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Effective temperature of detached eclipsing binaries from Hipparcos parallax*

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Abstract. Effective temperatures of detached eclipsing binaries computed through Hipparcos trigonometric parallaxes are compared with the photometric determinations. The former are based on the values of the radius, the apparent visual magnitude and the bolometric correction of the star, whereas the latter are obtained from standard calibrations using Strömgren or Johnson colour indices.

The working sample contains all well-studied detached double-lined eclipsing binaries belonging to the Hipparcos catalogue and with relative errors in the parallaxes smaller than 20%. They cover a temperature range from 5000 K to 25000 K.

A small systematic trend of 0.010 dex (s.d. 0.010) for $T_{\rm eff} \leq$ 10000 K and of 0.015 dex (s.d. 0.060) for $T_{\rm eff} >$ 10000 K is observed between the two temperature determinations, that could be due to inaccuracies on photometric effective temperatures.

Key words: stars: fundamental parameters – stars: distances – stars: binaries: eclipsing – stars: early-type – stars: late-type

1. Introduction

Detached double-lined eclipsing binaries are a well known source of information for the study of stellar structure and evolution. Masses and radii of stars can be accurately determined (Andersen 1991) allowing the test of stellar models. This, of course, assumes that the components of detached binaries behave like single stars from the point of view of stellar structure and evolution. In addition, binary stars with accurate absolute dimensions are also used to derive distances independently of absolute magnitude calibrations. This is the case of some binaries in clusters and associations (Giménez 1996) or even more for eclipsing binaries in the Magellanic Clouds (Giménez et al. 1994).

A detailed comparison of binary star data with theoretical models requires knowledge of the individual effective temperatures of the component stars. The temperatures are usually estimated from the observed photometric indices after separation of the components through the luminosity ratios provided by the analysis of the light curves.

European Space Agency Hipparcos satellite has provided new and accurate determinations of trigonometric parallaxes (ESA 1997). Of course, it is evident that a comparison of these trigonometric distances with those derived from detached eclipsing binaries using the standard procedures should be in agreement if the involved calibrations are appropriate. On the other hand, since we know the absolute radii of the component stars, the distance provided by Hipparcos should lead to an absolute magnitude and hence a new estimation of the effective temperature. Thus, the calibrations currently applied to obtain the input parameters for the study of stellar models by means of eclipsing binaries can be tested with Hipparcos data, using the direct comparison of distances, or equivalently, the comparison of the effective temperatures.

2. The sample

The selection criteria of the eclipsing binaries to be included in the sample were based on the following considerations:

- We selected all well-studied detached double-lined eclipsing binary stars, with accurate determination of their radii (1-2%). Thus, the sample was based on the systems listed in Andersen's (1991) critical review and, for one system, a revision published later (Nordström & Johansen 1994) was considered;
- they had obviously to be included in the Hipparcos Catalogue; and
- since the uncertainty of the temperature should not be larger than 10%, we restricted our study to those systems with a relative error in the trigonometric parallax smaller than 20% (see Sect. 3).

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* Based on data from the ESA Hipparcos astrometry satellite

The previous selection criteria led to a sample composed of 19 detached eclipsing binary systems. Nevertheless, one additional system with larger relative error in parallax, CW Cep, was added since its membership to Cepheus OB3 association (Clausen & Giménez 1991) allowed us to estimate its distance. This system is especially interesting because it contains the hottest stars in the sample, ant thus allow us to extend the effective temperature analysis up to 25000 K.

The photometric effective temperature ($T_{\rm eff}$ (phot)) of each component, to be compared with Hipparcos parallax-based determination, was computed, when possible, from the individual Strömgren photometric indices (Jordi et al. 1997) by means of the grids published by Moon & Dworetsky (1985). Nevertheless, due to the lack of Strömgren photometry for several systems, their effective temperatures were taken from the literature, and were based on calibrations relating the Johnson colour index $(B-V)_\circ$ with the temperature (Popper 1980). The estimated errors in $T_{\rm eff}$ (phot) increase from 200 to 1200 K when the temperature increases from 5000 to 20000 K.

3. The procedure

The distance to a single star is usually determined by means of trigonometric parallaxes or photometric calibrations. The latter using the photometric indices of the star to estimate its absolute magnitude. Nevertheless, the photometric distance (d (phot)) to an eclipsing binary is usually determined in a different way, since the radius is known. In this case, the luminosity, and hence the bolometric magnitude, is obtained from the photometric effective temperature (from colour indices) and the radius. Then, the absolute visual magnitude is derived in a straightforward way provided we apply a bolometric correction. Finally, the distance comes from relating the absolute magnitude and the apparent visual magnitude, which is known. If the observational data are consistent, the distance derived for both components should be equivalent.

When we have previous knowledge of the distance to the eclipsing binary, i.e. accurate trigonometric parallaxes, the procedure can be inverted to determine the effective temperature ($T_{\rm eff}$ (Hip)) of each component by using its apparent visual magnitude, its radius, the interstellar absorption and a bolometric correction. From this scheme we find that the effective temperature of the star can be computed by means of the following expression:

$$T_{\rm eff} = T_{\rm eff\odot}\left(10\pi\frac{R}{R_\odot}\right)^{-1/2}10^{-0.1(V_\circ+BC-M_{\rm bol\odot})}, \qquad (1)$$

where π is the parallax in arcsec, $R/R_\odot$ is the radius of the star in solar units, $V_\circ$ is the apparent visual magnitude corrected for absorption ($V_\circ = V - A_{\rm v}$), BC is the bolometric correction and $T_{\rm eff\odot}$ and $M_{\rm bol\odot}$ are the solar effective temperature and bolometric magnitude, respectively. Since BC depends on the temperature, an iterative algorithm was used in order to reach an agreement between these two values. $M_{\rm v\odot}$ was taken as 4.82 mag, and $BC_\odot$ was computed from the BC calibration adopted (see Sect. 3.2) from $T_{\rm eff\odot}$ = 5780 K.

3.1. Errors

The uncertainty on the temperature determination from the parallax can be estimated by propagation of the errors associated with the parameters of Eq. (1), and we obtain

$$\left(\frac{\Delta T_{\rm eff}}{T_{\rm eff}}\right)_\pi \simeq 0.5\,\frac{\Delta\pi}{\pi} \qquad (\leq 10\% \text{ if } \tfrac{\Delta\pi}{\pi}\leq 20\%)$$
$$\left(\frac{\Delta T_{\rm eff}}{T_{\rm eff}}\right)_R \simeq 0.5\,\frac{\Delta R}{R} \qquad (\sim 1\%)$$
$$\left(\frac{\Delta T_{\rm eff}}{T_{\rm eff}}\right)_{V_\circ} \simeq 0.1\,\ln 10\,\Delta V_\circ \approx 0.23\,\Delta V_\circ \qquad (\sim 0.4\%)$$
$$\left(\frac{\Delta T_{\rm eff}}{T_{\rm eff}}\right)_{BC} \simeq 0.1\,\ln 10\,\Delta BC \approx 0.23\,\Delta BC \qquad (\sim \text{4-5}\%)$$

The rough estimation of the errors on the right of the expressions comes from adopting 2%, 0.02 mag and 0.2 mag as uncertainties of the values of R, $V_\circ$ and BC, respectively. Since the largest contribution to the final error is due to the parallax, it was necessary to impose a restriction on its relative error to keep the uncertainty of the temperature below a certain level.

3.2. Bolometric correction

As seen in Eq. (1), a bolometric correction calibration is needed to compute the effective temperature from the trigonometric parallax and the empirical data. Several BC calibrations were considered: Code et al. (1976), Popper (1980), Habets & Heintze (1981), Schmidt-Kaler (1982), Malagnini et al. (1986) and Flower (1996). The mean differences between them for the temperature interval covered by our sample range from 0.01 mag to 0.14 mag, meaning a maximum effect on the temperature determination of about 3% (see Sect. 3.1). Only the calibration of Habets & Heintze (1981) shows a strong systematic trend with a mean difference of 0.43 mag. Excluding the latter, our result is a consequence of the fact that there are only B-G-type stars in the sample, which cover a temperature range where the discrepancies between different BC calibrations are small. Flower's (1996) calibration was finally adopted, since it is the most recent of those considered in the comparison.

4. Results

The procedure described in Sect. 3 was applied to the whole sample, and Table 1 summarizes the input and the resulting output parameters. Errors are explicitly shown for the Hipparcos parallax-based effective temperature determination, and they were computed as the maximum contribution of the uncertainty in the parallax.

Very good agreement is observed in Table 1 between the photometric distance determination for both components of the systems. EK Cep is the only system that shows a clear difference between the photometric distances of the primary and secondary components. This fact can be explained if we consider that the secondary component appears to be a pre-main sequence star (Popper 1987), for which standard photometric calibrations (effective temperature or bolometric correction) may not be suitable.

Table 1. Effective temperatures and distances (Hipparcos parallax-based and photometric) in parsecs, together with radius in solar units, apparent visual magnitude corrected for absorption, bolometric correction (Flower 1996) and relative error in parallax for the eclipsing binaries in the sample. Notice the good agreement between the photometric distance of the system components. Ref.: references for the photometric temperatures, the radii and the visual magnitudes

HIC	Name	Cp.	Sp.	$T_{\rm eff}$(Hip)		$T_{\rm eff}$(phot)	d(Hip)	d(phot)	$R/R_\odot$	$V_\circ$	BC	$\frac{\Delta\pi}{\pi}$(%)	Ref.
3572	YZ Cas	A	A1m	8624	±290	9220	89	98	2.534	5.77	−0.01	4.9	1,2
		B	F2V	6528	155	6700		94	1.348	8.34	0.01		3
5348	ζ Phe	A	B6V	14631	1150	14295	86	84	2.851	4.30	−1.20	6.6	1,2
		B	B8V	12249	1100	11750		83	1.853	5.55	−0.75		
15092	TZ For	A	G8III	4804	280	5000	171	195	8.318	7.51	−0.41	16.4	1,4
		B	F7IV	6056	500	6350		190	3.932	7.76	−0.04		
25760	UX Men	A	F8V	6164	175	6190	101	102	1.347	8.85	−0.02	6.2	1,2
		B	F8V	6117	170	6210		104	1.274	9.01	−0.03		
25776	TZ Men	A	A0V	9489	490	10675	107	120	2.016	6.35	−0.14	5.3	1,2
		B	A8V	6880	190	7295		121	1.432	8.32	0.03		
28360	β Aur	A	A1IV	9230	150	9435	25.2	25.9	2.769	2.59	−0.09	2.0	5,2
		B	A1IV	9186	145	9310		25.6	2.627	2.72	−0.08		
31173	WW Aur	A	A5m	8180	425	8130	84	83	1.883	6.48	0.01	8.9	1,6
		B	A7m	7766	420	7760		84	1.883	6.68	0.03		
42794	RS Cha	A	A8V	7687	180	7810	98	101	2.137	6.77	0.03	4.5	1,2
		B	A8V	7331	170	7295		97	2.338	6.78	0.03		
45184	KW Hya	A	A5m	7826	340	8080	83	87	2.125	6.34	0.03	7.1	1,2
		B	F0V	6626	230	6940		91	1.480	7.87	0.01		
52381	RZ Cha	A	F5V	6681	400	6625	184	181	2.264	8.64	0.02	11.6	1,2
		B	F5V	6513	385	6630		191	2.264	8.76	0.01		
54255	χ^2 Hya	A	B8V	13630	3050	11565	245	215	4.384	5.78	−1.02	16.7	1,2
		B	B8V	12521	3010	11290		226	2.165	7.46	−0.80		
74950	GG Lup	A	B7V	16128	2080	14795	158	146	2.381	5.82	−1.43	11.4	1,2
		B	B9V	12129	1960	11515		151	1.726	7.05	−0.72		
84500	U Oph	A	B5V	13706	2800	16900	186	225	3.290	5.79	−1.04	15.4	7
		B	B6V	12825	2770	16000		225	3.010	6.10	−0.87		
86809	V624 Her	A	A3m	8160	515	8147	144	144	3.030	6.62	0.01	10.7	1,8
		B	A7V	7904	515	7943		146	2.209	7.42	0.03		
88069	V1647 Sgr	A	A1V	7460	735	9565	115	174	1.831	7.59	0.03	16.1	1,2
		B	A1V	7189	660	8970		172	1.666	7.95	0.03		
94335	FL Lyr	A	F8V	6109	340	6152	130	132	1.282	9.56	−0.03	11.6	1,9
		B	G8V	5253	245	5297		133	0.962	11.02	−0.21		
96620	V1143 Cyg	A	F5V	6484	70	6620	39.8	41.7	1.346	6.59	0.01	2.2	1,10
		B	F5V	6473	70	6570		41.1	1.323	6.63	0.01		
106712	EE Peg	A	A3m	8435	720	8710	131	139	2.089	7.09	0.00	12.0	1,11
		B	F5V	6273	370	6455		140	1.312	9.40	−0.01		
107083	EK Cep	A	A1.5V	8523	530	9100	153	169	1.579	7.99	0.00	8.9	1,12
		B	G5Vp	5535	210	6000		187	1.315	10.39	−0.13		
113907	CW Cep	A	B0.5V	23804		27475	725	820	5.685	6.39	−2.27	70.3	1,2
		B	B0.5V	23272		27275		833	5.177	6.64	−2.22		

1: Andersen (1991), 2: Jordi et al. (1997), 3: Lacy (1981), 4: Andersen et al. (1991), 5: Nordström & Johansen (1994), 6: Hauck & Mermilliod (1990), 7: Popper & Hill (1991), 8: Popper (1984), 9: Popper et al. (1986), 10: Andersen et al. (1987), 11: Lacy & Popper (1984), 12: Popper (1987)

The direct comparison of distances (photometric vs. Hipparcos) for the whole sample is shown in Fig. 1. Apart from the obvious larger scatter with increasing distance, a systematic trend leading to photometric larger than Hipparcos distances is also observed. An equivalent plot comparing the photometric and Hipparcos effective temperature determinations is shown in Fig. 2. The general behaviour is very similar to that observed in Fig. 1 since the hottest systems are usually more distant, and so they show larger scatter. Again, a systematic trend is observed, and the effective temperatures coming from Hipparcos distances tend to be slightly smaller than the photometric determinations. No different behaviour is found between those systems with effective temperatures obtained through Johnson calibrations and those systems with effective temperatures coming from Strömgren photometry.

Table 2 summarizes the statistics of the differences between temperature determinations considering the stars hotter and cooler than 10000 K in separate subsamples. The small dif-

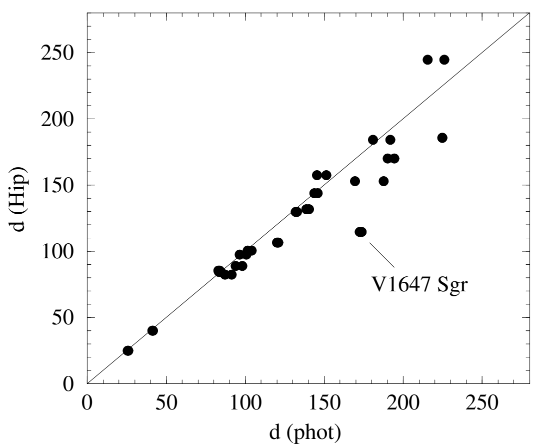

Fig. 1. Comparison between the photometric distance determination for the eclipsing binaries and the direct determination of distance using the Hipparcos parallax (relative error $< 20\%$). The system V1647 Sgr is labelled

Table 2. Statistics of the difference between the Hipparcos parallax-based and the photometric determination of effective temperatures. Two different $T_{\rm eff}$ intervals were considered. n is the number of stars in each subsample. V1647 Sgr was not considered (see text)

	$T_{\rm eff}$(phot) $\leq$ 10000 K	$T_{\rm eff}$(phot) $>$ 10000 K	All
n	27	11	38
$< \Delta\pi/\pi >$ (%)	8.1	11.7†	9.0†
$< \Delta \log T_{\rm eff} >^{\dagger\dagger}$	−0.010	−0.015	−0.012
s.d.: σ	0.010	0.060	0.032

† CW Cep not included
$^{\dagger\dagger}\Delta \log T_{\rm eff} = \log T_{\rm eff}(\rm Hip) - \log T_{\rm eff}(\rm phot)$

ference between determinations is not temperature dependent and could be explained either by systematic effects on photometric effective temperatures (about 2-3%) or by an unsuitable adoption of $T_{\rm eff\odot}$ or $M_{\rm v\odot}$. $T_{\rm eff\odot}$ should increase up to about 5900 K or $M_{\rm v\odot}$ up to 4.92 mag to remove the discrepancy. These values are unlikely to be realistic, so inaccuracies on effective temperatures coming from photometric calibrations are probably the cause.

Concerning the early-type eclipsing binary CW Cep, despite the large error of the Hipparcos parallax (70%), the agreement with the distance to Cepheus OB3 association, and consequently, the agreement between the effective temperature determinations, turned out to be good.

If the errors in the input parameters are considered, both photometric distances and photometric effective temperatures are compatible (2σ) with the determinations using Hipparcos parallaxes for all systems but V1647 Sgr.

V1647 Sgr is an apparently normal 7th mag A-type detached eclipsing binary, with main-sequence components of similar mass. The large discrepancy in effective temperatures ($\simeq$ 2000 K) is unlikely to be related with errors in the photometric determination, since all Strömgren photometric indices are coherent with the spectral type (Andersen & Giménez 1985).

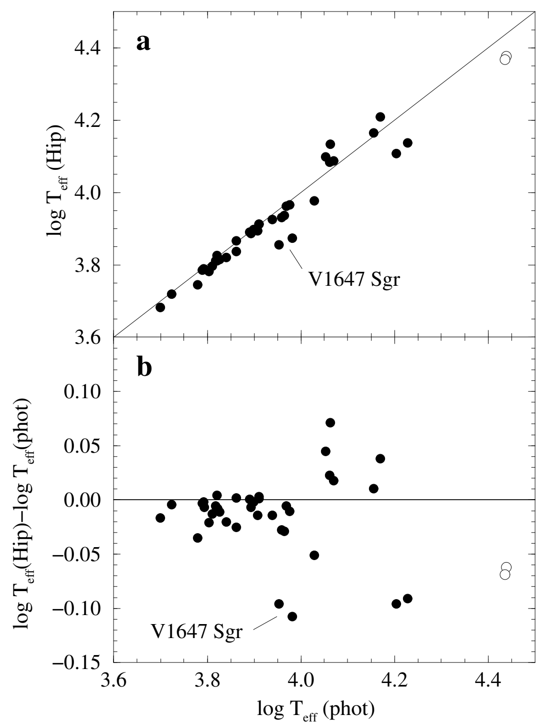

Fig. 2a and b. Comparison between the effective temperature determination using standard photometric calibrations and that based on the Hipparcos parallax. Both components of the eclipsing binary CW Cep are represented with open circles, and the system V1647 Sgr is labelled

To obtain a good agreement with the behaviour of the whole sample, the visual magnitude or the BC of both components should be decreased by about 0.8 mag or their radii should be about 30% smaller. Actually, there is no reason to consider such a large error in the BC, since there are other stars in the sample with similar temperatures that do not show such anomalous behaviour. The only distinctive feature of this system is the presence of a relatively bright visual component. V1647 Sgr is the bright member of the visual binary CCDM 17592-3656 with a companion with V = 9.1 mag at a separation of 7.5 arcsec. This visual companion might have caused a significant effect on the determination of the parameters and an additional source of uncertainty not included in the formal errors.

An additional analysis concerning possible metallicity effects was performed for those systems with Strömgren photometry and effective temperature below 8500 K, i.e. belonging to the late region (Strömgren 1966). For these stars the photometric index $\delta m_\circ$ ($\delta m_\circ = m_\circ$(Hyades) $- m_\circ$(observed)) is related to the atmospheric metallic abundance. The temperature differences were plotted against $\delta m_\circ$ and no clear correlation was observed, although the number of stars was low (10), which rules out metallicity effects in the scatter of the cool stars.

Finally, we add some additional remarks for the two systems of the sample with the smallest relative errors in the parallax: β Aur and V1143 Cyg.

A very detailed study of the bright eclipsing binary β Aur was published by Nordström & Johansen (1994). Their photometric analysis was performed in seven different passbands: Johnson B and V and five filters close to Strömgren u, v, b, y and $H_{\beta_{\rm w}}$. In our study we adopted their determination of the radii and the photometric effective temperatures were computed from the individual Strömgren indices (Jordi et al. 1997). We obtained the individual visual magnitudes from the luminosity ratio in the y passband since the light curves in V were less well covered. The final result is that the photometric and Hipparcos parallax-based effective temperatures show differences of 2-3% well within the general behaviour of the whole sample.

Nordström & Johansen (1994) also discussed the different distance estimators to β Aur. They found good agreement between several methods and pointed out that the trigonometric distance showed the largest error by almost a factor of three. The photometric distance and the determination using the semi-major orbital axis and the spectroscopic information are in good agreement with the Hipparcos value (25.2 $\pm$ 0.5 pc), which is at present the most accurate.

The input parameters of the system V1143 Cyg also deserve further discussion. In this case, we computed the individual V magnitudes from the luminosity ratio in the V passband and the joint magnitude taken from Andersen et al. (1987). However, since both components are very similar, we derived the effective temperature from the joint Strömgren indices, obtaining 6600 K. Finally, the temperatures adopted for the A and B components were 6620 K and 6570 K, respectively, because the temperature difference ($T_{\rm A} - T_{\rm B}$) is 50 K (van Hamme & Wilson 1984). The small error in the trigonometric distance (39.8 ± 0.9 pc) yields a very accurate determination of the effective temperature showing the same results as β Aur.

5. Conclusions

A sample containing all detached eclipsing binaries with accurate radii (1-2%) and relative error in the Hipparcos parallax below 20% was used to test the photometric determination of effective temperature. One additional system (CW Cep) was added since its distance could be checked from its membership to Cepheus OB3 association.

The comparison of the photometric determination of effective temperature with that obtained from the Hipparcos parallax, the radius of the star, the visual magnitude and the bolometric correction showed a small trend leading to an Hipparcos-parallax based determination about 2-3% smaller than the photometric one. Only one system, V1647 Sgr, shows an anomalously large scatter that could be associated with the presence of a visual companion, which might have an unregarded negative influence in the observed parameters, and so it deserves further study.

Due to the completely independent nature of the two temperature determinations, we conclude that a small systematic difference of about 0.012 dex is present in the temperature range covered by our sample (from 5000 K to 25000 K). Moreover, the two systems of the sample with the smallest relative errors in the Hipparcos parallax, β Aur and V1143 Cyg, agree with this result. In these cases, the Hipparcos parallax-based determinations would be more accurate than the photometric ones.

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References

Andersen, J., 1991, A&AR 3, 91
Andersen, J., García, J.M., Giménez, A., Nordström, B., 1987, A&A 174, 107
Andersen, J., Clausen, J.V., Nordström, B., Tomkin, J., Mayor, M., 1991, A&A 246, 99
Andersen, J., Giménez, A., 1985, A&A 145, 206
Clausen, J.V., Giménez, A., 1991, A&A 241, 98
Code, A.D., Davis, J., Bless, R.C., Hanbury Brown, R., 1976, ApJ 203, 417
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Flower, P.J., 1996, ApJ 469, 355
Giménez, A., 1996, in "The Origins, Evolutions, and Destinies of Binary Stars in Clusters", eds. E.F. Milone and J.-C. Mermilliod, A.S.P. Conf. Series, vol. 90, p. 109
Giménez, A., Clausen, J.V., Guinan, E.F., Maloney, F.P., Bradstreet, D.H., Storm, J., Tobin, W., 1994, Experimental Astronomy, 5, 181
Habets, G.M.H.J., Heintze, J.R.W., 1981, A&AS 46, 193
Hauck, B., Mermilliod, M., 1990, A&AS 86, 107 (1992 revision; private communication)
Jordi, C., Ribas, I., Torra, J., Giménez, A., 1997, A&A 326, 1044
Lacy, C.H., 1981, ApJ 251, 591
Lacy, C.H., Popper, D.M., 1984, ApJ 281, 268
Malagnini, M.L., Morossi, C., Rossi, L., Kurucz, R.L., 1986, A&A 162, 140
Moon, T.T., Dworetsky, M.M., 1985, MNRAS 217, 305
Nordström, B., Johansen, K.T., 1994, A&A 291, 777
Popper, D.M., 1980, ARA&A 18, 115
Popper, D.M., 1984, AJ 89, 1057
Popper, D.M., 1987, ApJ 313, 81
Popper, D.M., Hill, G., 1991, AJ 101, 600
Popper, D.M., Lacy, C.H., Frueh, M.L., Turner, A.E., 1986, AJ 91, 383
Schmidt-Kaler, T., 1982, in Landolt-Börnstein, eds. K. Schaifers and H.H. Voigt, Vol. II, Subvol. B, p. 453
Strömgren, B., 1966, ARA&A 4, 433
van Hamme, W., Wilson, R.E., 1984, A&A 141, 1

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