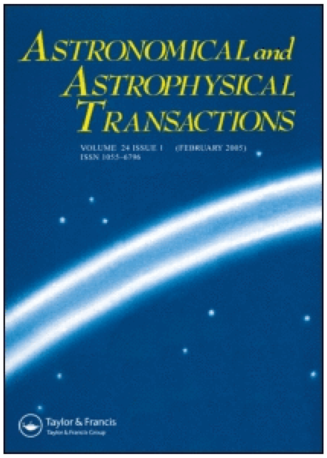

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Spectrophotometry of nine stars with planets

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Online Publication Date: 01 August 2005
To cite this Article: Tereschenko, V. M. (2005) 'Spectrophotometry of nine stars with planets', Astronomical & Astrophysical Transactions, 24:4, 327 - 333
To link to this article: DOI: 10.1080/10556790500483642
URL: http://dx.doi.org/10.1080/10556790500483642

Astronomical and Astrophysical Transactions
Vol. 24, No. 4, August 2005, 327–333

Spectrophotometry of nine stars with planets

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(Received 31 October 2005)

The energy distributions in the spectra of nine stars with planets were obtained from observations. The synthetic colour indices in the photometric *UBV*, *WBVR* and the Tycho catalogue systems were calculated on the basis of observations. The effective temperatures and metallicities of the investigated stars were determined by comparing the calculated colour indices in the *UBV* system with model colour indices.

Keywords: Stars with planets; Spectrophotometry; Effective temperatures; Metallicity

1. Introduction

In the last few years the search for and determination of exoplanetary characteristics as well as the definition of their orbital parameters have become highly prioritized topics in astronomy. For the majority of stars with planets, spectra with a high resolution were obtained and high-precision colour indices were measured in different photometric systems. At the same time, in spite of the existing extensive catalogues [1–4], data about the spectral energy distribution (SED) are not available for the majority of parent stars. Our work is intended to fill this gap. The importance of such data about energy distributions is not in doubt. On the one hand, the SED may be considered as a physical parameter of a star and, on the other hand, this consists of original data for determining the effective temperature, surface gravity and metallicity. As follows from photometric observations and common concepts, we do not expect a significant difference between the SEDs of stars with planets and their spectral analogues. However, this cannot be considered as an argument against the spectrophotometric study of parent stars. The results of our observations add to the increasing wealth of empirical data about the parent stars and may be used as standards for observations of different astronomical objects.

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2005 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790500483642

2. Selection of the stars; observations and data reduction

A sample of objects in the northern hemisphere was selected from the list of parent stars. Then the choice was defined by the possibilities of our equipment, by the season and by the method of observations. A list of the stars studied and their main characteristics are presented in table 1. All the stars except τ Boo belong to the main sequence and are of F8–K0 spectral classes. Each of the three stars ϵ And, 55 Cnc and 47 UMa possesses several planets. For eight of the nine targets the SEDs were obtained for the first time.

Observations were carried out with a single-channel spectrometer equipped with a concave grating. A detailed description of the apparatus, method of observations and processing may be found in [1]. The differential method of observations was applied, and averaged values of the extinction coefficients for the season were used for reductions. Observations of the two stars: 51 Peg and ϵ And were conducted with the 1 m telescope at Tian–Shan Observatory (2800 m altitude). Other stars were observed with the 50 cm reflector at Kamenskoe Plato (1400 m altitude). The star α Peg was used as the standard for the stars 51 Peg and ϵ And; for other stars, η UMa was chosen as the standard. The absolute values of the energy distribution for α Peg are taken in accordance with [5], and that for η UMa from [1]. A number of observations for each standard are indicated, together with the name of a star in the eighth column of table 1. Each observation consists of four scans. The next column shows ΔM, the average values of the absolute differences between the air masses for the studied star and the standard. The Δt values are equal to the difference between the moments of observations of the star and the standard and are presented in the last column. The measurements covered the observable spectral region $\lambda = 3100$–7600 Å. For the primary standards the SEDs were extrapolated for the spectral region $\lambda = 3100$–3200 Å in accordance with [6]. The spectral resolution of data equals the step of a histogram which is equal to 50 Å.

The results of observations on the extra-atmospheric monochromatic illuminances $E(\lambda)$ for the investigated stars are presented in table 2. The standard error of data in the visual region equals 2–3%, and it increases at the edges of the spectral interval up to 4–5%.

3. Synthetic colour indices

On the basis of the SEDs obtained for the studied stars the synthetic colour indices were calculated in the three photometric systems *UBV*, *WBVR* [7] and the Tycho catalogue [8]. The main goal of such calculations is to check indirectly the SEDs. Such calculations are necessary because of an absence of analogous data from other workers for most of the stars. The method

Table 1. The list of the investigated stars, their basis characteristics and main data about the method of observations.

Name	α_{2000}	δ_{2000}	V	$B-V$	Spectral type	Standard	$\lvert\Delta M\rvert$	$\lvert\Delta t\rvert$
υ And	01 h 36.8 m	41°28′	4.09	0.54	F8V	α Peg-3	0.05	0:16
ρ^1 Cnc	08 h 52.6 m	28°20′	5.95	0.87	G8V	η UMa-3	0.16	0:11
47 UMa	10 h 59.5 m	40°26′	5.05	0.61	G0V	η UMa-3	0.04	0:20
HD114762	13 h 12.3 m	17°31′	7.31	0.54	F9V	η UMa-4	0.09	0:16
70 Vir	13 h 28.4 m	13°47′	4.98	0.71	G3V	η UMa-4	0.08	0:18
τ Boo	13 h 47.3 m	17°27′	4.50	0.48	F6IV	η UMa-4	0.06	0:25
ρ CBr	16 h 01.0 m	33°18′	5.41	0.60	G2V	η UMa-3	0.05	0:11
14 Her	16 h 10.4 m	43°49′	6.66	0.90	K0V	η UMa-3	0.06	0:13
51 Peg	22 h 57.5 m	20°46′	5.49	0.67	G2.5V	α Peg-3	0.05	0:08

Table 2. SDEs $E(\lambda)$ for the parent stars.

	$E(\lambda)$ (10^{-4} erg cm^{-3} s^{-1}) for the following stars								
λ(Å)	υ And	ρ^1 Cnc	47 UMa	114762	70 Vir	τ Boo	ρ CBr	14 Her	51 Peg
3125	40.8	2.4	14.0	–	10.0	29.6	9.8	1.89	7.6
3175	41.7	2.3	14.8	–	11.1	31.3	11.1	1.48	8.4
3225	43.9	3.4	15.5	–	12.1	31.8	12.5	1.53	8.4
3275	52.4	4.2	18.8	–	15.6	36.9	14.6	1.86	11.9
3325	52.4	4.0	19.1	–	15.5	37.6	14.4	2.12	11.6
3375	51.8	3.6	18.3	–	15.1	35.9	14.0	2.06	10.9
3425	51.8	3.6	18.8	–	15.7	37.0	14.2	1.94	11.4
3475	50.8	3.6	19.2	–	15.4	35.5	14.4	1.81	10.7
3525	56.0	4.2	19.8	–	17.2	38.9	15.2	2.04	11.8
3575	52.5	4.3	19.2	–	16.0	38.5	14.7	1.92	10.9
3625	55.4	4.8	20.3	–	17.3	38.4	15.7	2.43	12.3
3675	63.1	5.8	23.5	–	20.9	43.0	18.1	3.18	15.2
3725	64.1	4.6	23.5	–	19.7	44.4	17.2	2.75	14.6
3775	69.0	4.6	22.8	–	20.1	44.7	17.5	2.44	14.7
3825	63.2	3.7	20.3	–	17.0	44.6	16.2	2.01	11.6
3875	70.9	3.6	21.4	–	17.7	50.6	17.7	1.99	12.7
3925	60.1	5.0	23.0	–	19.6	48.0	16.8	2.76	12.6
3975	69.0	6.8	25.1	–	21.9	49.8	18.7	3.54	15.7
4025	94.9	9.6	34.3	4.93	31.8	68.5	25.6	5.30	23.0
4075	90.0	9.6	33.7	4.92	30.7	64.8	25.2	5.35	22.2
4125	94.6	9.8	34.4	4.83	32.7	63.7	25.1	5.54	23.1
4175	95.0	9.2	33.9	4.96	32.4	67.2	25.7	5.16	22.9
4225	95.0	9.7	33.8	4.77	31.5	66.7	24.7	5.27	22.9
4275	88.3	9.6	32.2	4.66	30.2	65.9	22.9	5.52	21.6
4325	85.6	11.0	32.4	4.54	31.4	60.9	23.4	6.06	21.5
4375	95.0	11.7	34.2	4.82	32.9	66.7	25.1	6.56	23.6
4425	98.0	12.7	36.6	4.94	35.9	68.5	26.6	6.90	25.6
4475	99.0	13.9	38.2	5.02	37.9	69.5	27.4	7.83	26.4
4525	99.8	14.0	38.0	5.03	37.9	68.7	27.4	8.01	27.1
4575	100.6	14.8	38.6	5.02	38.4	69.1	28.1	8.38	27.3
4625	101.1	14.6	38.8	5.15	39.0	69.7	28.1	8.52	27.3
4675	98.2	14.1	37.7	5.07	38.5	67.8	27.7	7.82	26.1
4725	98.5	14.5	38.3	5.02	38.9	67.0	28.1	8.04	26.8
4775	98.6	15.1	38.9	4.94	39.2	67.2	27.8	8.40	27.3
4825	97.2	14.8	37.8	4.92	39.5	64.7	26.4	8.53	26.8
4875	88.2	14.0	35.2	4.80	37.2	57.6	25.3	7.98	24.6
4925	93.4	14.6	37.0	4.80	38.4	64.1	26.5	8.29	25.9
4975	93.2	14.6	36.9	4.92	38.8	64.2	26.5	8.27	26.2
5025	89.8	14.2	36.3	4.80	37.2	62.3	26.3	7.87	25.2
5075	91.2	14.2	36.6	4.71	38.7	63.2	26.6	8.03	25.5
5125	89.7	13.4	35.4	4.67	37.5	61.6	26.0	7.65	25.1
5175	85.3	12.8	33.6	4.55	34.9	58.3	24.7	6.99	23.2
5225	86.9	14.2	34.9	4.59	36.8	59.5	25.6	7.73	24.9
5275	86.6	14.7	35.2	4.55	36.8	59.0	25.8	8.11	24.3
5325	86.8	15.1	35.3	4.62	38.1	60.4	26.9	8.56	25.2
5375	87.0	14.9	35.0	4.65	38.3	59.5	26.3	8.71	25.1
5425	85.6	15.0	35.2	4.69	38.1	59.0	26.2	8.42	24.5
5475	86.5	15.5	35.6	4.66	38.2	59.1	26.9	8.84	24.9
5525	85.5	15.3	34.7	4.57	38.2	59.0	25.2	8.79	24.8
5575	83.7	15.4	34.2	4.61	37.7	58.0	25.7	8.83	24.1
5625	82.3	15.6	33.9	4.57	37.5	57.5	25.4	8.57	24.1
5675	81.8	15.3	33.3	4.50	37.4	56.5	24.8	8.65	24.0
5725	82.0	15.0	33.2	4.44	36.8	55.0	23.8	8.46	24.3
5775	81.3	14.5	30.8	4.25	35.6	52.6	22.7	8.18	24.5
5825	81.6	16.0	33.5	4.57	37.6	55.0	24.2	8.62	24.6
5875	80.7	15.7	33.0	4.51	37.4	53.8	24.3	8.44	23.8
5925	80.2	15.6	32.1	4.25	36.6	53.8	23.7	8.51	23.6

(*continued*)

Table 2. Continued.

λ(Å)	$E(\lambda)$ (10^{-4} erg cm^{-3} s^{-1}) for the following stars								
	υ And	ρ^1 Cnc	47 UMa	114762	70 Vir	τ Boo	ρ CBr	14 Her	51 Peg
5975	79.7	15.3	32.8	4.23	36.5	52.0	23.0	8.42	23.5
6025	79.6	15.3	31.5	4.16	35.4	50.1	22.6	8.35	23.0
6075	77.6	14.7	30.7	4.13	34.6	49.3	22.5	8.33	22.9
6125	75.8	14.7	30.1	4.01	33.8	47.5	21.8	7.98	22.3
6175	74.7	14.5	29.4	3.94	33.2	46.9	21.7	8.01	22.1
6225	73.9	14.2	29.8	3.88	32.9	47.0	21.6	8.01	22.1
6275	72.4	14.1	29.1	3.82	32.8	46.4	21.5	7.79	22.2
6325	71.4	14.3	28.5	3.74	32.7	45.3	21.4	7.60	21.7
6375	70.8	14.1	28.0	3.76	32.9	45.8	21.1	7.60	21.7
6425	69.9	14.1	28.0	3.65	32.2	44.8	21.0	7.65	21.4
6475	69.0	14.0	27.7	3.61	32.0	44.2	21.0	7.52	21.0
6525	68.1	13.9	27.2	3.58	32.2	43.3	20.3	7.48	21.0
6575	63.3	14.0	25.9	3.49	31.1	41.2	19.9	7.30	19.6
6625	66.5	13.9	26.4	3.54	32.0	42.6	19.8	7.66	20.8
6675	65.5	14.0	27.2	3.60	31.6	43.2	20.0	7.50	20.7
6725	64.6	13.7	26.6	3.67	31.5	42.8	20.0	7.45	20.5
6775	64.4	13.7	25.9	3.66	31.4	42.1	19.4	7.17	20.5
6825	62.8	13.4	25.4	3.61	30.8	40.8	18.7	6.96	20.2
6875	61.7	13.6	25.4	3.73	30.3	41.2	18.7	7.35	19.7
6925	60.7	13.0	24.5	3.34	30.1	39.3	18.7	6.93	19.4
6975	60.2	12.6	24.2	3.28	29.5	39.3	18.3	6.98	19.1
7025	58.9	12.6	24.3	3.37	29.4	38.5	18.3	6.90	18.9
7075	58.7	12.6	24.6	3.31	29.6	38.7	18.9	6.93	18.4
7125	57.8	12.7	23.8	3.33	29.5	37.8	17.6	6.62	18.3
7175	56.3	12.6	23.3	3.26	28.8	38.9	17.9	6.40	18.1
7225	54.8	12.6	22.9	3.31	28.4	37.1	17.6	6.37	17.8
7275	55.0	12.6	22.4	3.25	29.3	36.8	17.7	6.28	17.6
7325	53.3	12.3	21.8	3.10	27.7	36.0	17.3	6.42	17.2
7375	52.9	12.0	21.1	2.90	26.7	36.3	17.6	6.04	16.8
7425	51.0	11.7	21.2	2.84	26.8	35.4	17.4	6.21	16.7
7475	52.4	11.3	20.1	2.73	27.0	34.0	17.1	6.13	16.7
7525	52.1	11.2	19.6	2.71	26.7	34.1	16.0	5.90	16.7
7575	52.0	11.4	20.9	2.98	27.5	35.7	15.7	6.04	16.6

of calculation of synthetic colours and colour indices on the basis of SEDs, is widely known (see, for example [9]). In our previous papers the colour indices in the *UBV* system were calculated from the curves of spectral response obtained from [10]. In the present paper, the colour indices $U - B$ and $B - V$ calculated from our SEDs are compared with the indices calculated from the models [11]. Lejeune *et al.* [11] calculated the synthetic colour indices for their models using the response curves obtained by Buser and Kurucz [12]. Thus, we also used their curves. The observed values of the stellar magnitudes V and colour excesses in the *UBV* system were taken from the BS and SC catalogues [13]. When the colour indices in the *WBVR* and Tycho systems were calculated, the response functions from the corresponding catalogues were used.

The necessary constants for the *UBV* and *WBVR* systems were calculated using data for α Lyr, and those for the system of Tycho catalogue using data for the star HD221525. The results of the calculations are given in table 3. The calculated values of the colour indices $(m_i - m_j)_c$ are given together with their discrepancies $\Delta(m_i - m_j) = (m_i - m_j)_o - (m_i - m_j)_c$.

As is evident from table 3, the discrepancies $\Delta(U - B)$ in the *UBV* system are sufficiently high for the majority of stars; moreover, they are systematic. Our data prove to be bluer. Unfortunately, the reason; for the discrepancies are unclear. It is possible that they are caused by errors in the response functions of [12]. It is well known that true response functions for the *UBV* system do not exist in principle [9]. Note, that the discrepancies in the *WBVR* system are

Table 3. Synthetic colour indices and discrepancies in the *UBV*, *WBVR* and Tycho catalogue systems.

	Magnitude of the colour indices for the following stars									
	υ And	ρ^1 Cnc	47 UMa	114762	70 Vir	τ Boo	ρ CBr	14 Her	51 Peg	$\sum/n$
UBV										
$(U-B)_c$	0.02	0.58	0.08	–	0.24	0.01	0.02	0.64	0.24	
$\delta(U-B)$	0.04	0.05	0.05		0.02	0.03	0.06	0.04	−0.03	0.032
$(B-V)_c$	0.50	0.86	0.58	0.52	0.70	0.46	0.59	0.86	0.65	
$\delta(B-V)$	0.04	0.01	0.03	0.02	0.01	0.02	0.01	0.03	0.2	0.021
WBVR										
δV	0.003	−0.030	−0.046	–	−0.018	−0.027	−0.002	0.009	0.013	−0.012
$(W-B)_c$	−0.105	0.424	0.064	–	0.090	−0.102	−0.112	0.509	0.055	
$\delta(W-B)$	0.011	0.046	0.008	–	−0.015	0.001	0.007	−0.024	0.014	0.006
$(B-V)_c$	0.524	0.895	0.606	0.557	0.730	0.490	0.616	0.893	0.689	
$\delta(B-V)$	0.018	−0.018	0.016	–	−0.003	−0.002	−0.001	−0.014	−0.013	−0.002
Tycho										
δV	0.009	−0.044	−0.035	0.029	−0.017	−0.027	−0.004	−0.003	0.019	−0.018
$(B-V)_c$	0.564	1.009	0.678	0.571	0.799	0.521	0.655	1.17	0.729	
$\delta(B-V)$	0.020	−0.008	0.000	−0.008	−0.001	0.007	0.004	−0.001	−0.006	0.001

three times smaller, but in the system of the Tycho catalogue they are lower by almost an order of magnitude. Also, there are no correlations between certain discrepancies in the different systems. This fact testifies that not only our SDE values but also photometric data have errors.

4. The preliminary determination of the effective temperatures and metallicities

We decided to use the synthetic colour indices $U-B$ and $B-V$ calculated from the SDEs for preliminary determination of the effective temperatures T_{eff} and metallicities [Fe]/[H] for the studied stars. They were determined by comparison of our colour indices with model synthetic colour indices from the worth of Lejeune *et al.* [11], who combined the modern models of different researchers in a common and homogeneous system. This system covers, the temperature range 50 000–2000 K, the log g range 5.50–1.02 and the metallicity range from -5.0 to $+1.0$. The microturbulence velocity was taken as equal to 2 km s^{-1}, and the ratio of the mixing length to the height of the homogeneous atmosphere as 1.25. The stellar fluxes are given for 1221 points within the spectral range 9.1–160 000 Å. The spectral resolution is equal to 10 Å in the ultraviolet region and to 20 Å in the visual range. On the basis of the obtained values the colour indices in four photometric systems including the *UBV* system were calculated. It is impossible to derive all three parameters of a star, namely T_{eff}, log g and [Fe]/[H], if only two colour indices are used. It is necessary to utilize additional data in order to determine the third parameter. Taking into account the imperfection in the calculated synthetic colour indices $U-B$ and $B-V$ and the fact that the expected region of parameters of investigated stars is known (from their spectral classes), we decided to fix one of the parameters beforehand. It is reasonable to fix the parameter whose variations in the considered ranges of T_{eff}, log g and [Fe]/[H] have a minimal influence on the accuracy of definition of the other two parameters. We chose the surface gravitation as this parameter. Since all investigated stars belong to the main sequence, we accepted for all of them the same value of -4.5. Of course, thereby an additional error is included in the values of the effective temperature and metallicities, but this error is smaller than the errors in the initial data. The determination of metallicities of the parent stars is of special interest. The spectroscopic investigations showed that [Fe]/[H] increases for the majority of parent stars [14]. It may be concluded that the increased metallicity of the parent cloud stimulates the process of formation of the planetary systems. The effective temperatures $T_{\rm eff}$ and metallicities [Fe]/[H] were determined by the following method. A two-colour diagram of $U-B$ versus $B-V$ for the expected ranges of the stellar parameters (5000 K $< T_{\rm eff} <$ 6750 K; $-0.20 <$ [M/H] < 1.0; $\log g$ fixed to be equal to 4.50) was constructed on the basis of the model data [11]. Then lines of equal temperatures and metallicities were drawn on the diagram. The interval between the isothermal lines was equal to 250 K and the interval between the lines of metallicities varied from 0.1 to 0.5. Points corresponding to the synthetic colours of our stars from table 3 were plotted in figures 1 and 2.

The corresponding values of $T_{\rm eff}$ and [Fe]/[H] were selected by graphical interpolation. The accuracy of the obtained effective temperatures was 5–10 K, and the accuracy of the metallicities 0.01–0.02 dex. However, the real accuracy is an order lower because of

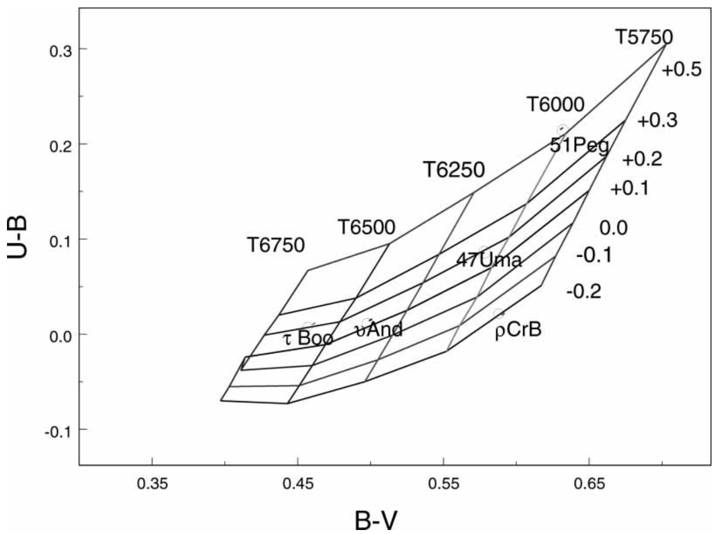

Figure 1. Two-colour diagram of $U-B$ versus $B-V$ for the stellar atmosphere models ($\log g = 4.5$; 5750 K $< T_{\rm eff} <$ 6750 K; -0.20 dex $<$ [Fe]/[H] < 0.50 dex).

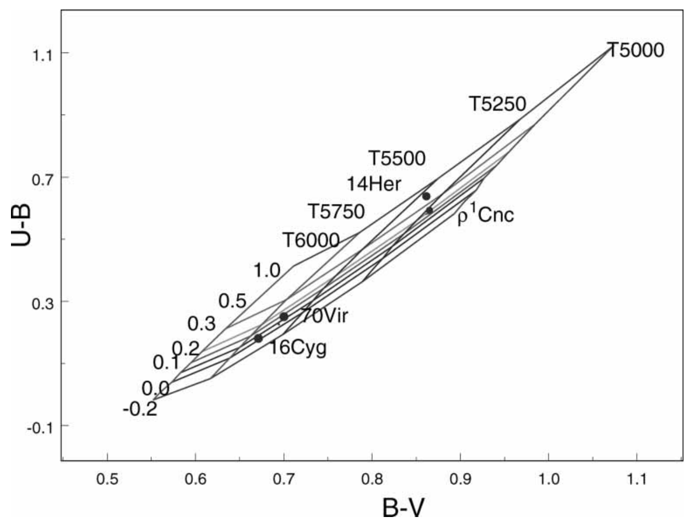

Figure 2. Two-colour diagram $(U-B, B-V)$ for the stellar atmosphere models ($\log g = 4.50$; 5000 K $< T_{\rm eff} <$ 6000 K; -0.20 dex $<$ [Fe]/[H] < 1.00 dex).

Table 4. The effective temperatures and metallicities of parent stars.

	T_{eff} (K)			[M]/[H] (dex)		
Star	Present work	[15]	[14]	Present Work	[15]	[14]
υ And	6390	6210	6143	0.14	0.10	−0.03
ρ^1 Cnc	5230	5250	5279	0.30	0.16	0.33
47 UMa	6080	5780	5954	0.20	0.01	0.06
HD114762	–	6110	5884	–	−0.70	−0.70
70 Vir	5620	5770	5560	0.13	−0.03	−0.06
τ Boo	6600	6498	6339	0.22	0.28	0.23
ρ CrB	5860	5860	5853	−0.20	−0.19	−0.21
14 Her	5455	5255	5311	0.78	0.51	0.43
16 CygB	5650	5760	5772	0.01	0.05	0.08
51 Peg	6030	5946	5804	0.53	0.20	0.20

simplification of the method employed and errors in both our SEDs and the response functions. Because of our estimations the real accuracy of the T_{eff} values is about 200–250 K, and that of the metallicities 0.2–0.3 dex. The results of the determination of T_{eff} and [Fe]/[H] are given in table 4. The star 16 Cyg is included in table 4 as well.

The SDE data for this were taken from our catalogue [1]. For comparison the analogous data from [14, 15] are presented in table 4. As a whole the metallicity turns out to be increased for the majority of parent stars. As expected, our values of the temperatures and metallicities appeared to be overestimated systematically because of the 'blueness' of the calculated colour indices $U - B$. In future we plan to determine the three main stellar parameters by direct comparison of the observed SDEs with those from models.

Acknowledgements

In conclusion, I wish to express my gratitude to A.V. Mironov (Sternberg Astronomical Institute) for a CD of the Lejeune *et al.* models and to T.A. Bobryashova for help with the calculations.

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