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Letter to the Editor

The effect of rotation on the absolute visual magnitudes of OB stars measured with Hipparcos[⋆]

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Abstract. We derive the absolute visual magnitudes of 14 OB-stars of luminosity class III to V from the parallaxes measured by Hipparcos. The values of M_V can differ by as much as $1.^m5$ from the M_V-spectral type calibration. Slowly rotating stars, v sin i< 100 km s^{-1}, are significantly fainter in M_V than stars with v sin i> 100 km s^{-1}*of the same spectral type* by about 1 magnitude. We discuss this effect and argue that it is due to the influence of rotation on the assignment of spectral types and luminosity class. Slowly rotating stars are also fainter than the standard M_V-spectral type relation. This effect has important consequences on the distance determinations of stars and clusters from M_v and V.

1. Introduction

Knowledge of the relation between the absolute visual magnitudes and spectral types of OB stars is important for the determination of spectroscopic distances from M_V and spectral type. In this paper we test the M_V versus spectral type relation of OB stars of class III-V based on parallax measurements of the Hipparcos satellite. We find that the values of M_V for a given spectral type depend on v sin i and that the effect is surprisingly large. This has significant implications for spectroscopic distance determinations.

2. The program stars and the observations

The program stars used for this study consist of a group of 14 stars of spectral types between O7.5 and B5 and luminosity class III to V. The stars were selected because they are optically bright, with $V \leq 5.0$ and hence their Hipparcos parallaxes should be accurate. The program stars are listed in Table 1, ordered by luminosity class (LC) and spectral type. The spectral types are from Walborn (1972,1973) for all O-stars except ζ Oph; from the Michigan spectral catalogue for τ Ori, δ Sco and β^1 Sco; and from the Bright Star Catalogue, BSC (Hoffleit and Jaschek, 1982) for the remaining stars.

3. Hipparcos data

The trigonometric parallaxes given in the Hipparcos Catalogue (ESA, 1997) have been obtained by fitting an astrometric model for stellar motion (with five parameters for stars assumed single) to a set of one-dimensional measurements obtained in a number of transits through the Hipparcos field between 1989 and 1993. Systematic errors in the astrometry have been estimated to be less than 0.1 milli-arcsec (Arenou et al. 1995, Lindegren 1995). The relevant Hipparcos results are given in Table 1. The quality of the results is indicated by the parameters $F1$ and $F2$. These quantities lie within acceptable limits for the program stars. The error in the parallax measurement causes an asymmetric error in the distance. The distance and its uncertainty (1 σ) is given in the last column.

4. The absolute visual magnitudes

4.1. The values of M_V derived from Hipparcos distances

The absolute visual magnitudes can be derived from V, A_V and d in the usual way. The data are listed in Table 2. The visual magnitudes (V) and the $(B-V)$ values are taken from Nicolet (1978). The magnitude and colour of λ Ori A are from Garmany (Private Communications), and those of ι Ori are from the BSC. The colour excess was derived from $B-V$ and from

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[⋆] Based on data from the ESA Hipparcos astrometry satellite

Table 1. The program stars

HD	Name	Type	HIP	π mas	σ_π mas	F1	F2 %	Trans nr	log d pc	Remark
214680	10 Lac	O9 V	111841	3.08	0.62	0	-0.87	119	$2.51^{+0.10}_{-0.08}$	ST
149757	ζ Oph	O9.5 Vn	81377	7.12	0.71	0	0.17	67	$2.15^{+0.04}_{-0.04}$	RA
149438	τ Sco	B0.2 V	81266	7.59	0.78	0	0.13	79	$2.12^{+0.05}_{-0.04}$	ST
144217	β^1 Sco	B0.5 V	78820	6.15	1.12	11	2.66	64	$2.21^{+0.09}_{-0.07}$	
22951	40 Per	B0.7 V	17313	3.53	0.88	0	-0.15	83	$2.45^{+0.13}_{-0.09}$	
36822	ϕ^1 Ori	B0.2 IV	26176	3.31	0.77	2	-0.36	70	$2.48^{+0.12}_{-0.09}$	
143275	δ Sco	B0.3 IV	78401	8.12	0.88	0	2.77	72	$2.09^{+0.05}_{-0.04}$	
24912	ξ Per	O7.5 III(n)((f))	18614	1.84	0.70	2	1.32	98	$2.73^{+0.21}_{-0.13}$	ST & RA
135240	δ Cir	O7.5 III((f))	74778	0.51	0.71	0	2.05	94	$3.29^{+\infty}_{-0.38}$	
36861	λ Ori A	O8 III ((f))	26207	3.09	0.78	1	1.05	65	$2.51^{+0.13}_{-0.10}$	ST
37043	ι Ori	O9 III	26241	2.46	0.77	0	1.37	77	$2.61^{+0.16}_{-0.12}$	
35468	γ Ori	B2 III	25336	13.42	0.98	0	0.47	47	$1.87^{+0.04}_{-0.03}$	
37490	ω Ori	B3 III e	26594	2.01	0.94	2	1.19	76	$2.70^{+0.27}_{-0.17}$	
34503	τ Ori	B5 III	24674	5.88	0.77	2	0.89	81	$2.23^{+0.06}_{-0.05}$	

Column (5) and (6): π is the parallax, σ_π its standard error in milli-arcsec.
Column (7): F1 is percentage of rejected observations. Column (8): F2 is the goodness of the fit (F2 <3 is acceptable).
Column (9): The number of field transits; a small number of consecutive transits was combined into one measurement.
Column (10): RA = run-away star, ST = standard for its spectral type.

the relation between the intrinsic colour $(B-V)_0$ and spectral type. We adopted the relations from Schmidt-Kaler (1982) (SK). A visual extinction of $A_V = 3.1E(B-V)$ was adopted (Mathis, 1990). The rotational velocities are from the BSC.

The resulting M_V values of the program stars are listed in Table 2 with the uncertainty in M_V corresponding to a 1 σ error in the Hipparcos parallax. The values are plotted versus spectral type for different luminosity classes and compared with the SK-calibration in Fig. 1. The M_V values derived from the calibration with spectral type have an uncertainty due to the fact that the spectral types and the luminosity classes occur in intervals, with an uncertainty of half a luminosity class and half a spectral sub-type. Therefore we adopted an uncertainty in the SK-magnitudes (ΔM_V(SK))

$$\Delta M_V(\mathrm{SK}) = \sqrt{(\Delta M_V(\mathrm{LC}))^2 + (\Delta M_V(\mathrm{ST}))^2} \tag{1}$$

in which ΔM_V(LC) and ΔM_V(ST) are half the difference in M_V between two adjoining luminosity classes and spectral subtypes respectively. We also compared our results with the new M_V calibration of Vacca et al. (1996), (VGS), for luminosity classes V, III and Ia.

Figure 1 shows the comparison between M_V(Hip) and the spectral type - M_V calibrations. Notice that for many stars M_V(Hip) is fainter than predicted by the standard calibration. For some stars M_V(Hip) even differs from the calibration by as much as $\pm 1^m.5$.

4.2. Discussion of several individual stars

- **10 Lac**: A standard star for spectral type O9 V, but the star is $1^m.5$ (3 σ) fainter than the calibration of both SK and VGS. Also fainter than the calibration in the cluster study by Garmany and Stencel (1992).
- ζ **Oph**: A run-away star from the Upper Cen region (Blaauw, 1961). Very good agreement with the calibration. Herrero et al. (1992) and Puls et al. (1996) have shown that the gravity of the star is that of a class III star, rather than a class V star.
- τ **Sco**: A standard star for spectral type B0.2 V, but $1^m.0$ (4.2 σ) fainter than the calibration. Also fainter than the calibration in the cluster study of Humphreys (1979)
- β^1 **Sco**: $0^m.5$ (1.4 σ) brighter than the calibration, but within the uncertainty range of half a spectral subtype. It fits very well with the calibration of VGS.
- ϕ^1 **Ori**: $1^m.1$ (1.9 σ) fainter than the SK calibration.
- δ **Sco**: $0^m.8$ (3.2 σ) fainter than the SK calibration, but it is within the uncertainty of half a spectral subtype.
- ξ **Per**: A spectral standard star of type O7.5 III and run-away star. M_V(Hip) agrees with the SK calibration.
- λ **Ori A**: A standard star for spectral type O8 III, but $1^m.5$ (2.4 σ) and $1^m.3$ fainter than the calibrations of SK and VGS respectively. Also fainter in the cluster study by Humphreys (1979).
- γ **Ori**: $1^m.1$ (6.9 σ) fainter than the calibration of SK. Significantly closer than the other Orion stars: obviously a foreground star.

5. The dependence of M_V on stellar rotation

Figure 1 shows that the stars which deviate most strongly from the standard M_V calibration are slow rotators with $v \sin i < 100$ km s^{-1}.

A clear example of this is the pair 10 Lac (O9 V, $v \sin i$=31) and ζ Oph (O9.5 V, $v \sin i$=379) which are supposed to have about the same value of M_V, but differ by more than a magnitude. Another example is the pair 40 Per (B0.7 V, $v \sin i$=51)

Table 2. The distances and absolute magnitudes

Name	Type	V	$(B-V)$	A_V	v sin i km.s^{-1}	M_V (Hip)	M_V (SK)	ΔM_V (SK)	M_V (VGS)
10 Lac	O9 V	4.88	-0.20	0.34	31	$-3.02^{+0.40}_{-0.49}$	$-4.5^{+0.3}_{-0.4}$	1.5	-4.43
ζ Oph	O9.5 Vn	2.56	+0.02	1.02	379	$-4.20^{+0.21}_{-0.23}$	$-4.3^{+0.2}_{-0.4}$	0.1	-4.32
τ Sco	B0.2 V	2.82	-0.25	0.12	24	$-2.90^{+0.21}_{-0.24}$	$-3.9^{+0.4}_{-0.4}$	1.0	-4.17
β^1 Sco	B0.5 V	2.62	-0.07	0.65	130	$-4.09^{+0.36}_{-0.44}$	$-3.6^{+0.4}_{-0.4}$	-0.5	-4.10
40 Per	B0.7 V	4.97	-0.01	0.84	51	$-3.13^{+0.48}_{-0.62}$	$-3.4^{+0.4}_{-0.4}$	0.3	-4.06
ϕ^1 Ori	B0.2 IV	4.41	-0.16	0.40	39	$-3.39^{+0.45}_{-0.57}$	$-4.5^{+0.5}_{-0.4}$	1.1	
δ Sco	B0.3 IV	2.32	-0.12	0.50	181	$-3.63^{+0.22}_{-0.25}$	$-4.4^{+0.5}_{-0.4}$	0.8	
ξ Per	O7.5 III (n)((f))	4.04	+0.01	1.02	216	$-5.66^{+0.70}_{-1.04}$	$-5.8^{+0.2}_{-0.1}$	0.2	-5.62
δ Cir	O7.5 III ((f))	5.09	-0.06	0.81	189	$-7.18^{+1.89}_{-\infty}$	$-5.8^{+0.2}_{-0.1}$	-1.4	-5.62
λ Ori A	O8 III ((f))	3.66	-0.19	0.37	66	$-4.26^{+0.49}_{-0.63}$	$-5.8^{+0.2}_{-0.1}$	1.5	-5.57
ι Ori	O9 III	2.77	-0.24	0.22	130	$-5.50^{+0.59}_{-0.82}$	$-5.6^{+0.3}_{-0.2}$	0.1	-5.46
γ Ori	B2 III	1.64	-0.22	0.06	50	$-2.78^{+0.15}_{-0.16}$	$-3.9^{+0.6}_{-0.5}$	1.1	
ω Ori	B3 IIIe	4.57	-0.11	0.28	194	$-4.19^{+0.83}_{-1.37}$	$-3.0^{+0.4}_{-0.9}$	-1.2	
τ Ori	B5 III	3.60	-0.11	0.19	46	$-2.74^{+0.27}_{-0.30}$	$-2.2^{+0.3}_{-0.9}$	-0.5	

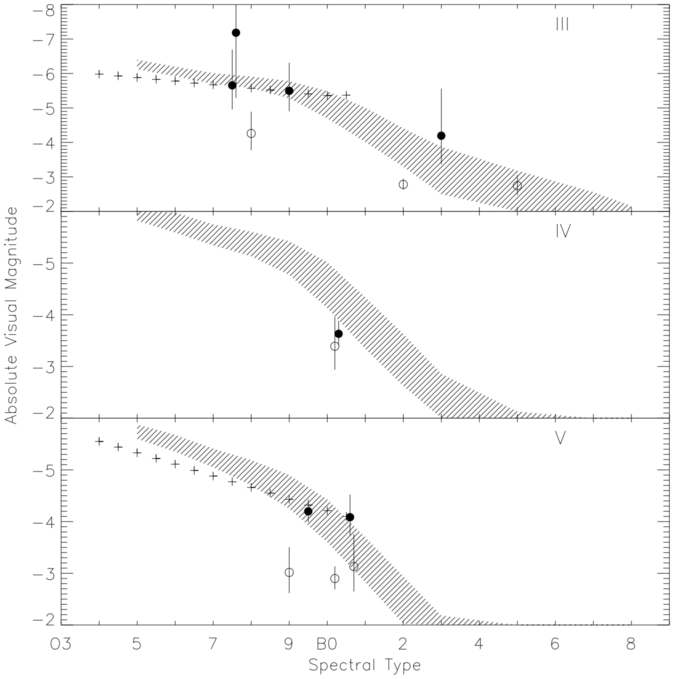

Fig. 1. M_V(Hip) versus spectral type for three luminosity classes. The error bars correspond to a 1 σ uncertainty in the parallax. The calibrations by Schmidt-Kaler (1982), with the uncertainty (dashed regions) and Vacca et al. (1996) (pluses) are shown for comparison. Slow rotators, with v sin $i < 100$ km s^{-1}, (open circles) are generally fainter than the fast rotators with v sin $i > 100$ km s^{-1}(filled circles) and than the standard calibration

with β^1 Sco (B0.5 V, v sin i=130), which differ by about a magnitude. In both cases the rapidly rotating star is the brighter one.

Figure 2 shows the relation between $M_V(Hip) - M_V(SK)$ as a function of log (v sin i). Although the number of stars is small and the errors are significant for several stars, the figure shows evidence for a trend of decreasing ΔM_V (brightening of the star) with increasing rotational velocity.

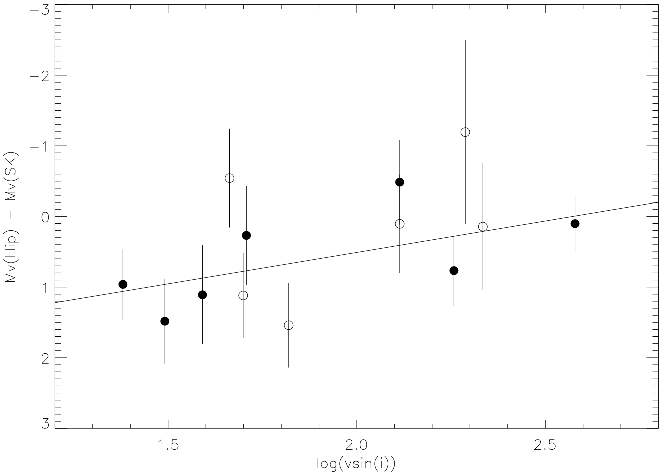

Fig. 2. The difference between the values of M_V from the Hipparcos data and the standard calibration as a function of v sin i. Open symbols: class III; closed symbols: classes IV and V. Solid line: weighted least-squares-fit.

The effect of rotation on stellar evolution tracks has been studied by Langer (1992). He found that rotation induced mixing can increase the luminosity during the H-core burning stage by about 0.1 dex in log L_*, depending on the mixing. The rapid rotators are brighter than the slow rotators for the same value of $T_{\rm eff}$ and M_*. However if we compare two stars of the same $T_{\rm eff}$ (Spectral type=ST) and log g (LC) the rapid rotating one will be *fainter* than the slow rotator. This is opposite to the observed trend.

The effect of stellar rotation on M_V and spectral type has been discussed by Collins (1974 and references therein) and reviewed by Cassinelli (1987). Fast rotators have lower gravities and smaller $T_{\rm eff}$ at their equators due to the von Zeipel effect. The predicted effect becomes most noticable for high rotational velocities. This may affect the classification of the star in ST and

LC, which is based on line ratios and line strength, and hence the expected values of M_V in three ways:

(1) The lower equatorial gravity of a rapid rotator may mimic a star of brighter LC. This will result in a too high assigned luminosity. If this were the dominant effect, we would expect that of two stars with the same *assigned* ST and LC, the fast rotating one would be of a lower luminosity that the slow rotating one. This is opposite to the observed trend.

(2) The lower equatorial flux mimics a cooler star, which may result in a too late assigned ST. If this is the dominant effect, we expect that of two stars with the same *assigned* ST, the fast rotating one would in fact be hotter than the slowly rotating star. Since M_V gets brighter to higher temperatures for class III to V stars, the fast rotating star would be brighter. This is in agreement with the observed trend in Fig (1), however this effect is expected to occur only if the star rotates close to the break-up velocity.

(3) The expected value of M_V is very sensitive to the assigned LC because M_V increases by more than 1^m from class V to III at B0. The assigned LC can be affected by rotation because it is based on the line ratios of SiIV/HeI and NII/HeI for early-B stars and the lines of SiIV and NII are harder to see in the spectrum of a rapid rotator. If the strength of these lines is underestimated a too faint LC will be assigned. Therefore we expect that of two stars with the same *assigned* LC, the fast rotator would be the brighter one. This is in agreement with the observed trend in Fig. 1.

We see that rotation is expected to affect the LC that has been assigned on the basis of the optical spectrum. The observed differences in M_V between rapid and slow rotators of the same *assigned* spectral type and LC can be qualitatively explained by this effect. The remaining question is: why are the slowly rotating stars, which are often calibration standards, fainter than the M_V - spectral type calibration?

The calibration of M_V versus ST is based on large numbers of cluster stars (Blaauw 1963, Vacca et al. 1995). Since many of the cluster stars are rapid rotators for which the above mentioned effect may play a role, the absolute magnitude scale is biased to the bright side. The result is that the *standard stars* for spectral classification, which are usually slow rotators, may systematically be too faint compared to the M_V spectral type calibration. This effect was already noticed by Walborn (1972) who found that the main sequence standard stars are fainter than the M_V calibration by Blaauw (1963), which is incorporated in the SK calibration. The same effect can also be seen in the clusters studies by Humphreys (1978) for τ Sco and λ Ori and by Garmany and Stencel (1992) for 10 Lac, although these authors did not comment on it.

6. Summary and discussion

We have derived the absolute visual magnitudes of 14 O and early-B stars of luminosity class III-V from the parallaxes measured by Hipparcos. We find that the difference between M_V(Hip) and $M_V(SK)$ derived from the spectral types, depends on v sin i: the slow rotators with v sin i< 100 km s^{-1} are fainter than indicated by their spectral type by as much as 1^m to $1^m.5$. This effect can already be seen in some of the earlier cluster studies. We suggest that this is due to the influence of rotation on the assigned luminosity class, which causes the fast rotating one of two stars with the same *assigned* spectral type and luminosity class, to have a higher luminosity. This explanation is supported by the detailed study of ζ Oph by Herrero et al. (1992) and Puls et al. (1996). They suggested on the basis of the low spectroscopic gravity that this rapid rotator of type O9.5 Vn is in fact a giant of type O9 III.

Our result has important consequences for spectroscopic distance determinations, because the stellar rotation should be taken into account. A preliminary study of a larger sample of stars in the Sco-Cen association observed with Hipparcos shows a similar trend (de Zeeuw et al., in preparation).

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