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Improved Baade-Wesselink surface-brightness relations

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ABSTRACT
Recent, and older accurate, data on (limb-darkened) angular diameters is compiled for 221 stars, as well as $BVRIJK[12][25]$ magnitudes for those objects, when available. Nine stars (all M-giants or supergiants) showing excess in the $[12-25]$ colour are excluded in the analysis as this may indicate the present of dust influencing the optical and near-infrared colours as well. Based on this large sample, Baade-Wesselink surface-brightness (SB) relations are presented for dwarfs, giants, supergiants and dwarfs in the optical and near-infrared. M-giants are found to follow different SB-relations from non-M giants, in particular in V-$(V-R)$. The preferred relation for non-M giants are compared to earlier relation by Fouqué & Gieren (1997, based on 10 stars) and Nordgren et al. (2002, based on 57 stars). Increasing the sample size does not lead to a lower rms value. It is shown that the residuals do not correlate with metallicity at a significant level. The finally adopted observed angular diameters are compared to those predicted by Cohen et al. (1999) for 45 stars in common, and there is reasonable overall, to good agreement when θ <6 mas. Finally, I comment on the common practice in the literature to average, and then fix, the zero point of the V-$(V-K)$, V-$(V-R)$ and K-$(J-K)$ relations, and then re-derive the slopes. Such a common zero point at zero colour is not expected from model atmospheres for the $(V-R)$ colour and depends on gravity. Relations derived in this way may be biased.

Key words: Stars: distances - Stars: fundamental parameters - Cepheids - Magellanic Clouds - distance scale

1 INTRODUCTION

The Period-Luminosity (PL) relation of Cepheids is of fundamental importance in establishing the cosmic distance scale. Determining whether or not the slope of the Galactic relation is different from that for the LMC and/or SMC Cepheids relations is of prime importance, as this could imply a metallicity dependence of the slope of the relation, with important consequences for the application of the PL-relation to other galaxies. The apparent zero point and slope of the fundamental (FU) and first-overtone (FO) PL-relations in the LMC and SMC have now been well determined in V, I, W (the reddening free, so-called Wesenheit-index based on V and I), and J and K (Udalski et al. 1999, Groenewegen 2000, Nikolaev et al. 2004, Sandage et al. 2004).

The situation is less clear for our Galaxy. The accuracy of the HIPPARCOS parallax data was not high enough to determine slope *and* zero point. Instead, the data had to be analysed in a statistical way, such that for an *assumed* slope, a zero point could be derived (e.g., Feast & Catchpole 1997; Groenewegen & Oudmaijer 2000)

There are basically two alternatives to obtain direct distance estimates to Galactic Cepheids, namely, using Cepheids in open clusters (e.g. Feast 1999, Tammann et al. 2003) where the distance to the cluster has been obtained in another way (basically main-sequence fitting), or, in combining linear diameter determinations (as determined from integration of the radial velocity curve and assuming a projection factor), with angular diameter determinations coming from direct measurements using an interferometer (e.g. Kervella et al. 2003) or coming from a surface-brightness (SB) relation and a reddening-corrected magnitude (e.g. Fouqué et al. 2003, Storm et al. 2004).

For the latter method to work one has therefore to determine and calibrate accurate SB relations. There is a whole body of work on this subject (e.g., Barnes et al. 1978; Di Benedetto 1993 [DB93]), and more recently, with direct application to Cepheids, the works by Fouqué & Gieren (1997; herafter FG97), and Nordgren et al. (2002; hereafter Nord02). The latter calibration is used by Fouqué et al. (2003) to establish the most recent slopes and zero points of the Galactic PL-relation for FU Cepheids in $BVIWJHK$ colours.

In addition, SB-relations are important in estimating angular diameters for planning interferometric observations (either to check if a potential science target would be resolved, or to check if a calibrator is indeed unresolved, for a given baseline), and for distance estimates in eclipsing binaries (Salaris & Groenewegen 2002).

The calibration by Nord02 is based on 57 giants observed with the Navy Prototype Optical Interferometer (NPOI) by this group (Nordgren et al. 1999; Nordgren et al. 2001). On the other hand there have been other recent papers presenting new diameter determinations (e.g., 69 stars in van Belle et al. 1999), and there exist older data of high quality; recently, Richichi & Percheron (2002)

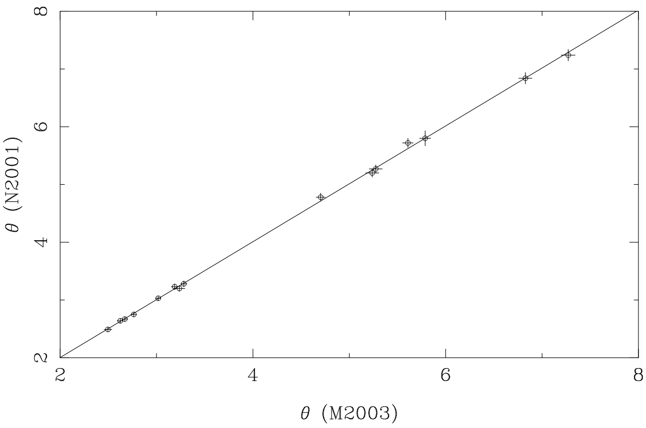


Figure 1. Limb-darkened angular diameters (in mas) from Nordgren et al. (2001) plotted against those from Mozurkewich et al. (2003) for the stars in common. The line is a least-squares fit to the 15 data points plotted: $\theta_{\rm N2001} = (1.002 \pm 0.007)\ \theta_{\rm M2003} + (0.000 \pm 0.031)$ (rms = 0.039).

Table 2. Objects with three or more independent angular diamter estimates.

ID	$\theta \pm \sigma_\theta$ (mas)	$\theta \pm \sigma_\theta$ (mas)	$\theta \pm \sigma_\theta$ (mas)	$\theta \pm \sigma_\theta$ (mas)
168	5.608 ± 0.056 (1)	5.72 ± 0.08 (2)	5.60 ± 0.06 (3)	
617	6.827 ± 0.068 (1)	6.84 ± 0.10 (2)	6.88 ± 0.04 (3)	
1017	3.188 ± 0.035 (1)	3.23 ± 0.05 (2)	3.10 ± 0.02 (3)	
1409	2.671 ± 0.032 (1)	2.67 ± 0.04 (2)		2.57 ± 0.06 (4)
2473	4.703 ± 0.047 (1)	4.78 ± 0.07 (2)	4.73 ± 0.03 (3)	
3249	5.238 ± 0.069 (1)	5.20 ± 0.07 (2)	5.03 ± 0.04 (3)	
4932	3.283 ± 0.033 (1)	3.28 ± 0.05 (2)	3.17 ± 0.03 (3)	
5681	2.764 ± 0.030 (1)	2.75 ± 0.04 (2)	2.74 ± 0.03 (3)	2.71 ± 0.06 (4)
6220	2.624 ± 0.034 (1)	2.64 ± 0.04 (2)	2.42 ± 0.07 (3)	
6418	5.275 ± 0.067 (1)	5.27 ± 0.07 (2)	5.20 ± 0.03 (3)	
7525	7.271 ± 0.073 (1)	7.24 ± 0.10 (2)	7.08 ± 0.05 (3)	
7796	3.017 ± 0.030 (1)	3.03 ± 0.04 (2)	3.02 ± 0.08 (3)	
8079	5.787 ± 0.058 (1)	5.80 ± 0.13 (2)	5.56 ± 0.04 (3)	
8414	3.237 ± 0.057 (1)	3.20 ± 0.05 (2)	3.08 ± 0.03 (3)	
8684	2.496 ± 0.040 (1)	2.49 ± 0.04 (2)	2.50 ± 0.08 (3)	2.60 ± 0.06 (4)

References. (1) Mozurkewich et al. (2003); (2) Nordgren et al. (2001); (3) Nordgren et al. (1999); (4) van Belle et al. (1999).

conveniently presented a catalog of high angular resolution measurements.

The aim of the present paper is to present updated SB relations based on the largest set of accurate angular diameter determinations. Section 2 presents the angular diameter data and the search for apparent magnitudes. Section 3 briefly recalls the relevant equations, and Section 4 presents the results. The discussion in Section 5 ends this paper.

2 THE DATA

The principal sources of *limb-darkened* angular diameters are the recent papers by Mozurkewich et al. (2003), Nordgren et al. (1999, 2001), van Belle et al. (1999), Kervella et al. (2003, 2004) and Wittkowski et al. (2004). From the compilation by Richichi & Percheron (2002), those stars were selected which have a *limb-darkened* angular diameter determined, and with a relative accuracy of better than 3%. This selection is based on the typical accuracy that can be achieved with modern instrumentation and was selected

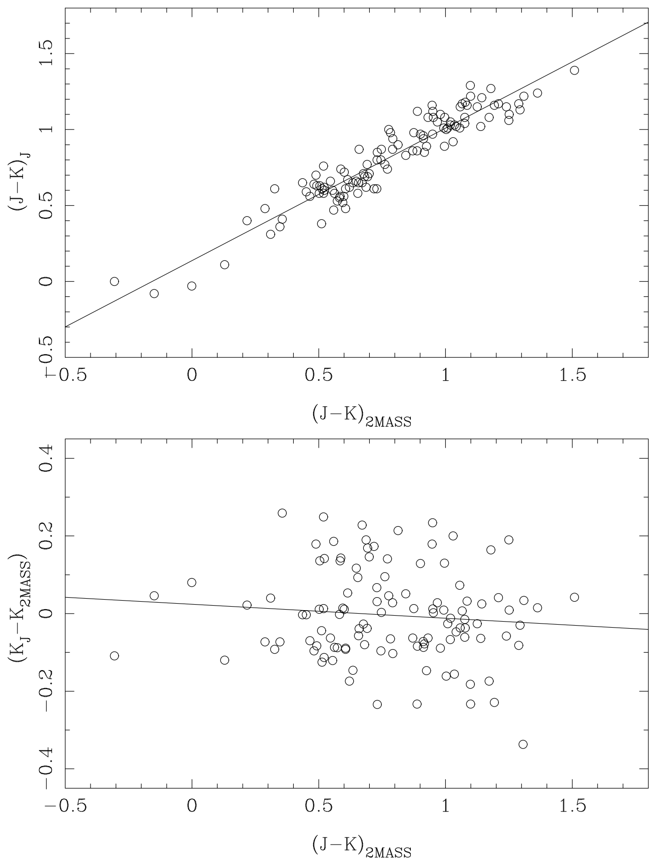


Figure 2. Top: $(J-K)$ versus $(J-K)$ of 2MASS. The line is a least-squares fit to the 115 data points plotted: $(J-K) = (0.872 \pm 0.029)\ (J-K)_{\rm 2mass} + (0.137 \pm 0.026)$ (rms = 0.096). Bottom: $(K - K_{\rm 2mass})$ versus $(J-K)$ of 2MASS. The line is a least-squares fit: $(K - K_{\rm 2mass}) = (-0.036 \pm 0.035)\ (J-K)_{\rm 2mass} + (0.024 \pm 0.029)$ (rms = 0.12).

to weed out most of the less accurate, older, data in this compilation. The stars already in the other references were removed, as well as the carbon- and S-stars. In total this added another 27 objects. The final list contains 221 (different) objects, listed in Table 1. In case of multiple angular diameter determinations the one with the smallest relative error on the limb-darkened angular diameter was retained.

For fifteen objects there are three or four independent determinations available and its interesting to compare them as e.g. slightly different approaches are used in the literature to proceed from uniform-disk to limb-darkened disk angular parameters. Table 2 lists those stars and the measurements, and Figure 1 plots the values from Nordgren et al. (2001) against those in Mozurkewich et al. (2003). The agreement is extremely good, and the rms in the fit of 0.039 indicates that the quoted errorbars in the determinations are realistic.

Apart from the angular diameters, one needs apparent magnitudes and reddening to apply the SB method. Most of the photometric data come from consulting the SIMBAD database. In particular, IRAS 12 and 25 μm fluxes, and $BVRIJK$ magnitudes were collected from the entries marked (in order of preference), “JP11”, “UBV”, “IRC”. In addition, the galactic coordinates, spectral type, and the HIPPARCOS parallax was retrieved, as well as the most recent listed value for the metallicity, available under the item marked “Fe_H”. To collect more photometric data, the Gezari et al. (1999) catalog was checked for infrared data, and the SIMBAD

Table 1. Identification (HR or IRC identifier, unless otherwise listed in the remarks), adopted angular diameter and error, adopted visual reddening and error, $BVRIJK$[12][25] photometry, reference to the angular diameter and photometry (when not taken from SIMBAD as discussed in the text), and remarks, of the sample studied. An entry with -9.99 means that this magnitude is not available.

ID	Spectral Type	θ (mas)	σ_θ (mas)	$A_{\rm V}$	$\sigma_{A_{\rm V}}$	B	V	R	I	J	K	[12]	[25]	References	Remarks
21	F2_IV_SB	2.12	0.05	0.04	0.02	2.61	2.27	1.96	1.76	1.65	1.48	1.36	1.30	Nord99	
79	K5_III	2.51	0.05	0.23	0.14	7.39	5.79	4.44	3.44	-9.99	1.80	1.64	1.59	vB99, 6, 7	
163	G8_III	1.77	0.08	0.08	0.02	5.25	4.38	3.70	3.19	2.84	2.21	2.14	2.11	Nord99	
165	K3_III_SB	4.14	0.04	0.05	0.01	4.56	3.28	2.36	1.70	1.24	0.48	0.29	0.27	MAH03	
168	K0_IIIa	5.61	0.06	0.11	0.03	3.40	2.23	1.45	0.85	0.42	-0.25	-0.49	-0.39	MAH03	
259	M4_III	3.67	0.10	0.27	0.01	7.83	6.20	5.33	3.73	2.21	1.03	0.86	0.75	vB99, 14	
265	G8_IIIb	1.63	0.11	0.18	0.06	5.60	4.64	3.87	3.37	-9.99	2.35	2.24	2.21	Nord99	
274	G6_III	2.80	0.11	0.40	0.01	6.50	5.42	-9.99	-9.99	-9.99	2.93	2.98	2.93	vB99	
294	G9_III	1.74	0.10	0.05	0.04	5.24	4.28	3.50	2.98	2.60	2.00	1.90	1.78	Nord99	
337	M0_III	13.81	0.13	0.06	0.02	3.62	2.05	0.81	-0.19	-0.81	-1.83	-2.11	-9.99	MJS91	
351	G9_III	1.64	0.07	0.14	0.01	5.69	4.66	3.90	3.36	-9.99	2.36	2.30	2.32	vB99	
389	K5_III	2.22	0.06	0.08	0.01	6.62	5.23	-9.99	-9.99	-9.99	1.93	1.89	1.76	vB99	
402	K0_III	2.08	0.03	0.10	0.03	4.65	3.59	2.83	2.27	1.84	1.18	1.06	0.98	KTFS04	
424	F7_Ib-II	3.28	0.02	0.02	0.01	2.62	2.03	1.53	1.22	-9.99	0.52	0.50	0.50	Nord99, 3	
437	G7_IIa	2.64	0.11	0.08	0.06	4.59	3.62	2.90	2.40	2.03	1.43	-9.99	-9.99	Nord99	
442	G9_IIIb	1.64	0.10	0.18	0.06	5.72	4.72	3.95	3.43	-9.99	2.33	2.30	2.24	Nord99	
450	M2_III	2.42	0.05	0.29	0.01	7.42	5.89	-9.99	-9.99	-9.99	1.85	1.70	1.57	vB99	
464	K3_III	3.76	0.07	0.08	0.01	4.85	3.57	2.61	1.96	1.53	0.79	0.68	0.64	Nord99	
489	K3_IIIb	2.81	0.03	0.09	0.07	5.80	4.44	3.38	2.67	2.13	1.24	1.16	1.10	Nord99	
564	M2_III	2.96	0.06	0.17	0.01	7.42	5.82	-9.99	-9.99	-9.99	1.50	1.28	1.19	vB99	
603	K3_IIb	7.84	0.07	0.27	0.16	3.31	2.10	1.16	0.48	0.02	-0.81	-0.95	-1.01	MAH03	
617	K2_III_SB	6.88	0.04	0.00	0.01	3.15	2.00	1.16	0.54	0.10	-0.64	-0.70	-0.83	Nord99	
631	M3_III	3.75	0.11	0.37	0.01	7.35	5.70	4.83	3.49	2.09	0.93	0.69	0.63	vB99, 14	
643	K4_III	2.91	0.05	0.16	0.05	6.30	4.82	-9.99	-9.99	-9.99	1.29	1.21	1.09	MAH03	
681	M7_IIIe	48.20	0.60	0.10	0.07	4.46	3.04	1.03	-0.87	-1.96	-3.07	-5.19	-5.94	WDH00	eliminated: $m_{12} - m_{25}$
736	K5_III	2.60	0.11	0.12	0.07	6.62	5.15	-9.99	-9.99	-9.99	1.66	1.49	1.45	vB99	
753	K3_V	0.94	0.07	0.01	0.01	6.81	5.83	5.01	4.49	4.07	3.45	-9.99	-9.99	KTFS04, 19	
824	K1.5_III	1.88	0.11	0.05	0.03	5.63	4.52	3.72	3.14	2.70	2.02	1.98	1.92	Nord99	
834	K3_Ib	5.38	0.05	0.92	0.35	5.48	3.79	2.56	1.67	1.05	0.09	-0.11	-0.11	MAH03	
843	K5_III	4.06	0.04	0.12	0.08	6.09	4.53	3.32	2.37	1.76	0.78	0.64	0.60	MAH03	
867	M6_III	10.30	0.21	0.10	0.01	7.44	5.93	3.51	1.34	0.24	-1.05	-1.39	-1.49	WF87	
882	K2_III	2.08	0.07	0.10	0.06	6.17	4.93	4.05	3.41	-9.99	2.09	1.98	1.99	vB99	
911	M1.5_III	13.23	0.16	0.06	0.05	4.17	2.53	1.18	0.02	-0.56	-1.64	-1.89	-1.92	MJS91	
921	M4_II	16.56	0.17	0.09	0.06	5.04	3.39	1.59	-0.03	-0.78	-1.93	-2.19	-2.30	MAH03	
951	K2_III	1.87	0.13	0.01	0.01	5.40	4.37	3.60	3.09	2.69	2.08	1.97	1.94	Nord99	
1017	F5_Iab	3.10	0.02	0.32	0.07	2.27	1.79	1.34	1.01	0.87	0.56	0.44	0.37	Nord99	
1084	K2_V	2.15	0.03	0.00	0.01	4.61	3.73	3.01	2.54	2.24	1.70	1.59	1.39	KTFS04	
1136	K0_IV	2.39	0.03	0.01	0.01	4.46	3.54	2.82	2.32	1.96	1.40	1.36	1.38	KTFS04	
1231	M1_III	9.33	0.17	0.17	0.02	4.54	2.94	1.68	0.68	0.13	-0.88	-1.07	-1.14	MAH03	
1256	K0_III	1.69	0.08	0.08	0.03	5.44	4.37	3.58	3.05	2.63	1.97	-9.99	-9.99	Nord99	
1318	K3_III	1.74	0.03	0.16	0.02	6.04	4.86	4.01	3.44	2.94	2.23	2.16	2.09	KNB03	
1325	K1_V	1.65	0.06	0.02	0.01	5.25	4.43	3.74	3.29	2.95	2.40	-9.99	-9.99	KTFS04	
1326	M1.5_V	1.00	0.05	0.01	0.01	9.63	8.07	6.72	5.53	4.85	4.01	-9.99	-9.99	KTFS04, 19	
1343	G8_III	1.44	0.13	0.45	0.23	5.87	4.93	-9.99	-9.99	-9.99	2.76	-9.99	-9.99	vB99	
1373	K0_III	2.29	0.03	0.06	0.03	4.75	3.76	3.03	2.56	2.23	1.64	1.52	1.58	Nord01	
1409	G9.5_III	2.67	0.03	0.06	0.03	4.55	3.54	2.81	2.31	1.94	1.33	1.26	1.19	MAH03	
1457	K5_III	21.10	0.21	0.03	0.02	2.40	0.86	-0.37	-1.31	-1.84	-2.81	-3.08	-3.02	MAH03	
1533	K4_III	2.93	0.08	0.33	0.12	6.31	4.88	3.80	2.95	-9.99	1.46	1.29	1.23	vB99, 8	
1551	K3_III	2.79	0.06	0.35	0.13	6.18	4.77	3.68	2.90	-9.99	1.48	1.25	1.01	vB99	
1577	K3_II	7.50	0.08	0.95	0.48	4.22	2.69	1.63	0.81	0.27	-0.63	-0.82	-0.84	MAH03	
1601	K2_II	2.78	0.06	0.51	0.21	5.89	4.49	3.44	2.74	-9.99	1.41	1.26	1.22	MAH03	
1605	A8_Iab	2.17	0.03	1.07	0.40	3.53	2.99	2.47	2.02	1.82	1.46	1.62	1.33	Nord01	
1713	B8_Iab	2.55	0.05	0.20	0.09	0.10	0.13	0.13	0.14	0.22	0.20	-0.01	-0.13	HBD74	
1739	G8_III	1.42	0.13	0.24	0.12	5.84	4.90	-9.99	-9.99	-9.99	2.89	2.75	2.70	vB99	
1791	B7_III	1.59	0.11	0.07	0.02	1.52	1.65	1.66	1.76	1.97	2.05	-9.99	-9.99	vB99	
1845	M2_Iab	10.00	0.30	0.89	0.45	6.41	4.35	2.59	1.14	0.32	-1.25	-1.37	-1.72	WF87	eliminated: $m_{12} - m_{25}$
1865	F0_Ib	1.77	0.09	0.15	0.01	2.77	2.57	2.35	2.14	2.05	1.87	1.76	1.74	Nord99	
1995	G8_III	1.97	0.08	0.07	0.02	5.47	4.53	3.80	3.31	2.92	2.34	-9.99	-9.99	vB99	
2012	G9.5_III	2.79	0.06	0.07	0.02	5.11	3.97	3.15	2.59	2.18	1.51	1.36	1.39	vB99	
2061	M1_Iab	45.20	0.20	0.10	0.01	2.29	0.40	-1.19	-2.37	-2.93	-4.01	-5.14	-5.66	Dea96	eliminated: $m_{12} - m_{25}$

Table 1. Contiued

ID	Type	θ	σ_θ	$A_{\rm V}$	$\sigma_{\rm A_V}$	B	V	R	I	J	K	[12]	[25]	References	Remarks
2091	M3_II	9.56	0.10	0.48	0.11	5.97	4.25	2.56	1.08	0.30	-0.85	-1.05	-1.16	MAH03	
2189	M1_III	2.94	0.06	0.30	0.09	7.44	5.78	-9.99	-9.99	-9.99	1.47	1.30	1.23	vB99	
2216	M3_III	11.79	0.12	0.18	0.05	4.89	3.28	1.79	0.48	-0.23	-1.31	-1.67	-1.74	MAH03	
2219	G8.5_IIIb	2.16	0.09	0.05	0.03	5.36	4.35	3.55	3.01	2.59	1.94	1.72	1.82	vB99	
2286	M3_III	15.12	0.15	0.12	0.04	4.51	2.87	1.30	-0.08	-0.73	-1.85	-2.18	-2.22	MAH03	
2421	A0_IV	1.38	0.09	0.03	0.02	1.92	1.92	1.86	1.87	1.90	1.90	-9.99	-9.99	KTFS04	
2473	G8_Ib	4.73	0.03	0.23	0.07	4.38	2.98	2.02	1.41	0.99	0.22	0.01	0.03	Nord99	
2491	A1_V	6.01	0.02	0.00	0.01	-1.46	-1.46	-1.46	-1.43	-1.34	-1.31	-1.36	-1.38	KTFS04	
2630	G5_Ib-II	1.50	0.21	0.32	0.09	6.13	5.18	-9.99	-9.99	-9.99	3.40	3.00	2.82	vB99, 16	
2696	K4_Iab	2.92	0.10	0.07	0.03	6.37	4.93	3.84	3.07	-9.99	1.51	1.41	1.36	vB99, 8	
2805	K0_IIIa	1.94	0.17	0.10	0.04	6.46	5.22	4.40	3.80	3.10	2.49	2.38	2.36	vB99, 8, 11	
2943	F5_IV-V	5.49	0.04	0.00	0.01	0.79	0.37	-0.05	-0.28	-0.40	-0.64	-0.71	-0.72	KTFS04	
2973	K1_III_SB	2.31	0.05	0.00	0.01	5.41	4.29	3.37	2.79	2.35	1.65	1.30	1.46	Nord99	
2990	K0_IIIb	7.98	0.08	0.00	0.01	2.14	1.14	0.39	-0.11	-0.49	-1.11	-1.21	-1.19	MAH03	
3249	K4_III	5.03	0.04	0.00	0.01	5.01	3.53	2.41	1.63	1.07	0.14	0.03	-0.08	Nord99	
3547	G9_II-III	3.18	0.09	0.03	0.02	4.10	3.10	2.39	1.90	1.48	0.87	0.80	0.76	Nord01	
3576	M3_III	5.64	0.14	0.00	0.01	6.29	4.76	3.29	2.03	1.33	0.29	0.07	0.01	MAH03	
3705	K7_III	7.54	0.08	0.00	0.01	4.68	3.13	1.90	1.00	0.39	-0.61	-0.82	-0.79	MAH03	
3748	K2_III	9.73	0.10	0.07	0.01	3.42	1.97	0.93	0.16	-0.33	-1.19	-1.46	-1.37	MAH03	
3873	G1_III	2.60	0.05	0.03	0.01	3.79	2.98	2.33	1.93	1.63	1.15	0.96	1.03	Nord01	
3950	M2_III	4.62	0.06	0.02	0.01	6.30	4.70	3.27	2.19	1.54	0.50	0.33	0.26	Nord99	
3980	K4_III	3.33	0.04	0.04	0.01	5.82	4.37	3.24	2.47	1.91	1.04	0.92	0.90	Nord99	
4050	K3_IIa	5.18	0.05	0.14	0.07	4.89	3.36	2.26	1.50	-9.99	0.03	-0.17	-0.18	KNB03, 20	
4069	M0_III_SB	8.54	0.09	0.09	0.09	4.64	3.05	1.77	0.81	0.09	-0.88	-0.98	-1.07	MAH03	
4247	K0_III	2.54	0.03	0.03	0.02	4.87	3.83	3.00	2.46	2.07	1.39	1.28	1.28	Nord99	
4301	K0_Iab_SB	7.11	0.10	0.00	0.01	2.86	1.79	0.98	0.40	0.05	-0.65	-0.80	-0.81	Nord01	
4335	K1_III	4.12	0.04	0.05	0.04	4.15	3.01	2.17	1.60	1.16	0.44	0.30	0.27	MAH03	
4377	K3_III_SB	4.76	0.05	0.05	0.03	4.89	3.49	2.43	1.73	1.18	0.31	0.15	0.15	MAH03	
4432	K3.5_III	3.21	0.03	0.02	0.01	6.31	4.55	3.40	2.52	2.10	1.16	1.08	0.99	Nord99, 4, 5	
4434	M0_III	6.43	0.07	0.00	0.01	5.47	3.85	2.54	1.55	0.87	-0.14	-0.31	-0.42	MAH03	
4517	M1_III	6.26	0.10	0.04	0.02	5.54	4.04	2.78	1.77	1.12	0.09	-0.05	-0.15	Nord01	
4518	K0.5_IIIb	3.23	0.02	0.06	0.04	4.90	3.72	2.84	2.24	1.72	0.95	0.82	0.76	Nord99	
4534	A3_V	1.45	0.03	0.01	0.01	2.22	2.14	2.08	2.06	2.03	1.99	1.92	1.63	KTFS04	
4546	K3_III	2.94	0.03	0.18	0.02	5.76	4.46	3.52	2.85	2.36	1.56	1.44	1.41	KNB03	
4853	B0.5_IV	0.72	0.02	0.16	0.06	1.02	1.25	1.38	1.64	1.80	1.99	-9.99	-9.99	HBD74	
4910	M3_III	10.71	0.11	0.04	0.01	4.97	3.38	1.85	0.52	-0.17	-1.25	-1.49	-1.57	MAH03	
4932	G8_III	3.17	0.03	0.02	0.01	3.78	2.84	2.20	1.75	1.36	0.80	0.70	0.61	Nord99	
5200	K5.5_III	4.72	0.05	0.03	0.01	5.59	4.07	2.87	2.00	1.35	0.37	0.22	0.20	Nord99	
5215	M2_III	2.50	0.05	0.10	0.05	7.49	5.87	-9.99	-9.99	2.72	1.67	1.66	1.52	vB99, 9	
5235	G0_IB	2.27	0.03	0.01	0.01	3.26	2.68	2.24	1.95	1.70	1.37	1.23	1.25	KTFS04	
5299	M4.5_III	7.85	0.11	0.10	0.05	6.86	5.28	3.43	1.77	0.86	-0.29	-0.57	-0.73	Wea01	
5340	K1.5_III	21.00	0.20	0.01	0.01	1.18	-0.05	-1.02	-1.67	-2.08	-2.95	-3.22	-3.09	QMB96	
5429	K3_III	3.80	0.12	0.05	0.04	4.89	3.59	2.67	2.02	1.46	0.66	0.50	0.48	vB99	
5459	G2_V	8.51	0.02	0.00	0.01	0.72	0.01	-9.90	-9.90	-1.15	-1.38	-1.83	-1.83	KTFS04, 21	
5460	K1_V	6.01	0.03	0.00	0.01	2.21	1.33	-9.90	-9.90	-0.01	-0.60	-9.99	-9.99	KTFS04, 21	
5510	M1_III	2.07	0.05	0.10	0.07	7.86	6.28	-9.99	-9.99	3.07	2.05	1.96	1.87	vB99, 9	
5563	K4_III	10.30	0.10	0.00	0.01	3.55	2.08	0.97	0.21	-0.45	-1.39	-1.48	-1.51	MAH03, 9	
5568	K4_V	1.23	0.03	0.02	0.01	6.82	5.71	4.72	4.18	3.84	3.06	2.49	2.61	KTFS04	
5589	M4.5_III	10.59	0.17	0.06	0.01	6.18	4.59	2.73	1.02	0.22	-0.95	-1.21	-1.35	MAH03	
5602	G8_III	2.47	0.04	0.06	0.04	4.47	3.50	2.85	2.41	1.93	1.34	1.27	1.26	Nord01	
5638	K2_III	1.44	0.06	0.05	0.01	6.92	5.68	4.71	4.10	-9.99	2.67	2.58	2.58	Nord01	
5681	G8_III	2.76	0.03	0.04	0.01	4.44	3.49	2.76	2.25	1.87	1.22	1.14	1.04	MAH03	
5709	K0_III	1.18	0.07	0.05	0.01	6.53	5.51	-9.99	-9.99	-9.99	3.13	3.02	2.96	vB99	
5745	M1_III	2.42	0.05	0.05	0.01	7.64	6.02	-9.99	-9.99	2.84	1.76	1.72	1.59	vB99, 9	
5854	K2_III	4.85	0.05	0.06	0.05	3.81	2.64	1.83	1.27	0.76	0.07	0.00	-0.04	MAH03	
6056	M0.5_III	10.47	0.12	0.14	0.11	4.34	2.75	1.46	0.43	-0.20	-1.22	-1.41	-1.49	MAH03	
6107	M2_III	3.68	0.10	0.10	0.03	6.80	5.20	-9.99	-9.99	1.92	0.84	0.72	0.66	vB99, 9	
6132	G8_III_SB	3.68	0.05	0.03	0.01	3.65	2.74	2.13	1.67	1.17	0.59	0.54	0.49	Nord01	
6134	M1.5_Ib	39.76	0.40	0.73	0.27	2.75	0.91	-0.64	-1.87	-2.74	-3.79	-4.73	-4.65	MAH03, 4, 21	
6146	M6_III	19.09	0.19	0.10	0.03	6.58	5.05	2.51	0.28	-0.70	-1.97	-2.57	-2.99	MAH03	eliminated: $m_{12} - m_{25}$
6148	G7_IIIa_SB	3.46	0.04	0.05	0.03	3.71	2.77	2.13	1.66	1.21	0.60	0.56	0.54	MAH03	
6208	K2_III	1.24	0.06	0.07	0.04	7.38	6.06	-9.99	-9.99	-9.99	2.94	2.83	2.83	vB99	L.C. based on $M_{\rm V}$
6212	G0_IV_SB	2.27	0.03	0.02	0.01	3.46	2.81	2.30	1.98	1.70	1.30	1.22	1.19	KTFS04	

Table 1. Contiued

ID	Type	θ	σ_θ	$A_{\rm V}$	$\sigma_{A_{\rm V}}$	B	V	R	I	J	K	[12]	[25]	References	Remarks
6220	G7.5_III	2.62	0.03	0.05	0.02	4.42	3.50	2.83	2.35	1.98	1.35	1.27	1.24	MAH03	
6258	M1_III	2.32	0.06	0.10	0.03	7.31	5.72	-9.99	-9.99	2.82	1.78	1.59	1.64	vB99, 9	
6406	M5_Ib-II	36.03	0.44	0.69	0.20	4.92	3.48	-9.99	-9.99	-2.30	-3.47	-3.92	-4.14	MAH03	
6418	K3_Iab	5.20	0.03	0.10	0.03	4.60	3.16	2.20	1.48	0.85	-0.02	-0.18	-0.20	Nord99	
6536	G2_Iab	3.22	0.05	0.10	0.03	3.78	2.78	2.10	1.62	1.29	0.77	0.53	0.59	MAH03	
6584	M2_III	2.26	0.05	0.17	0.01	7.61	6.03	-9.99	-9.99	2.89	1.81	1.68	1.67	vB99, 9	
6623	G5_IV	1.93	0.03	0.01	0.01	4.17	3.42	2.89	2.51	2.18	1.77	-9.99	-9.99	KTFS04	
6695	K1_IIaCN	3.17	0.03	0.11	0.01	5.22	3.87	2.97	2.34	1.83	1.03	0.87	0.89	MAH03	
6705	K5_III	9.86	0.13	0.03	0.01	3.74	2.22	1.08	0.23	-0.39	-1.24	-1.44	-1.50	MAH03	
6820	K4_III	1.54	0.06	0.32	0.02	7.59	6.12	-9.99	-9.99	-9.99	2.63	2.49	2.41	vB99	
7001	A0_V	3.28	0.01	0.01	0.01	0.03	0.03	0.07	0.10	0.02	0.02	-0.01	-0.16	Cea01	
7139	M4_II	11.53	0.16	0.11	0.01	5.97	4.30	2.52	0.89	-0.02	-1.23	-1.45	-1.68	MAH03	
7157	M5_III	18.02	0.22	0.07	0.01	5.66	4.08	2.04	0.13	-0.85	-2.07	-2.39	-2.54	MAH03	
7176	K1_III	1.99	0.11	0.10	0.03	5.10	4.02	3.26	2.74	2.33	1.69	-9.99	-9.99	Nord99	
7193	K1_III	2.42	0.01	0.19	0.07	5.11	4.02	3.23	2.69	2.23	1.44	1.43	1.42	Aea01	
7237	M0_III	2.27	0.05	0.16	0.01	7.14	5.59	-9.99	-9.99	2.79	1.78	1.79	1.67	vB99, 9	
7238	M2_III	2.40	0.05	0.19	0.01	7.61	6.06	-9.99	-9.99	2.80	1.70	1.64	1.50	vB99, 9	
7310	G9_III	3.25	0.05	0.01	0.01	4.07	3.07	2.37	1.86	1.43	0.80	0.72	0.66	MAH03	
7314	K0_III	2.23	0.09	0.19	0.01	5.62	4.37	3.50	2.91	2.37	1.66	-9.99	-9.99	Nord99	
7328	G9_III	2.07	0.09	0.01	0.01	4.73	3.76	3.12	2.66	2.25	1.67	1.55	1.52	Nord99	
7405	M0_III	4.46	0.05	0.12	0.04	5.95	4.45	3.24	2.27	1.55	0.55	0.38	0.33	MAH03	
7417	K3_II	4.83	0.05	0.20	0.08	4.21	3.08	2.21	1.55	1.01	0.16	0.03	-0.06	MAH03	
7517	G7_III	1.18	0.06	0.04	0.04	5.86	4.90	-9.99	-9.99	-9.99	2.73	2.66	2.78	vB99	
7525	K3_II	7.08	0.05	0.23	0.06	4.24	2.72	1.65	0.90	0.30	-0.59	-0.68	-0.81	Nord99	
7536	M2_II	9.15	0.12	0.18	0.06	5.24	3.83	2.39	1.10	0.37	-0.79	-0.99	-1.08	MAH03	
7557	A7_V	3.46	0.04	0.01	0.01	0.98	0.76	0.62	0.48	0.39	0.26	0.24	0.18	MAH03	
7570	F6_Iab_SB	1.73	0.05	0.62	0.15	4.73	3.86	3.27	2.83	2.45	1.98	1.89	1.87	Nord99, 1, 6	
7602	G8_IV	2.18	0.09	0.02	0.01	4.58	3.72	3.06	2.57	2.26	1.71	1.65	1.60	Nord99	
7635	M0_III	6.22	0.06	0.06	0.01	5.04	3.47	2.27	1.35	0.79	-0.16	-0.39	-0.42	MAH03	
7735	K2_II_SB	4.36	0.04	1.04	0.36	5.08	3.80	2.83	2.07	1.41	0.49	0.38	0.18	MAH03	
7751	K3_Ib_SB	5.42	0.05	0.26	0.09	5.50	3.98	2.78	1.86	1.19	0.16	-0.04	-0.09	MAH03	
7759	K5_Iab	1.19	0.06	0.64	0.23	6.90	5.25	4.07	3.20	-9.99	1.45	1.39	1.36	vB99, 2	
7796	F8_Iab	3.02	0.03	0.94	0.34	2.90	2.23	1.74	1.40	1.16	0.72	0.67	-9.99	MAH03	
7806	K3_III	2.99	0.08	0.17	0.06	5.77	4.44	3.43	2.76	2.29	1.44	1.26	1.26	vB99	
7834	F5_Iab	1.43	0.08	0.26	0.12	4.42	4.02	3.66	3.43	3.21	2.94	2.83	2.85	vB99, 13	
7847	F5_Iab	1.23	0.14	0.97	0.35	7.19	6.18	5.33	4.64	4.17	3.54	3.26	2.18	vB99	
7924	A2_Ia	2.42	0.06	1.39	0.63	1.34	1.25	1.14	1.04	1.00	0.89	-9.99	-9.99	MAH03	
7942	G9.5_III	2.35	0.05	0.08	0.04	5.29	4.23	3.46	2.93	2.56	1.87	1.68	1.65	vB99	
7949	K0_III	4.62	0.04	0.03	0.02	3.49	2.46	1.73	1.19	0.77	0.11	-0.04	-0.01	MJS91	
7957	K0_IV	2.67	0.04	0.06	0.03	4.35	3.43	2.76	2.27	1.90	1.28	1.12	1.16	KTFS04	
7995	G7_III	1.54	0.29	0.09	0.04	5.43	4.61	3.93	3.47	3.11	2.63	2.57	2.57	vB99, 17	
8008	K4_III	2.46	0.05	0.25	0.12	6.50	5.02	-9.99	-9.99	2.47	1.58	1.54	1.47	vB99, 9	
8044	M3_III	3.33	0.08	0.11	0.03	7.26	5.65	-9.99	-9.99	-9.99	1.21	1.11	0.96	vB99	
8079	K4.5_Ib_SB	5.56	0.04	0.53	0.24	5.35	3.70	2.50	1.60	1.00	-0.05	-9.99	-9.99	Nord99	
8115	G8_III	2.82	0.03	0.06	0.03	4.19	3.20	2.50	2.02	1.65	1.09	1.03	0.94	MAH03	
8225	M1_III	4.52	0.05	0.08	0.02	6.19	4.57	3.32	2.23	1.54	0.51	0.37	0.33	MAH03, 14	
8252	G8_III	1.82	0.10	0.09	0.03	4.91	4.02	3.31	2.81	2.55	1.97	-9.99	-9.99	Nord99	
8306	M2_III	3.24	0.07	0.07	0.05	7.09	5.49	-9.99	-9.99	-9.99	1.31	1.11	1.09	vB99	
8308	K2_Ib	7.54	0.14	0.13	0.10	3.91	2.39	1.34	0.58	0.03	-0.81	-1.01	-1.05	Nord01	
8316	M2_Iae	20.58	0.48	2.00	0.70	6.43	4.17	2.07	0.31	-0.52	-1.65	-3.75	-4.52	MAH03	eliminated: $m_{12}-m_{25}$
8387	K4.5_V	1.89	0.02	0.01	0.01	5.74	4.69	3.80	3.25	2.83	2.18	-9.99	-9.99	KTFS04	
8414	G2_Ib	3.08	0.03	0.15	0.03	3.90	2.93	2.27	1.80	1.48	0.96	0.82	0.84	Nord99	
8465	K1.5Ib_SB	5.23	0.05	0.69	0.24	4.90	3.35	2.27	1.49	0.97	0.11	0.07	-0.14	MAH03	
8538	G8.5_III	1.92	0.02	0.17	0.06	5.46	4.44	3.69	3.12	2.69	2.07	1.88	1.86	Nord99	
8555	K2_II	1.52	0.06	0.15	0.08	7.43	5.98	-9.99	-9.99	-9.99	2.62	2.47	2.38	vB99	L.C. based on $M_{\rm V}$
8571	F5_Iab	1.52	0.02	0.91	0.32	4.35	3.70	-9.99	2.95	2.69	2.31	2.23	2.02	Nord99, 17	
8621	M4_III	7.39	0.12	0.42	0.15	6.67	5.09	-9.99	-9.99	-9.99	-0.22	-0.39	-0.52	Wea01	
8632	K2_III	2.63	0.05	0.15	0.05	5.79	4.46	3.54	2.86	2.36	1.51	1.40	1.26	Nord99	
8650	G2_III_SB	3.26	0.07	0.04	0.02	3.81	2.95	2.31	1.83	1.46	0.93	0.78	0.80	Nord01	
8667	G8_III	2.39	0.05	0.09	0.07	5.02	3.94	3.18	2.67	2.25	1.65	1.53	1.50	MAH03	
8684	G8_III	2.50	0.04	0.06	0.01	4.42	3.48	2.80	2.33	2.01	1.43	1.32	1.31	MAH03	
8698	M2_III	8.19	0.10	0.07	0.02	5.44	3.79	2.37	1.18	0.43	-0.70	-9.99	-9.99	MAH03	
8728	A3_V	2.23	0.02	0.02	0.01	1.25	1.16	1.10	1.08	1.02	0.97	-9.99	-9.99	KTFS04	

Table 1. Contiued

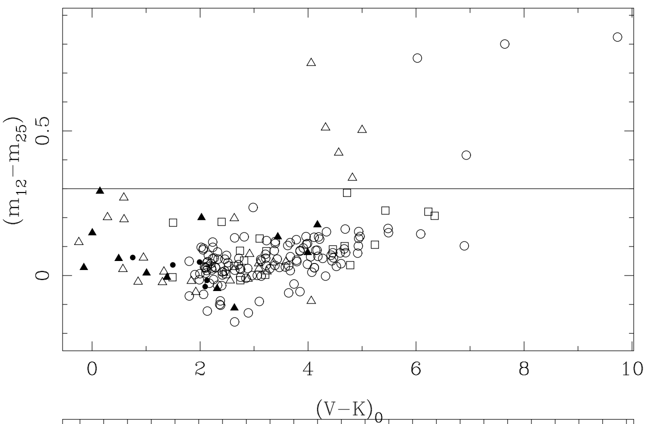
ID	Type	θ	σ_θ	$A_{\rm V}$	$\sigma_{A_{\rm V}}$	B	V	R	I	J	K	[12]	[25]	References	Remarks
8775	M3_II-III	17.98	0.18	0.03	0.02	4.15	2.50	0.93	-0.38	-1.04	-2.20	-2.44	-2.53	MJS91	
8796	K0_Iab_SB	2.34	0.05	0.15	0.03	6.12	4.77	3.80	3.12	-9.99	1.72	1.62	1.54	MAH03	
8923	G7_III	1.61	0.17	0.07	0.02	5.50	4.56	3.82	3.37	3.00	2.44	2.35	2.25	Nord99	
8930	G8_III	1.79	0.07	0.13	0.08	6.24	5.22	-9.99	-9.99	-9.99	2.73	2.60	2.69	vB99	
8942	M3_III	3.70	0.10	0.15	0.03	7.79	6.06	-9.99	-9.99	-9.99	0.99	0.80	0.65	vB99	
8953	M1_III	2.53	0.05	0.15	0.03	8.18	6.45	-9.99	-9.99	-9.99	1.86	1.74	1.66	vB99	
8961	G8_III	2.66	0.08	0.05	0.02	4.84	3.82	3.04	2.47	1.97	1.32	1.19	1.17	Nord99	
8974	K1_V	3.24	0.03	0.01	0.01	4.24	3.21	2.46	1.95	-9.99	0.89	0.74	0.79	Nord99	
9035	M2_III	2.46	0.05	0.15	0.03	7.71	6.11	-9.99	-9.99	-9.99	2.01	1.78	1.67	vB99	
9045	G2_Ia	2.47	0.05	2.47	0.89	5.85	4.49	3.63	2.89	2.59	2.03	0.77	0.53	Nord99	
9055	M2_III	2.41	0.05	0.15	0.03	7.75	6.15	-9.99	-9.99	-9.99	1.96	1.78	-9.99	vB99, 12	
551	M5.5_V	1.05	0.08	0.00	0.01	13.02	11.05	8.68	6.42	5.33	4.37	3.89	4.25	KTFS04	GJ 551
555	M4_III	8.66	0.20	0.10	0.03	6.00	4.41	2.68	1.17	0.52	-0.64	-0.84	-0.98	WAK04, 21	GJ 555
887	M0.5_V	1.39	0.04	0.01	0.01	8.82	7.36	-9.90	-9.90	4.20	3.36	3.02	2.94	KTFS04	GJ 887
33793	M1_V	0.69	0.06	0.01	0.01	10.40	8.55	-9.90	-9.90	5.77	5.05	4.66	-9.99	KTFS04	HD 33793
36395	M1.5_V	1.15	0.11	0.01	0.01	9.44	7.97	6.53	5.39	4.72	3.82	3.60	3.79	KTFS04	HD 36395
87937	M4_V	1.00	0.04	0.00	0.01	11.28	9.54	7.71	6.03	5.45	4.53	3.90	-9.99	KTFS04	HIP 87937
88230	K7_V	1.29	0.04	0.00	0.01	7.94	6.59	5.36	4.56	3.97	3.15	3.11	2.98	KTFS04	HD 88230
95735	M2_V	1.44	0.03	0.01	0.01	9.00	7.49	5.99	4.80	4.10	3.31	3.04	2.86	KTFS04	HD 95735
+20092	M2_III	2.41	0.07	2.31	1.16	10.26	8.47	-9.99	-9.99	3.28	2.11	1.81	1.78	vB99, 18	
+20282	M5_II-III	10.00	0.30	0.05	0.01	7.97	6.65	-9.99	-9.99	0.20	-1.04	-1.66	-2.46	Dea96, 15, 18	eliminated: $m_{12} - m_{25}$
+30086	M3_III	2.41	0.05	2.31	1.16	9.51	7.75	-9.99	-9.99	3.19	2.09	1.83	1.69	vB99, 12, 18	
+30105	M2_III	2.87	0.06	1.78	0.89	8.16	6.38	-9.99	-9.99	-9.99	1.59	1.39	1.33	vB99	
+30115	M1.5_Ia	3.11	0.07	1.19	0.34	9.55	7.35	-9.99	-9.99	-9.99	1.74	1.23	0.78	vB99	eliminated: $m_{12} - m_{25}$
+30257	M7.5_III	18.80	0.50	0.10	0.07	9.24	7.97	-9.99	-9.99	-9.99	-1.85	-3.29	-4.11	Dea96, 18	eliminated: $m_{12} - m_{25}$
+30309	M1_II	2.95	0.06	0.26	0.02	8.01	6.42	4.84	3.42	-9.99	1.41	1.19	1.15	vB99	
+30412	M3_Ib	2.91	0.06	1.50	0.55	10.21	7.99	5.83	4.06	3.06	1.67	1.25	0.72	vB99	eliminated: $m_{12} - m_{25}$
+30438	M5_II	2.54	0.06	0.84	0.38	11.07	9.30	-9.99	-9.99	-9.99	2.33	1.93	1.70	vB99	
+30465	M3_III	2.21	0.05	0.31	0.14	8.53	6.89	-9.99	-9.99	-9.99	2.09	1.81	1.78	vB99, 18	
+30468	M2_III	2.14	0.05	0.29	0.13	8.91	7.10	-9.99	-9.99	3.37	2.15	1.91	1.82	vB99, 10, 18	
+40018	M3_III	2.39	0.09	0.24	0.08	8.77	7.08	-9.99	-9.99	-9.99	2.18	1.96	1.80	vB99	
+40022	M4_III	2.49	0.05	0.24	0.08	8.61	7.00	-9.99	-9.99	-9.99	1.87	1.76	1.68	vB99	
+40254	K5_III	1.57	0.07	0.10	0.05	8.50	6.90	-9.99	-9.99	-9.99	2.85	2.76	2.62	vB99	
+40337	K5_II	1.34	0.06	0.20	0.19	9.40	7.76	-9.99	-9.99	-9.99	2.86	2.88	2.59	vB99	L.C. based on $M_{\rm V}$
Sun	G2_V	1919260.	(1919.)	0.00	0.00	-26.12	-26.75	-27.12	-27.48	-27.86	-28.22	-9.99	-9.99	22	

References:
HBD74 = Hanbury Brown et al. (1974) WF87 = White & Feierman (1987) MJS91 = Mozurkewich et al. (1991) Dea96 = Dyck et al. (1996) QMB96 = Quirrenbach et al. (1996) Nord99 = Nordgren et al. (1999) vB99 = van Belle et al. (1999) WDH00 = Weiner et al. (2000) Aea01 = Armstrong et al. (2001) Cea01 = Ciardi et al. (2001) Nord01 = Nordgren et al. (2001) Wea01 = Wittkowski et al. (2001) MAH03 = Mozurkewich et al. (2003) KNB03 = Kervella et al. (2003) KTFS04 = Kervella et al. (2004) WAK04 = Wittkowski et al. (2004)
1 = Wisniewski & Johnson (1968) 2 = Fernie (1972) 3 = Gehrz & Hackwell (1974) 4 = Honeycutt et al. (1977) 5 = Barnes et al. (1978) 6 = Moffett & Barnes (1980) 7 = Scharlach & Craine (1980) 8 = Fernie (1983) 9 = McWilliam & Lambert (1984) 10 = Arevalo et al. (1988) 11 = Smith (1988) 12 = Noguchi (1989) 13 = Blackwell et al. (1990) 14 = Fluks et al. (1994) 15 = Kerschbaum (1995) 16 = Richichi et al. (1996) 17 = Barnes et al. (1997) 18 = Richichi & Percheron (2002) 19 = Morel & Magnenat (1978) 20 = Cohen et al. (1999) 21 = Ducati (2002) 22 = Colina et al. (1996)

based list of references was checked for papers that, based on the title alone, might contain additional photometry. For 43 stars only a K-mag from the IRC-survey is available, and it was investigated if there is a systematic difference between Johnson K and IRC K. Based on 66 objects (minus 3 outliers) a difference K(Johnson - IRC) = 0.017 $\pm$ 0.045 was established, and therefore no correction to the IRC magnitudes was applied. It may appear attractive to include 2MASS photometry for all stars–for reasons of uniformity– or at least for those stars without infrared photometry sofar. However, the stars in the sample are so bright that no 2MASS photometry could be obtained in the standard way. Figure 2 shows for 119 stars with JK photometry on the Johnson system and 2MASS photometry with a quoted errorbar in both filters of less than 0.3 mag the correlation between $(J-K)_{\rm Johnson}$ and $(J-K)_{\rm 2MASS}$ and $K_{\rm Johnson} - K_{\rm 2MASS}$ and $(J-K)_{\rm 2MASS}$. The rms in the fits are about 0.1 mag, and so applying these relations would cause unwanted scatter, and therefore 2MASS data has not been used. It should be noted that some "natural" scatter is present in the adopted photometry because e.g. of non-simultaneous photometry or low level variability.

The finally adopted magnitudes are listed in Table 1, and are predominantly on the Johnson system. The IRAS flux densities were converted to magnitudes assuming zero points of 41.0 and 9.49 Jy at 12 and 25 μm respectively.

The reddening was estimated using the reddening model by Arenou et al. (1992), which returns the reddening estimate (with error) based on galactic coordinates and distance. The distance used was simply based on the HIPPARCOS parallax, and when no parallax was available a distance of 1 kpc was assigned. As discussed later, none of these assumptions is critical to the final results of this paper. The adopted values for $A_{\rm V}$ and its error are listed in Table 1. The relative reddening $A_\lambda/A_{\rm V}$ are adopted to be 1.33, 0.80, 0.49,



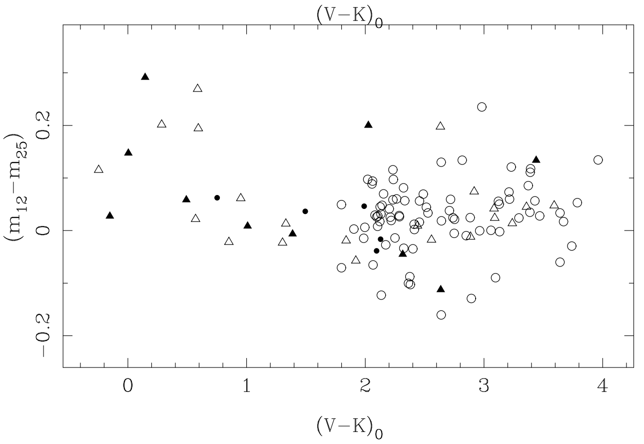


Figure 3. Top: $(m_{12} - m_{25})$ versus $(V - K)$ colour-colour relation. Symbols are giants (○, defined as luminosity class III objects), luminous giants (□, defined as luminosity class II objects), supergiants (△, defined as luminosity class I objects), sub-giants (●, defined as luminosity class IV objects) and dwarfs (filled triangle, defined as luminosity class V objects). The 5 supergiants and 4 giants with $(m_{12} - m_{25}) > 0.30$ are all of spectral type M. The line indicates the cut-off at $(m_{12} - m_{25}) = 0.30$. Below: as top panel, but without any star of spectral type M.

0.27, 0.12, 0.034 and 0.018 in $BRIJK$[12][25], respectively, following Draine (2003).

In what follows we will the use the following terminology: giants are objects which have "III" in their spectral type listed in Table 1 (i.e. includes stars with spectral type II-III), dwarfs are objects of luminosity class V, sub-giants are objects of luminosity class IV, supergiants are objects of luminosity class I, and luminous giants are objects of luminosity class II. Three objects have no luminosity class assigned in SIMBAD and for those the absolute V-magnitude and $(B - V)_0$ were determined from the parallax and reddening, and compared to the tables of Straižys & Kuriliene (1981) and Schmidt-Kaler (1982). Based on this, HR 6208 ($M_{\rm V} = 0.3 \pm 0.2$) was assigned luminosity class III, and HR 8555 ($M_{\rm V} = -1.5 \pm 0.4$) and IRC +40 337 ($M_{\rm V} = -1.6 \pm 0.8$) were assigned luminosity class II.

3 BASIC RELATIONS

A surface-brightness relation can be defined as follows (see van Belle 1999):

$$\theta_o = \theta \times 10^{(m_1/5)}, \tag{1}$$

where θ is the (limb-darkened) angular diameter (in mas), and m_1 a de-reddened magnitude (for example, V). The logarithm of this quantity is plotted against a de-reddened colour (for example, $(V - K)_0$),

$$\log \theta_0 = a \times (m_2 - m_3) + b, \tag{2}$$

and a linear fit is performed. An equivalent form is to use the quantity (see, e.g., Nord02)

$$F_{m_1} = 4.2207 - 0.1\, m_1 - 0.5 \log \theta, \tag{3}$$

and to plot this against a colour;

$$F_{m_1} = a' \times (m_2 - m_3) + b'. \tag{4}$$

The former mathematical formulation will be used in this paper, but it is trivial to show that,

$$a = -2\, a' \quad \text{and} \quad b = 2\,(4.2207 - b'). \tag{5}$$

In the analysis below, the error on θ_0 includes the error on θ, an arbitrary but representative error of 0.01 mag in the photometry, and the error on the reddening.

4 RESULTS

The assumption in the above relations is that, after correction for interstellar reddening, the colours represent the photospheric colours. As a large fraction of the stars among the sample of 221 are M giants (59) or supergiants (7) one might need to consider the influence of mass loss on the colours.

Figure 3 shows in the top panel the IRAS [12-25] colour versus $(V - K)$ with different luminosity classes indicated by different symbols for the 195 stars for which these four colours are available. The large majority of stars scatter around [12-25] ≈ 0, as expected, but for redder $(V - K)$ there are nine stars with a clear mid-IR excess. They are HR 681 (M7 IIIe), HR 1845 (M2 Iab), HR 2061 (M1 Iab), HR 6146 (M6 III), HR 8316 (M2 Iae), IRC +20282 (M5 II-III), IRC +30115 (M1.5 Ia), IRC +30257 (M7.5 III), IRC +30412 (M3 Ib), and are excluded in the fitting described below. For comparison, the lower panel of the figure presents the colour-colour diagram excluding all stars of spectral type M (giants and supergiants). Statistically, 9 of the 63 M-giants and supergiants in this sub-sample have a mid-IR excess. Of the 26 stars without V or K or IRAS photometry there are three additional M-stars, and therefore, statistically, none is expected to have an mid-IR excess.

Following the literature, the following SB relations are considered: V versus $(V - R)$, V versus $(V - K)$, and K versus $(J - K)$ (e.g. Fouqué & Gieren 1997). The results of the fitting are listed in Table 3 and shown in Figures 4-12. The table lists the values of the fitting coefficients a and b, the number of stars considered, the rms in the fit, the colour range over which the fit was performed, the luminosity class, and some additional remarks. In the bottom panel of all figures the residual is plotted against metallicity, and the fit is explicitly given when significant. The possible significance of this will be discussed in Section 5.

The fit was performed using a least-squares algorithm. Outliers were identified and removed, and the fit repeated. Outliers were again removed and the final fit made. An object was considered an outlier if the distance between a data point and the fitted line was more than 5 times either the error bar in the data point, or the rms in the fit. Table 3 also shows some results when the σ-clipping is more stringent. The rms in the fit are obviously reduced but not by much, and the coefficients change within their error bars.

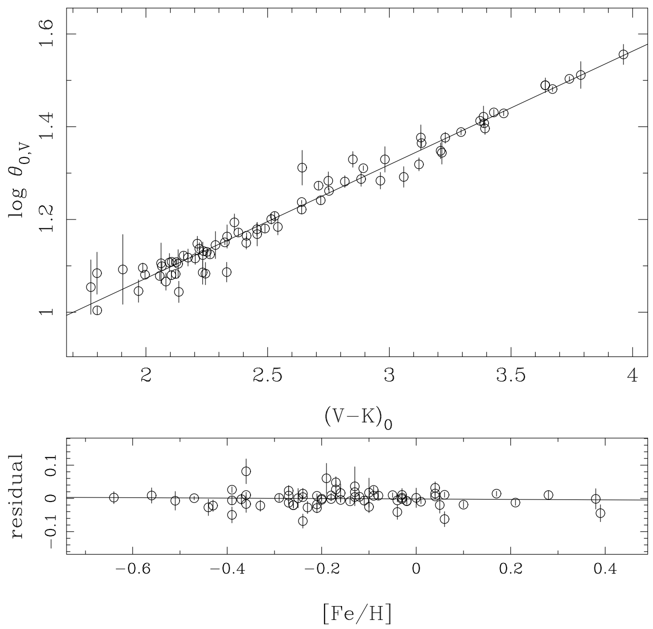


Figure 4. Preferred V-band surface-brightness relation versus colour $(V - K)_0$ for non-M giants. Symbols as in Figure 3. In the bottom panel the residuals are plotted versus metallicity.

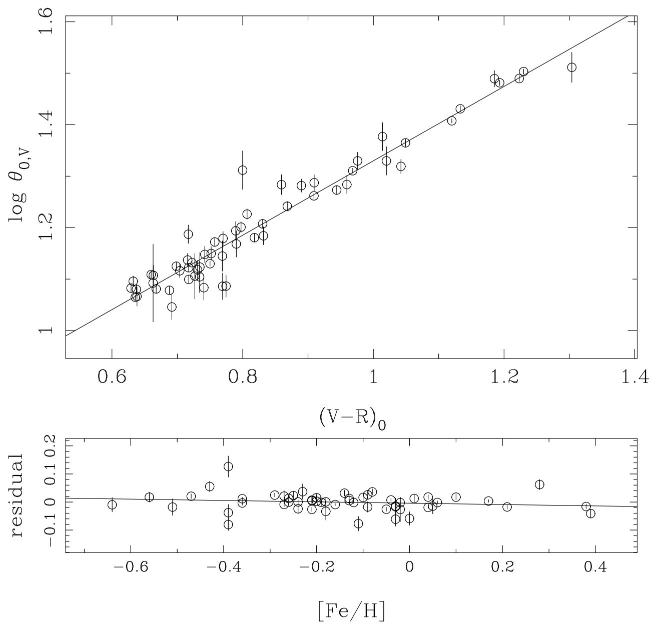


Figure 5. Preferred V-band surface-brightness relation versus colour $(V - R)_0$ for non-M giants. The residuals correlate at the 1σ level with metallicity: residual $= (-0.024 \pm 0.021)$ [Fe/H] + (-0.0041 ± 0.0050).

Table 3 also includes the result when not considering the M-giants. In that case the colour range over which the relation is applicable becomes smaller, but the relations might be more appropriate for Cepheids for which these relations are often used. The number of stars in the sample is reduced and hence the formal error on the coefficients becomes slightly larger. The rms in the fits are not appreciably reduced. Considering only the M-giants results in a relation which is significantly different from the relation for all giants, and all non-M giants, as suggested already by DB93.

To investigate the influence of reddening a set of 1000 Monte Carlo simulations was performed where each time the reddening was replaced by a value drawn from a Gaussian distribution with mean the adopted reddening and sigma the error therein. The 23rd and 977th ordered value correspond to $\pm 2\sigma$, and in the case of the giants (first entry in Table 3), the value and the error on a and b are (0.2368 $\pm$ 0.0005, 0.6080 $\pm$ 0.0012), (0.7279 $\pm$ 0.0011, 0.6076 $\pm$ 0.0010) and (0.1607 $\pm$ 0.0038, 0.5905 $\pm$ 0.0030), for the case V versus $(V - K)$, V versus $(V - R)$ and K versus $(J - K)$, respectively. The conclusion is that, formally, the influence of reddening is smallest in the case V versus $(V - K)$. However, in all three cases the error in the reddening is insignificant compared to the fit error.

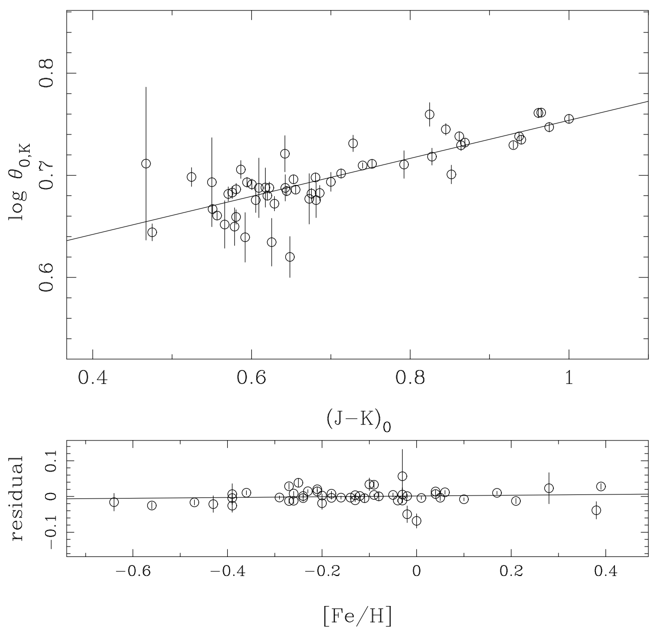


Figure 6. Preferred K-band surface-brightness relation versus colour $(J - K)_0$ for non-M giants.

5 DISCUSSION

Surface brightness relations have been derived for a large number of stars making use of the large datasets on angular diameter measurements for "normal" stars that have become available recently. In the present section the results will be discussed, and compared to earlier work. For convenience, SB relations reported in the literature have been compiled in Table 4 following the format of Table 3 (usually a' and b' are quoted, and they have been converted to a and b by me. The rms is the one quoted for the original fit–which therefore almost always refer to Eq. (4)–, and its value should be multiplied by a factor of 2 to compare to the rms values listed in Table 3 !)

Recently, Kervella et al. (2004) presented SB-relations for stars of luminosity class IV + V of the type m_1 versus $(m_1 - m_2)$ for all possible combinations for magnitudes $UBVRIJHKL$. The agreement is perfect in the case $V - (V - K)$ but this should not be surprising as essentially the same angular diameter and photometric data has been used. For the other 2 relations the fits not in good agreement. In those two cases the clipping at 4σ has removed a substantial number of objects in the present paper, while Kervella

Table 3. SB relations derived in this work. For the giants the solutions marked by a • are the preferred ones.

(m_1)	a	$(m_2 - m_3)$	b	N	rms	Range	Remark
V	0.237 ± 0.003	(V-K)	0.608 ± 0.009	122	0.027	1.7-5.0	giants, cut at 5σ
V	0.239 ± 0.002	(V-K)	0.597 ± 0.008	114	0.024	1.7-5.0	giants, cut at 4σ
V	0.236 ± 0.002	(V-K)	0.608 ± 0.007	99	0.020	1.7-5.0	giants, cut at 3σ
V	0.242 ± 0.006	(V-K)	0.595 ± 0.016	82	0.029	1.7-4.0	giants, no M-giants, cut at 5σ
• V	0.245 ± 0.005	(V-K)	0.584 ± 0.014	76	0.024	1.7-4.0	giants, no M-giants, cut at 4σ
V	0.241 ± 0.004	(V-K)	0.595 ± 0.012	70	0.020	1.7-4.0	giants, no M-giants, cut at 3σ
V	0.237 ± 0.007	(V-K)	0.610 ± 0.028	40	0.021	3.2-6.1	M-giants, cut at 4σ
V	0.728 ± 0.012	(V-R)	0.608 ± 0.012	75	0.031	0.6-1.8	giants
V	0.735 ± 0.011	(V-R)	0.601 ± 0.010	70	0.026	0.6-1.8	giants, cut at 4σ
V	0.724 ± 0.009	(V-R)	0.617 ± 0.009	60	0.020	0.6-1.8	giants, cut at 3σ
V	0.716 ± 0.022	(V-R)	0.613 ± 0.020	65	0.032	0.6-1.3	giants, no M-giants, cut at 5σ
• V	0.723 ± 0.025	(V-R)	0.607 ± 0.021	59	0.032	0.6-1.3	giants, no M-giants, cut at 4σ
V	0.730 ± 0.017	(V-R)	0.598 ± 0.015	47	0.021	0.6-1.3	giants, no M-giants, cut at 3σ
V	0.528 ± 0.045	(V-R)	0.912 ± 0.065	9	0.017	1.2-1.7	M-giants, cut at 4σ
K	0.161 ± 0.015	(J-K)	0.591 ± 0.012	81	0.027	0.5-1.3	giants
K	0.170 ± 0.012	(J-K)	0.579 ± 0.010	70	0.021	0.5-1.3	giants, cut at 4σ
K	0.196 ± 0.011	(J-K)	0.560 ± 0.009	56	0.015	0.5-1.3	giants, cut at 3σ
K	0.166 ± 0.026	(J-K)	0.585 ± 0.019	57	0.027	0.5-1.0	giants, no M-giants, cut at 5σ
• K	0.186 ± 0.021	(J-K)	0.568 ± 0.015	54	0.021	0.5-1.0	giants, no M-giants, cut at 4σ
K	0.186 ± 0.018	(J-K)	0.564 ± 0.012	42	0.015	0.5-1.0	giants, no M-giants, cut at 3σ
K	0.081 ± 0.042	(J-K)	0.682 ± 0.044	20	0.021	0.7-1.3	M-giants, cut at 4σ
V	0.223 ± 0.008	(V-K)	0.674 ± 0.033	18	0.046	1.5-6.3	luminous giants, cut at 4σ
V	0.684 ± 0.023	(V-R)	0.649 ± 0.025	12	0.024	0.7-1.8	luminous giants, cut at 4σ
K	0.198 ± 0.018	(J-K)	0.576 ± 0.017	7	0.009	0.5-1.2	luminous giants, cut at 4σ
V	0.240 ± 0.005	(V-K)	0.601 ± 0.014	86	0.026	1.7-4.0	Luminosity Class II + III, non-M giants, cut at 4σ
V	0.713 ± 0.024	(V-R)	0.616 ± 0.020	68	0.032	0.6-1.3	Luminosity Class II + III, non-M giants, cut at 4σ
K	0.184 ± 0.019	(J-K)	0.570 ± 0.014	61	0.020	0.5-1.0	Luminosity Class II + III, non-M giants, cut at 4σ
V	0.243 ± 0.008	(V-K)	0.607 ± 0.019	21	0.046	−0.9-4.1	supergiants, cut at 4σ
V	0.806 ± 0.023	(V-R)	0.510 ± 0.018	17	0.036	−0.2-1.4	supergiants, cut at 4σ
K	0.188 ± 0.024	(J-K)	0.574 ± 0.015	17	0.031	−0.1-1.2	supergiants, cut at 4σ
V	0.274 ± 0.004	(V-K)	0.519 ± 0.012	20	0.022	−0.1-4.2	dwarfs & sub-giants, cut at 4σ
V	0.776 ± 0.017	(V-R)	0.529 ± 0.016	13	0.028	0.1-1.8	dwarfs & sub-giants, cut at 4σ
K	0.387 ± 0.045	(J-K)	0.494 ± 0.032	11	0.036	0.0-1.0	dwarfs & sub-giants, cut at 4σ

et al. appear not to have used clipping but remark that the relation are in fact non-linear. It appears that for dwarfs the $V-(V-K)$ relation is to be preferred.

For the supergiants a comparison can be made with FG97. For the $V-(V-K)$ and $V-(V-R)$ relation the sample considered here is almost double that of FG97, and extends to bluer colours. The error on the coefficients is correspondingly smaller, yet the rms is in fact slightly larger. For typical colours $(V-K)_0 = 2.0$, $(V-R)_0 = 0.5$, and $(J-K)_0 = 0.5$ the relation in the present paper predicts $\log\theta_0$ of 1.093, 0.913 and 0.668, respectively, while FG97 predict 1.089, 0.947 and 0.666, respectively. There are some differences but not systematically so it appears. The relations in the present paper should be preferred because they are based on a larger number of stars.

Probably of most interest is the relation for giants. This is also the class of stars for which most data is available. A first important conclusion is that the relation for the M-giants is different from that for all giants and for all non-M giants. This was first hinted at by DB93 based on few stars only, but is confirmed here based on a much larger sample. Like him it is found that a is smaller and b larger for M-giants than for the non-M giants, in particular for the $V-(V-R)$ and $K-(J-K)$ relations at a level of 3-5σ. This makes a comparison with FG97 and Nord02 difficult as they did not exclude M-giants in deriving their SB-relations. For typical colours $(V-K)_0 = 2.5$, $(V-R)_0 = 0.9$, and $(J-K)_0 = 0.7$ the preferred relation for non-M giants in the present paper predicts $\log\theta_0$ of 1.197, 1.258 and 0.698, respectively, while FG97 (Nord02) predict for (all) giants 1.201 (1.188), 1.272 (1.248), 0.701 (0.690). For all three relations the sizes are slightly smaller than predicted by FG97–which is consistent with the fact that it is found in the present paper that the M-giants are bigger than the non-M giants–but smaller than the values listed in Nord02 which *includes* M-giants.

As was noted earlier in the literature, including more stars does not lead to a smaller rms. Considering giants of all types, the rms in, for example, the $V-(V-K)$ relation is 0.016 (based on 10 stars in FG97), 0.022 (based on 57 stars in Nord02) and 0.027 (based on 122 stars in the present paper). It is shown that the SB relations do not significantly depend on metallicity, and hence this scatter is not due to that parameter. Specifically for the giants, only

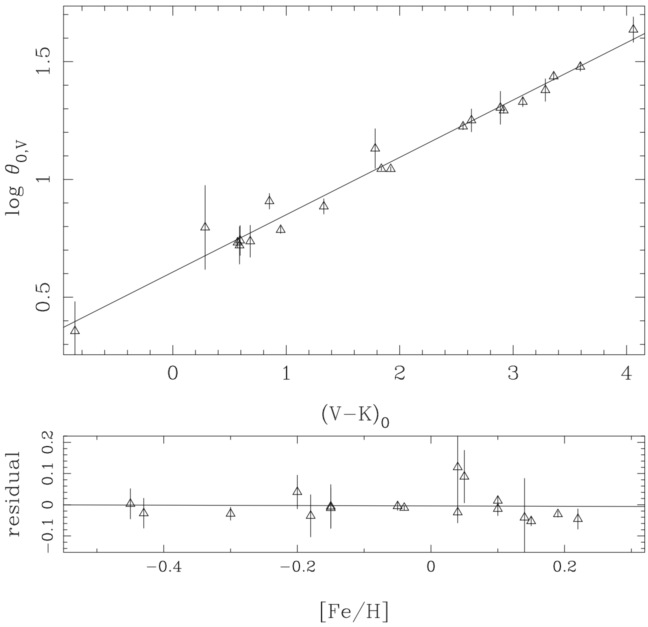


Figure 7. Final V-band surface-brightness relation versus colour $(V-K)_0$ for supergiants.

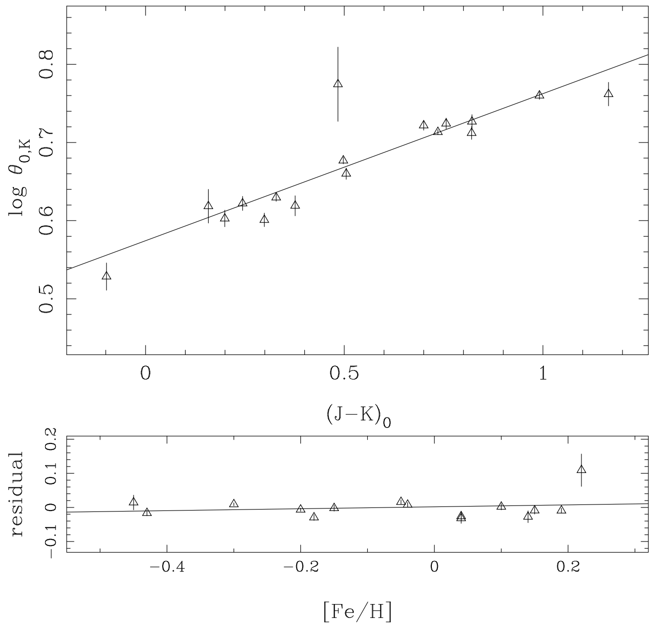


Figure 9. Final K-band surface-brightness relation versus colour $(J-K)_0$ for supergiants. The residuals correlate weakly with metallicity: residual $= (0.028 \pm 0.042)$ [Fe/H] + (0.002 ± 0.009).

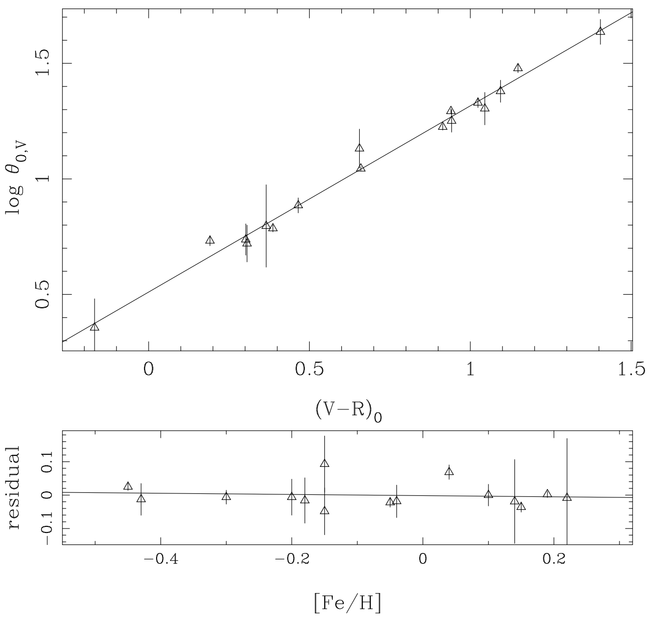


Figure 8. Final V-band surface-brightness relation versus colour $(V-R)_0$ for supergiants.

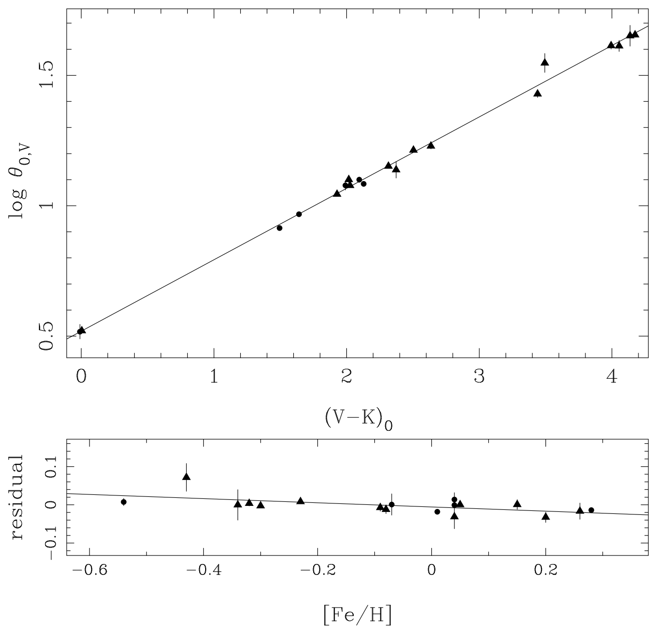


Figure 10. Final V-band surface-brightness relation versus colour $(V-K)_0$ for dwarfs and sub-giants. The residuals correlate significantly with metallicity: residual $= (-0.054 \pm 0.019)$ [Fe/H] + (-0.006 ± 0.005).

the residuals in the $V-(V-R)$ relation correlate at the 1σ level with metallicity (see caption of Figure 5).

Cohen et al. (1999) predict angular diameters for more than 400 giants in the spectral range G9.5 to M0 by fitting model atmospheres to absolute flux-calibrated broad-band photometry. Already in their paper they compared the predicted values to observed values, for about 20 stars. Figure 13 shows the same comparison but now for a sample twice in size. A least-square fit was made and outliers at the 4σ level removed (HR 2012, 4546). A new fit was made, and one additional outlier (HR 7942) was removed. The final fit is: $\theta_{\rm observed} = (1.049 \pm 0.010)\ \theta_{\rm model} + (-0.166 \pm 0.048)$, with an rms of 0.130. The slope is in the same sense as found by Cohen et al. (1.013 ± 0.008), i.e. slightly above unity, and found to be slightly steeper now, while the zero point is now significantly below zero, while the value in Cohen et al. was consistent with zero (0.035 ± 0.073). No immediate explanation is offered but it is simply noticed that the rms in the fit is larger than expected based on the assigned errorbars. As independent observations seem to be in very good agreement (see Figure 1) any possible problem seems more likely to be related to the models rather than the ob-

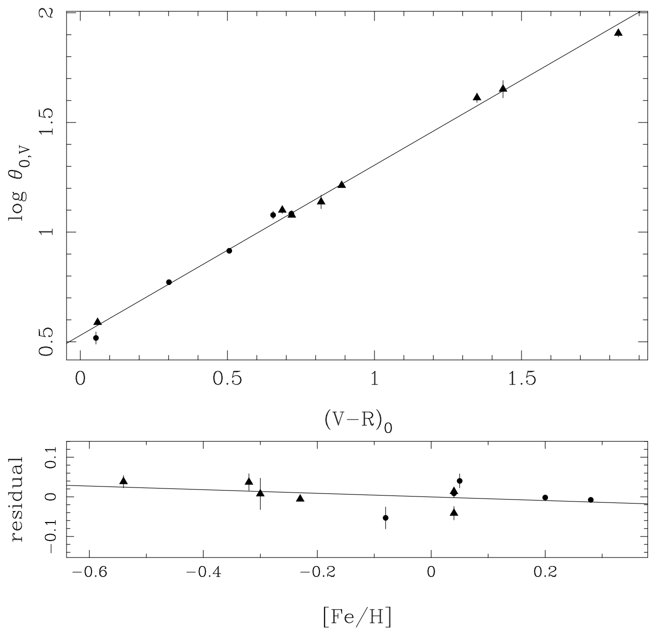


Figure 11. Final V-band surface-brightness relation versus colour $(V - R)_0$ for dwarfs and sub-giants. The residuals correlate at the 1σ level with metallicity: residual $= (-0.046 \pm 0.038)$ [Fe/H] + (0.000 ± 0.009).

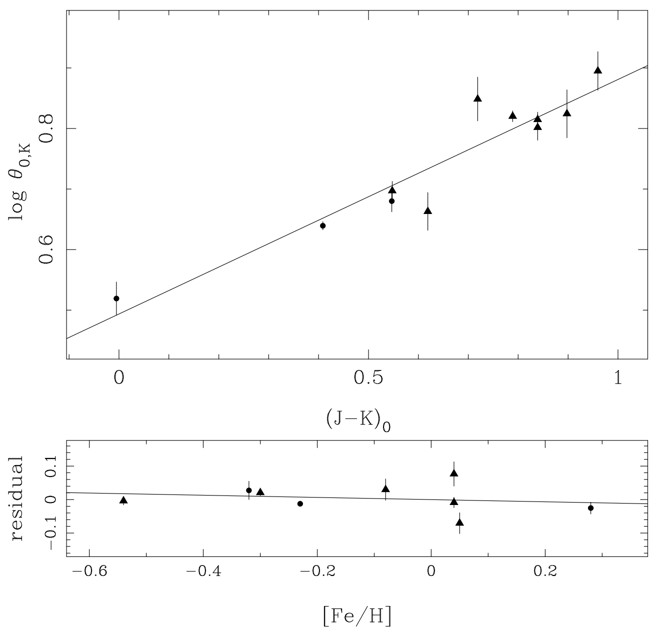


Figure 12. Final K-band surface-brightness relation versus colour $(J - K)_0$ for dwarfs and sub-giants. The residuals correlate weakly with metallicity: residual $= (-0.033 \pm 0.061)$ [Fe/H] + (0.000 ± 0.016).

servations. In addition, any possible problem appears to be for the larger objects. Selecting only stars smaller than a certain cut-of and monitoring the significance of the derived slope and zero point it is found that for $\theta < 6$ mas the expected 1-to-1 relation is found $\theta_{\rm observed} = (1.009 \pm 0.019)\ \theta_{\rm model} + (-0.028 \pm 0.066)$, although the rms is only reduced to 0.117 mas.

A final point that has to be addressed is the practice in the literature (FG97 and Nord02) to impose a common zero point of SB relations. In practice, the same three relations used here (i.e.

Table 5. Colours of normal solar metallicity stars (from Pietrinferni et al. 2004).

$T_{\rm eff}$	$\log g$	$(B-V)$	$(V-I)$	$(V-R)$	$(J-K)$	$(V-K)$
9500	2.0	-0.043	0.022	0.003	-0.002	0.003
9750	1.0	-0.022	0.060	0.026	-0.003	0.004
10000	0.5	-0.007	0.079	0.039	-0.003	0.002
10250	0.0	0.007	0.100	0.050	0.000	0.004

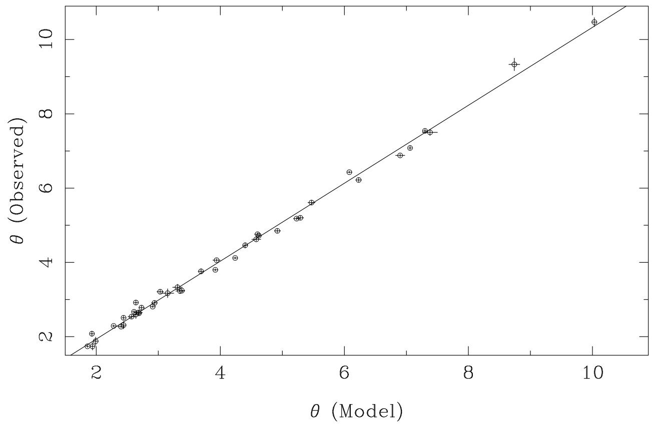


Figure 13. The adopted observed limb-darkened angular diameters (in mas) plotted against the radiometrically predicted values from Cohen et al. (1999). The line is a least-squares fit to the 42 data points plotted: $\theta_{\rm observed} = (1.049 \pm 0.010)\ \theta_{\rm model} + (-0.166 \pm 0.048)$ (rms = 0.130).

$V - (V - K)$, $V - (V - R)$ and $K - (J - K)$) are first derived independently. Then the zero point is averaged. Finally new slopes are derived for the three relations keeping the zero point fixed to this averaged value. The argument given is along the line that "For a star of spectral type A0, where $(V-R)_0 = (V-K)_0 = (J-K)_0 = 0$, each of the relations should yield a common surface brightness" (Nord02). Life is not that simple. Table 5 lists the (theoretical) colours of stars at various effective temperatures and gravities very near the colour $(V - K) = 0$ (from Pietrinferni et al. 2004). It can be remarked that indeed $(J - K)$ is in all cases also very near zero, but $(V - R)$ is near zero only for main-sequence stars but not for lower gravities. Imposing a common zero point based on simple averaging individual zero points is therefore not allowed for giants or supergiants. The value derived in such a way is biased (and this will also influence the then newly calculated slopes) if the common zero point is based on the zero point from the $V - (V - R)$ relation, like is the case in FG97 and Nord02.

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Table 4. Previous SB relations

(m_1)	a'	$(m_2 - m_3)$	b'	N	rms$^{(1)}$	Range	a	b	Remark	Reference
V	-0.123 ± 0.002	(V-K)	3.934 ± 0.005	57	0.011	0.7-4.1	0.246 ± 0.004	0.573 ± 0.010	giants	Nord02
V	-0.365 ± 0.009	(V-R)	3.925 ± 0.009	57	0.016	0.2-1.3	0.730 ± 0.018	0.591 ± 0.018	giants	Nord02
K	-0.095 ± 0.007	(J-K)	3.942 ± 0.006	57	0.011	0.18-1.1	0.190 ± 0.014	0.557 ± 0.012	giants	Nord02
V	-0.134 ± 0.005	(V-K)	3.956 ± 0.011	59	0.026	0.9-2.0	0.268 ± 0.010	0.529 ± 0.022	cepheids	Nord02
V	-0.364 ± 0.011	(V-R)	3.939 ± 0.006	59	0.026	0.3-0.7	0.728 ± 0.022	0.563 ± 0.012	cepheids	Nord02
K	-0.080 ± 0.021	(J-K)	3.934 ± 0.009	59	0.026	0.2-0.5	0.160 ± 0.042	0.573 ± 0.018	cepheids	Nord02
V	-0.125 ± 0.003	(V-K)	3.941 ± 0.004	59			0.250 ± 0.006	0.559 ± 0.008	cepheids	Nord02, forced common ZP
V	-0.368 ± 0.007	(V-R)	3.941 ± 0.004	59			0.736 ± 0.014	0.559 ± 0.008	cepheids	Nord02, forced common ZP
K	-0.096 ± 0.010	(J-K)	3.941 ± 0.004	59			0.192 ± 0.020	0.559 ± 0.008	cepheids	Nord02, forced common ZP
V	-0.124 ± 0.004	(V-K)	3.930 ± 0.012	10	0.008	2.22-4.11	0.248 ± 0.008	0.581 ± 0.024	giants	FG97
V	-0.379 ± 0.016	(V-R)	3.925 ± 0.017	10	0.012	0.72-1.32	0.758 ± 0.032	0.591 ± 0.034	giants	FG97
K	-0.100 ± 0.016	(J-K)	3.940 ± 0.013	10	0.008	0.60-1.06	0.200 ± 0.032	0.561 ± 0.026	giants	FG97
V	-0.119 ± 0.007	(V-K)	3.914 ± 0.023	13	0.032	0.52-5.53	0.238 ± 0.014	0.613 ± 0.046	supergiants	FG97
V	-0.392 ± 0.025	(V-R)	3.943 ± 0.026	12	0.033	0.23-1.78	0.784 ± 0.050	0.555 ± 0.052	supergiants	FG97
K	-0.101 ± 0.027	(J-K)	3.938 ± 0.023	13	0.027	0.17-1.21	0.202 ± 0.054	0.565 ± 0.046	supergiants	FG97
V	-0.131 ± 0.003	(V-K)	3.947 ± 0.003	10			0.262 ± 0.006	0.547 ± 0.006	cepheids	FG97, forced common ZP
V	-0.380 ± 0.003	(V-R)	3.947 ± 0.003	-			0.760 ± 0.006	0.547 ± 0.006	cepheids	FG97, forced common ZP
K	-0.110 ± 0.003	(J-K)	3.947 ± 0.003	11			0.220 ± 0.006	0.547 ± 0.006	cepheids	FG97, forced common ZP
V	-0.122 ± 0.001	(V-K)	3.927 ± 0.003	5	0.051	1.4-3.7	0.244 ± 0.002	0.587 ± 0.006	(G0-K5) giants	DB93
V	-0.101 ± 0.002	(V-K)	3.833 ± 0.008	6	0.090	3.7-6.3	0.202 ± 0.004	0.775 ± 0.016	M-giants	DB93
V	-0.139 ± 0.001	(V-K)	3.958 ± 0.005	13	0.120	0.5-4.5	0.278 ± 0.002	0.525 ± 0.01	supergiants	DB93
V		(V-K)		27	0.005	-0.3-4.1	0.275 ± 0.001	0.518 ± 0.003	IV + V	Kervella et al. (2004)
V		(V-R)		23	0.044	0.0-1.5	0.790 ± 0.008	0.522 ± 0.006	IV + V	Kervella et al. (2004)
K		(J-K)		27	0.029	0.1-0.9	0.319 ± 0.007	0.509 ± 0.003	IV + V	Kervella et al. (2004)

$^{(1)}$. rms listed in the original publication, which refer to Eq. (4) [except entries from Kervella et al. 2004]. In these cases, multiply by a factor of 2 to compare to the rms values listed in Table 3.

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