02	0.022
061227	7433	2.5	5.5	–0.16	0.284	210848	6238	3.0	3.2	0.08	0.001
074395	5247	1.8	3.0	–0.01	–0.028	216206	5003	2.1	3.2	0.02	0.158
077912	4975	2.0	2.4	0.01	0.061	218600	7458	2.4:	4.8	–0.07	0.653
084441	5281	2.15	2.15	–0.01	0.006	219135	5430	1.75	3.6	–0.01	0.296
092125	5336	2.4	2.7	0.05	0.020	220102	6832	2.5	5.8	–0.23	0.262
159181	5214	2.2	3.4	0.04	0.087	223047	4864	1.7	3.4	0.07	–0.005
164136	6483	3.1	4.5	–0.37	0.018	224165	4804	1.9	2.5	0.08	0.064
171237	6792	2.6	4.4	–0.09	0.175	+60 2532	6268	1.8	5.2	–0.01	0.597

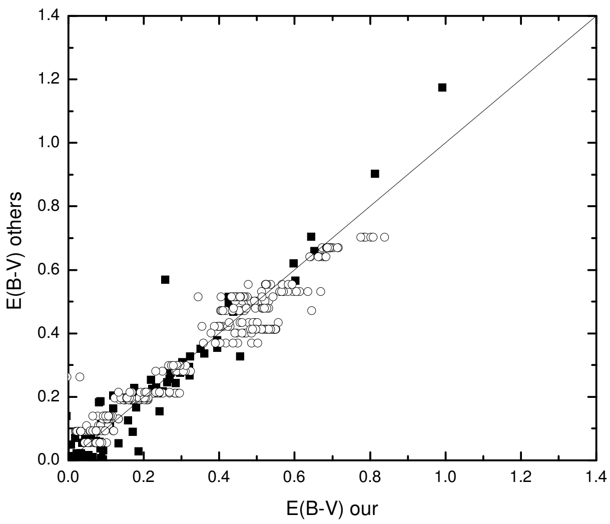

Figure 1: Comparison of our colour excesses with estimates from the literature: filled squares – Bersier (1996) for supergiants; open circles – Laney & Caldwell (2007) for Classical Cepheids (showed are the individual phases for each cepheid).

was generated for each moment of spectral observation. The colour excess should not vary during a pulsational cycle. Using the least-square method we have obtained the following relation (based on 376 individual equations between $(B-V)_0$ and $T_{\rm eff}$, log g, $\rm V_t$, and [Fe/H]):

$$(B-V)_0 = 57.984 - 10.3587(logT_{\rm eff})^2 +$$
$$+1.67572(logT_{\rm eff})^3 - 3.356logg + 0.0321V_t +$$
$$+0.2615[Fe/H] + 0.8833(logg)(logT_{\rm eff})$$

Using this relation the colour excesses E(B–V)=(B–V)–(B–V)$_0$ for 30 Classical Cepheids and 74 supergiants are determined in Tables 1, 2. The final precision of $(B-V)_0$ is 0.05 mag (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 rotation, chemical composition, binarity, etc.

5. Results and summary

Tables 1 and 2 list the results for Classical Cepheids and supergiants, respectively. For Cepheids the name and P (period) are given in columns (1) and (2) respectively; the average color excess determined as described above is in column (3); the standard error of the mean is in column (4); the number of determinations used to calculate the mean is in column (5). The average E(B–V) was obtained by averaging the values of E(B–V) over the pulsational cycle. Individual reddenings estimates from Laney & Caldwell (2007) are also listed in Table 1, and comparisons with our estimates are shown in Figure 1.

In Table 2 we report colour excesses for 74 supergiants derived from our calibration. Each entry includes the name of the star, mean $T_{\rm eff}$, log g, $\rm V_t$, [Fe/H] and E(B-V).

Fig. 1 compares for 104 objects our colour excesses with estimates from the literature.

Summarizing, supergiant colour excesses determined in this work using our expression, have been demonstrated to be of extremally high internal precision and agree well with the most accurate estimates from the literature.

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