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ASTRONOMY AND ASTROPHYSICS

A reliable transformation of Hipparcos H_p magnitudes into Johnson V and B magnitudes

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Abstract. A comparison of accurate UBV magnitudes, derived from numerous observations at Hvar and Skalnaté Pleso, and of the mean Hipparcos H_p magnitudes for a number of constant stars showed a very good mutual correspondence of these two data sets. Simple transformation formulæ are presented which allow calculating Johnson V and B magnitudes from the H_p magnitude and known $B-V$ and $U-B$ colours. For constant stars with well-known values of both colours the accuracy of the transformation is clearly better than $0\overset{\mathrm{m}}{.}01$. At the same time, the transformation is not critically sensitive to the exact values of $B-V$ and $U-B$. It is applicable over a wide range of colours ($B-V$ between $-0\overset{\mathrm{m}}{.}25$ and $2\overset{\mathrm{m}}{.}0$) and works well also for reddened stars. However, since it was defined for stars brighter than about $8\overset{\mathrm{m}}{.}0$ and for reddenings smaller than about $1\overset{\mathrm{m}}{.}0$, its application outside these limits should be made with some caution and further tested. Since the $B-V$ and $U-B$ colours are known for the majority of brighter stars and since there are many classes of variable stars which do change colours only very mildly during their light changes (like the majority of Be stars) or for which the instantaneous colours can be predicted or estimated from existing optical observations, the transformations presented here may turn out to be very useful for many researchers who need to combine Hipparcos and optical photometry into one homogeneous data set.

Key words: techniques: photometric

1. Introduction

Harmanec, Horn & Juza (1994) carefully reduced numerous UBV observations secured between 1972 and 1991 at Hvar and between 1980 and 1987 at Skalnaté Pleso. Since many constant stars, used as the comparison and/or transformation standard stars, were repeatedly observed at both observatories, it was possible to identify secularly constant stars and to derive their UBV magnitudes with an unprecendented accuracy. Harmanec et al. (1994) pointed out that two things were vital in the reduction process:

- the use of proper (non-linear) transformation equations, and
- a careful, iterative removal of accidental errors of the original Johnson's UBV values which led to the determination of much more accurate UBV values for all constant stars.

Note that Harmanec et al. also paid utmost care to avoid any systematic deviations from the original Johnson system. They give justification why non-linear transformation formulæ must be used if one wants to achieve an accuracy of $0\overset{\mathrm{m}}{.}01$ in all three standard UBV magnitudes over a large range of stellar colours, luminosities and reddenings.

I realized that the formulæ used to the transformation of instrumental magnitudes into standard ones should work equally well also for a transformation between two existing well-defined standard systems of stellar magnitudes.

2. The transformation from H_p to V and B

Recently, Perryman et al. (1997) published a catalogue of very accurate broad-band H_p magnitudes of many stars derived from observations of the Hipparcos satellite. The passband used in these observations is so broad that it effectively embraces both the V and B passbands of the Johnson's UBV system.

In the first step, I extracted the mean H_p magnitudes from the main Hipparcos catalogue for all standard stars from Table 5 of Harmanec et al. (1994), i.e. for those standards for which at least 5 calibrated all-sky observations per season were secured on at least two different seasons. To these stars, I added the following standards for which good Hvar UBV magnitudes were derived more recently: HD 141930, 176437, 177808, and 194317. Altogether, the data set contained 110 stars.

I used the following transformation formulæ:

$$\begin{aligned} V \;=\;& H_p + \alpha_1\,(B-V) + \alpha_2\,(U-B) + \\ &+\; \alpha_3\,(B-V)^2 + \alpha_4\,(B-V)^3 + \alpha_5 \end{aligned} \tag{1}$$

and

$$\begin{aligned} B \;=\;& H_p + \beta_1\,(B-V) + \beta_2\,(U-B) + \\ &+\; \beta_3\,(B-V)^2 + \beta_4\,(B-V)^3 + \beta_5. \end{aligned} \tag{2}$$

It is obvious that the transformation coefficients α and β are not mutually independent. Since $B = V + (B-V)$, the following relations hold:

$$\beta_1 \;=\; 1+\alpha_1,\; \beta_2=\alpha_2,\; \beta_3=\alpha_3,\; \beta_4=\alpha_4,\; \beta_5=\alpha_5. \tag{3}$$

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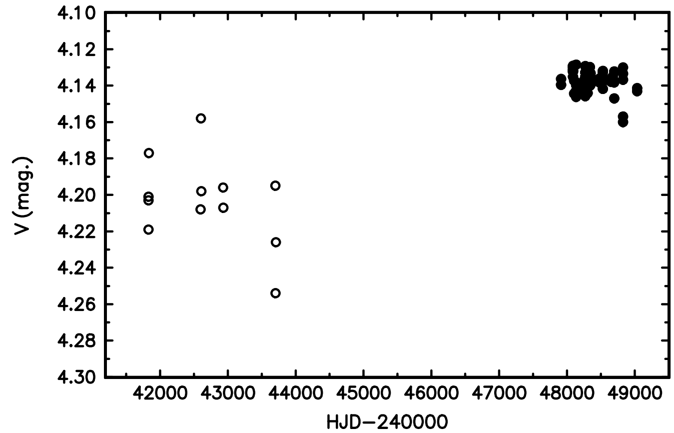

Fig. 1. Hvar and transformed Hipparcos photometry of 46 Lib

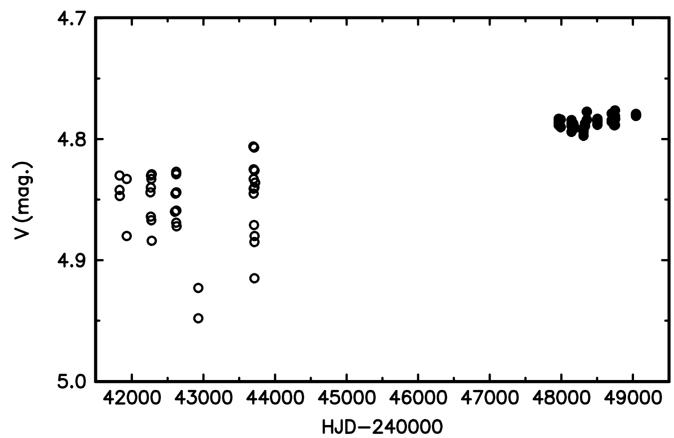

Fig. 2. Hvar and transformed Hipparcos photometry of 21 Sgr

It suffices, therefore, to investigate the transformation formula (1) and to use relations (3) to obtain the corresponding transformation formula for the B passband.

The transformation coefficients α were derived by the least-square fit using all the standard stars defined above. It turned out that the rms error of the fit per one data point was $0\overset{\mathrm{m}}{.}0131$, a promising initial result.

A closer inspection showed that two stars, 46 Lib (HD 142198) and 21 Sgr (HD 169420) give unacceptably large deviations $V_{\rm Hip.} - V_{\rm Hvar}$ of $-0\overset{\mathrm{m}}{.}058$ and $-0\overset{\mathrm{m}}{.}059$, respectively. For both these stars, the Hvar data come from early observations when these stars were used as extinction standards and observed at large airmasses of 2 or more. It is quite conceivable that the Hvar all-sky values derived by Harmanec et al. (1994) are inaccurate. Note that these stars are not listed in Table 4 of Harmanec et al. paper but only in their Table 5. Actually, the V magnitudes from various sources quoted in the Simbad bibliography range from $4\overset{\mathrm{m}}{.}12$ to $4\overset{\mathrm{m}}{.}16$ for 46 Lib ($V_{\rm Hvar} = 4\overset{\mathrm{m}}{.}200$), and from $4\overset{\mathrm{m}}{.}80$ to $4\overset{\mathrm{m}}{.}82$ for 21 Sgr ($V_{\rm Hvar} = 4\overset{\mathrm{m}}{.}851$). They are, therefore, in a better agreement with the transformed H_p magnitudes than the Hvar values. Fig. 1 is the plot of the Hvar and Hipparcos transformed V magnitudes vs. time for 46 Lib. Hvar observations are shown by open circles, those from Hipparcos by filled circles.

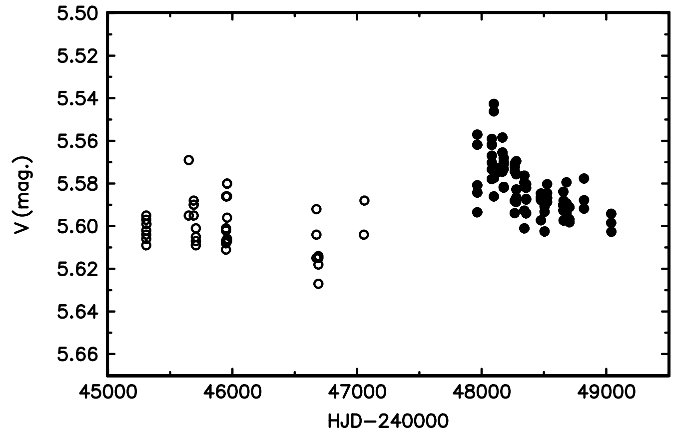

Fig. 3. Hvar and transformed Hipparcos photometry of HR 1037

Fig. 2 is a similar plot for 21 Sgr. These figures illustrate the poor quality of these particular Hvar observations. At the same time it seems that one can suspect the presence of real light variability of both stars from the Hipparcos data. I, therefore, omitted these two stars from the transformation standards and re-calculated the fit.

This time, the rms error per one observation was only $0\overset{\mathrm{m}}{.}0102$. However, there are still several stars for which the $O-C$ deviations exceed $0\overset{\mathrm{m}}{.}015$, the largest one being $-0\overset{\mathrm{m}}{.}040$. Since the study by Harmanec et al. (1994) demonstrated that the seasonal mean UBV magnitudes of almost all standard stars could be reproduced within $0\overset{\mathrm{m}}{.}01$, I decided to investigate the secular constancy of these particular stars, and also stars for which Harmanec et al. (1994) suspected mild variability, in detail.

The results for the individual stars are discussed below. Please, note that the Hvar all-sky observations are denoted by open circles, those from Skalnaté Pleso by open triangles and those from Hipparcos by filled circles in all plots shown here. Only observations from nights suitable for all-sky photometry were used for Hvar and Skalnaté Pleso. For Hipparcos, only observations with the error flag zero (i.e. reliable data) were used.

HR 1037 (HD 21362, HIP 16210); O − C = $-0\overset{\mathrm{m}}{.}016$
Table 5 of Harmanec et al. (1994) indicates a possible variability of HR 1037. Also Perryman et al. (1997) classify this B6Vn star as a variable of an unknown type.

Fig. 3 is a plot of Hvar and Hipparcos observations of HR 1037. There can be little doubt that this star is indeed a new variable and must be omitted from the list of standard stars.

I carried out Stellinwerf's (1978) PDM period search on the combined data set from Hvar and Hipparcos. A period of $81\overset{\mathrm{d}}{.}0403$ was detected as the best one. The light curve for this period and an arbitrary epoch is shown in Fig. 4. One can see that HR 1037 could perhaps be a binary. New photometric and especially spectroscopic observations are clearly desirable.

18 Tau (HD 23324, HIP 17527); O − C = $-0\overset{\mathrm{m}}{.}015$
As Fig. 5 shows, the discrepancy between the Hvar and Hipparcos data is marginal. It may be caused by the fact that 18 Tau

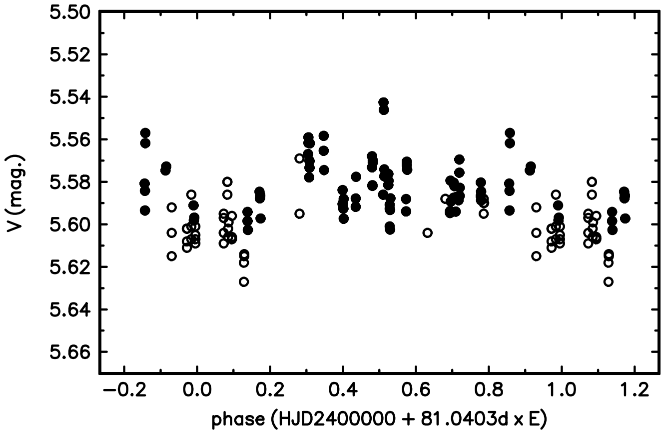

Fig. 4. A tentative light curve of HR 1037 with an $81\overset{\rm d}{.}0$ period

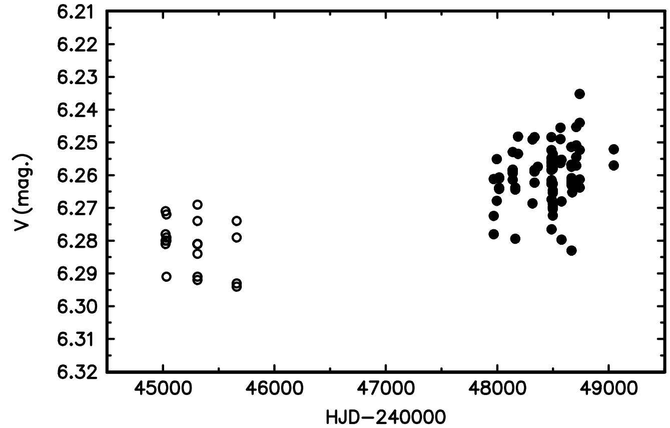

Fig. 6. Hvar and transformed Hipparcos photometry of HR 2532

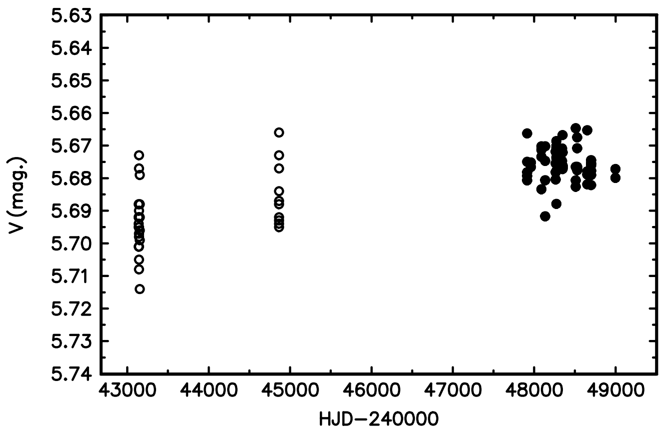

Fig. 5. Hvar and transformed Hipparcos photometry of 18 Tau

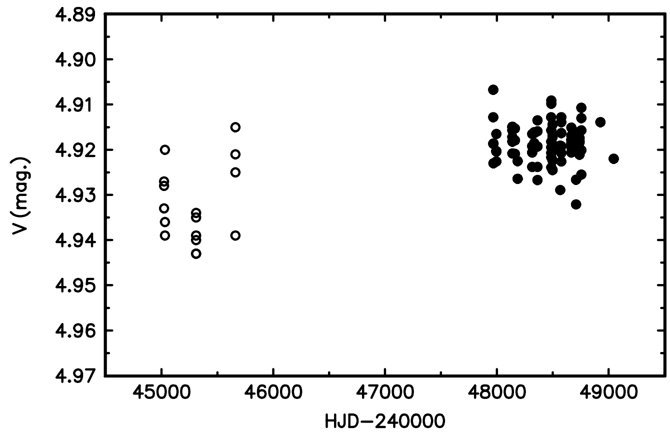

Fig. 7. Hvar and transformed Hipparcos photometry of 16 Lyn

was not observed frequently enough at Hvar. For the moment, I shall retain 18 Tau among the transformation standards.

HR 2532 (HD 49949, HIP 33056); $O - C = -0\overset{\rm m}{.}022$
This A8Vn star has only a limited number of observations from Hvar. Hipparcos observations indicate a slow increase of its brightness. Fig. 6 is a plot of Hvar and transformed Hipparcos V magnitudes vs. time. One can see a smooth secular change of brightness. Very probably, HR 2532 is a low-amplitude light variable which should not be used as a standard star.

16 Lyn (HD 50973, HIP 33485); $O - C = -0\overset{\rm m}{.}014$
Harmanec et al. (1994) noted a larger than expected scatter in the seasonal mean Hvar values for this star but attributed it to the small number of Hvar observations. The Hipparcos observations show a scatter within less than $0\overset{\rm m}{.}03$ without any obvious trends, i.e. no evidence of light changes. Since this A2n star is denoted as variable in the Simbad bibliography, I shall omit it from the final data set. Its constancy should be further tested.

43 Leo (HD 89962, HIP 50851); $O - C = -0\overset{\rm m}{.}016$
Both, the Hipparcos and Hvar photometry show a larger than usual scatter of individual observations (see Fig. 8). Two single Hipparcos observations deviate by more than $0\overset{\rm m}{.}04$ from the level defined by the rest of the data. The star must be considered a suspected variable and I shall omit it from the final data set.

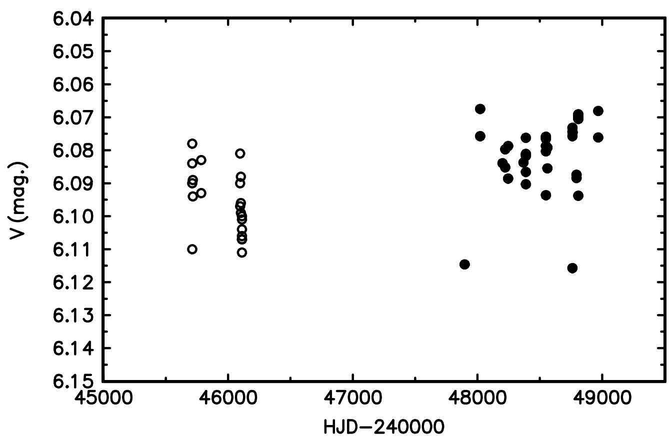

Fig. 8. Hvar and transformed Hipparcos photometry of 43 Leo

HR 4609 (HD 104985, HIP 58952); $O - C = -0\overset{\rm m}{.}017$
As seen in Fig. 9, all three data sets show a larger than usual scatter. The star must be considered a suspected variable. It shall not be used in the final data set.

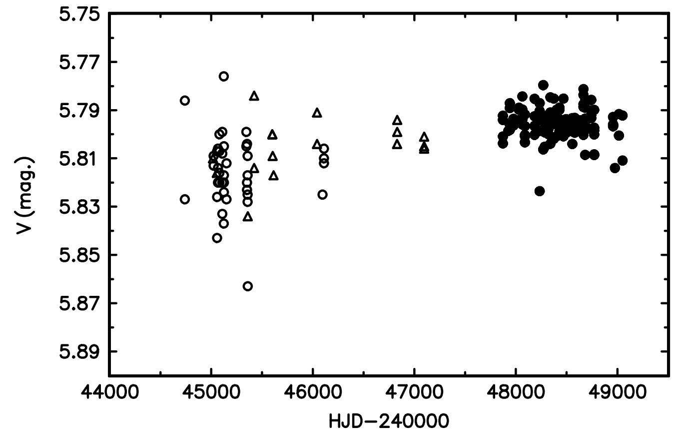

Fig. 9. Hvar and transformed Hipparcos photometry of HR 4609

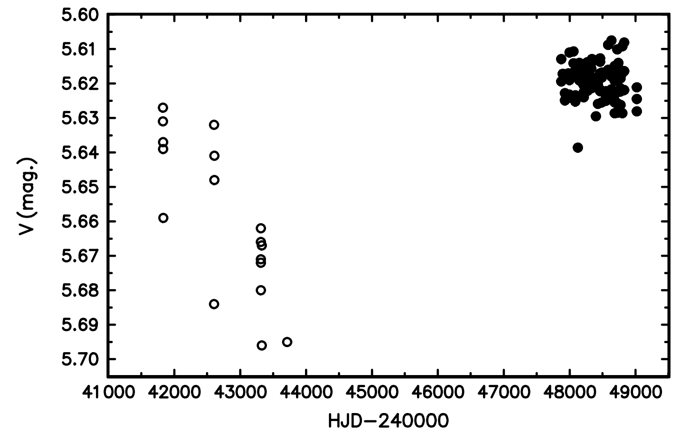

Fig. 10. Hvar and transformed Hipparcos photometry of 81 UMa

81 UMa (HD 118214, HIP 66198); O – C = $-0^{\mathrm{m}}.040$
This is an Ap star. As Fig. 10 shows, this star must be considered a suspected variable. The Simbad bibliography gives the range of V magnitudes between $5^{\mathrm{m}}.56$ and $5^{\mathrm{m}}.60$ from several sources. This is closer to the transformed Hipparcos value than the mean Hvar magnitude. I shall not use this star in the final data set.

ν Sco AB (HD 145502, HIP 79374); O – C = $-0^{\mathrm{m}}.037$
Fig. 11 shows that a rather small number of observations of this star is available. At Hvar, the star has always been observed at large airmasses. The Hipparcos data show a range of more than $0^{\mathrm{m}}.04$. Therefore, the star is suspected of some slight variability and it will be safer to omit it from the final data set.

93 Her (HD 164349, HIP 88128); O – C = $+0^{\mathrm{m}}.021$
As Fig. 12 illustrates, the Hvar data for this star show a large scatter. There is also a systematic difference between the Hvar and Hipparcos magnitude. Since there is no evidence of variability from the Hipparcos data, I prefer to keep this star among the transformation standards.

β Sge (HD 185958, HIP 96837); O – C = $+0^{\mathrm{m}}.020$
Although the plot of the data vs. time (Fig. 13) shows a slightly larger than usual scatter, there is no clear evidence of variability but only of some systematic difference between Hvar and

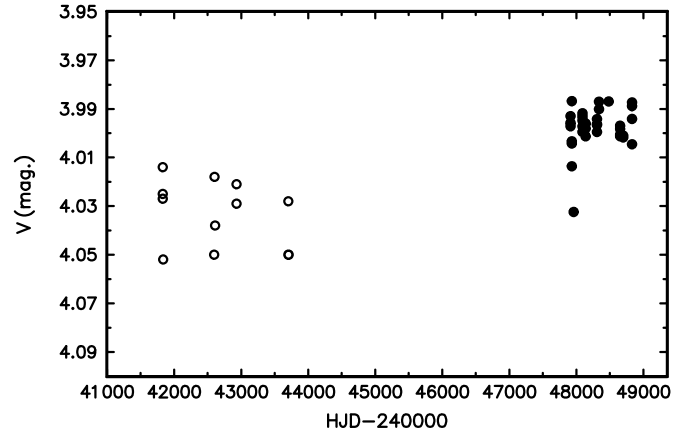

Fig. 11. Hvar and transformed Hipparcos photometry of ν Sco AB

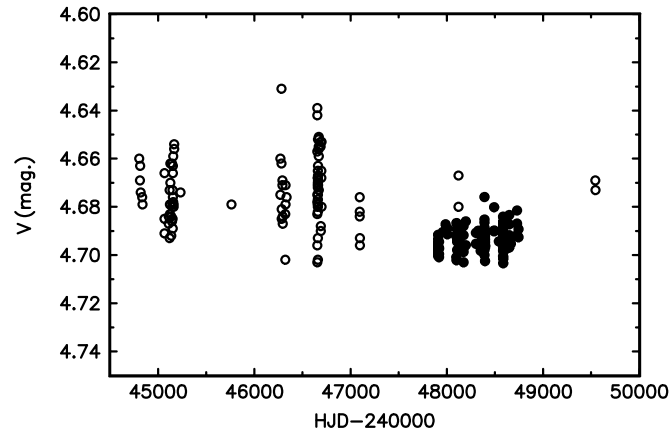

Fig. 12. Hvar and transformed Hipparcos photometry of 93 Her

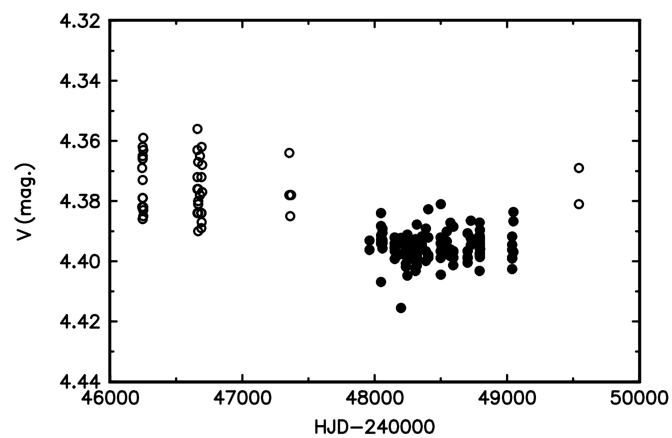

Fig. 13. Hvar and transformed Hipparcos photometry of β Sge

Hipparcos values. This star must remain among transformation standards.

19 Vul (HD 192004, HIP 99518); O – C = $+0^{\mathrm{m}}.027$
Fig. 14 is a time plot of the Hvar and transformed Hipparcos observations vs. time. It is not quite obvious whether it is indicative of a secular light variation of 19 Vul or of a systematic difference between Hvar and Hipparcos data. However, the range of

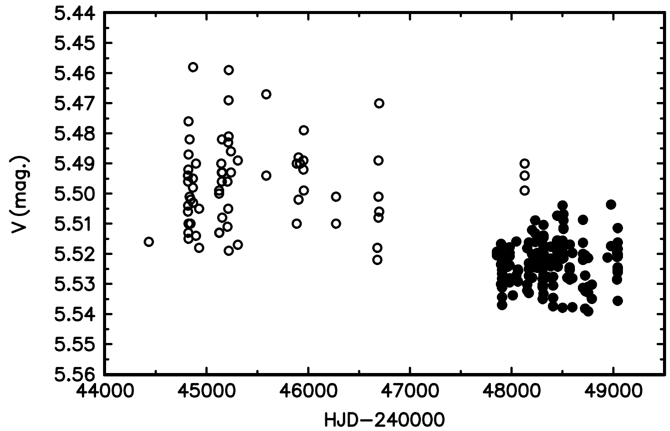

Fig. 14. Hvar and transformed Hipparcos photometry of 19 Vul

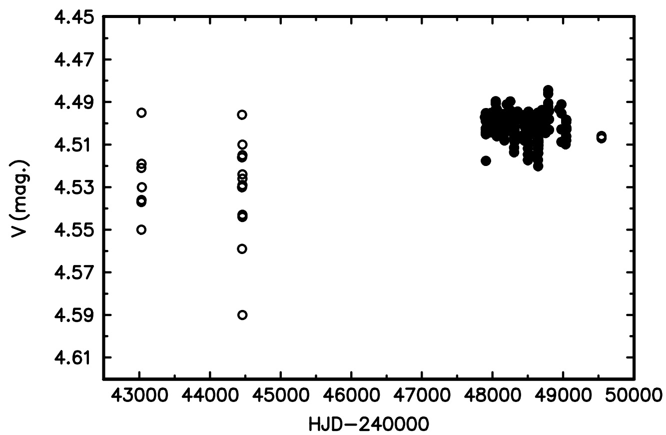

Fig. 15. Hvar and transformed Hipparcos photometry of 23 Vul

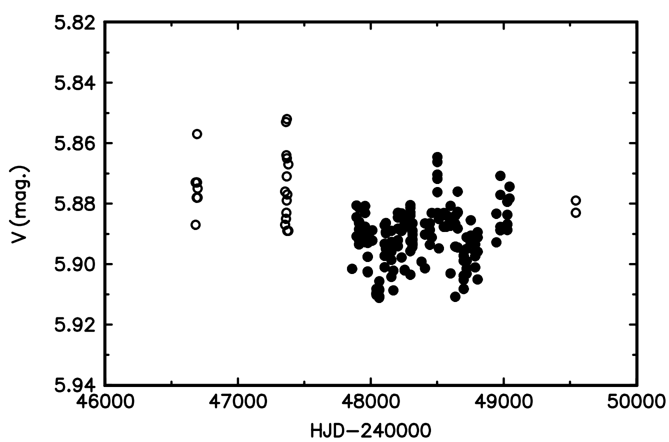

Fig. 16. Hvar and transformed Hipparcos photometry of 42 Cyg

Hipparcos data is almost $0\overset{\mathrm{m}}{.}04$. It seems safer to omit this star from the final data set.

23 Vul (HD 192806, HIP 99874); O – C = -$0\overset{\mathrm{m}}{.}025$
As seen in Fig. 15, the early Hvar observations show a great deal of scatter. It appears safer to omit this star from the final data set.

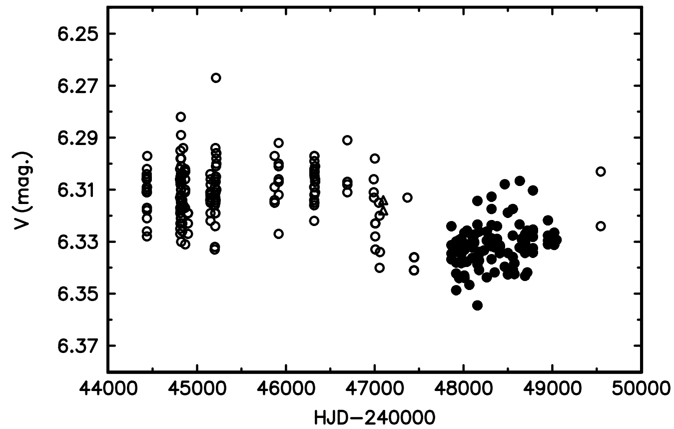

Fig. 17. Hvar and transformed Hipparcos photometry of V379 Cep

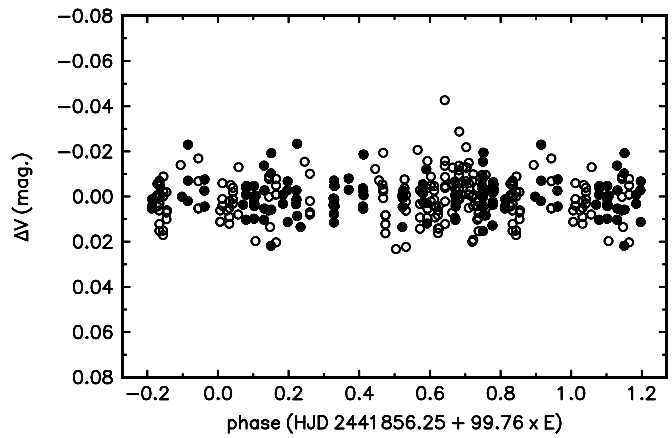

Fig. 18. Hvar and transformed Hipparcos photometry of V379 Cep plotted vs. phase of the $99\overset{\mathrm{d}}{.}76$ period

42 Cyg (HD 195324, HIP 101067); O – C = +$0\overset{\mathrm{m}}{.}015$
Fig. 16 shows that 42 Cyg is undoubtedly a light variable with a possible period of about 700 d. It must be omitted from the final set of transformation standards.

V379 Cep (HD 197770, HIP 102258); O – C = +$0\overset{\mathrm{m}}{.}021$
V379 Cep (HR 7940) is a strongly reddened B2III star. Jerzykiewicz (1993) discovered its variability and suggested that it is an eclipsing variable with a period of $24\overset{\mathrm{d}}{.}45$. He admitted, however, that the period is uncertain because of the small number of observations during the eclipse. The depth of the reported eclipse was about $0\overset{\mathrm{m}}{.}06$ only. Clayton (1996) obtained new UBV observations of the star and concluded that it is indeed an eclipsing binary but with a period of $99\overset{\mathrm{d}}{.}76 \pm 0\overset{\mathrm{d}}{.}04$ and with about equally deep primary and secondary eclipses. His light curve shows also occasional brightenings, in addition to the reported eclipses. Clayton also mentions a preliminary spectroscopic result indicating that the star is a double-lined spectroscopic binary.

V379 Cep was frequently observed at Hvar as one of the comparison stars and as a good transformation standard. Fig. 17 is a plot of numerous Hvar and Hipparcos observations vs. time. It clearly shows that the variability of the star is more compli-

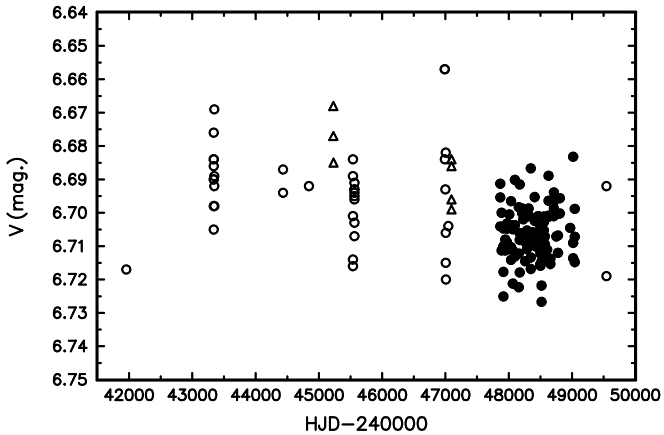

Fig. 19. Hvar and transformed Hipparcos photometry of HD 208218

Table 1. Coefficients of the transformation formula 1: The final values, recommended to interested users, are given in the first row of the table. Column "rms" gives the rms error of one observation with respect to the corresponding least-squares fit

	α_1	α_2	α_3	α_4	α_5	rms
OK	-0.2964	0.0050	0.1110	0.0157	0.0072	$0.^{\mathrm{m}}0067$
med	-0.3031	0.0075	0.1220	0.0095	0.0090	$0.^{\mathrm{m}}0102$
all	-0.3006	0.0039	0.1382	0.0008	0.0077	$0.^{\mathrm{m}}0131$

cated than believed so far. The data show a smooth long-term cyclic change over the interval covered by the observations. It would be important to obtain some Hα spectra of this star to see if it is not in fact a mild Be star.

Fig. 18 is a plot of the same data, prewhitened for the long-term change, vs. phase of the $99.^{\mathrm{d}}76$ period and epoch determined by Clayton (1996). One may suspect the presence of the secondary eclipse near phase $0.^{\mathrm{P}}50$. The primary eclipse is not seen and the scatter outside the expected eclipses is comparably large. The question is whether the star is not also a rapid physical variable. As a precaution, I shall omit it from the final data set.

HD 208218 (HIP 99874); O − C = $+0.^{\mathrm{m}}015$
This star is the brightest member of the cluster NGC 7160. As seen in Fig. 19, both Hvar and Hipparcos observations seem to indicate possible slight rapid variability but no systematic trend. Since this is another early-type reddened star, I decided to keep it in the final data set.

To obtain the final values of the transformation coefficients α, I omitted all of the above-discussed stars for which some evidence of variability could be found and calculated another fit to formula (1), using only the remaining stars.

The final coefficients are given under label "OK" in the first row of Table 1. It is seen that the rms errors decreased to $0.^{\mathrm{m}}0067$ and all individual $O-C$ deviations are now below $0.^{\mathrm{m}}02$. They are shown as a function of $(B-V)$ in Fig. 20. For comparison, I also give there the coefficients which resulted from the fit to

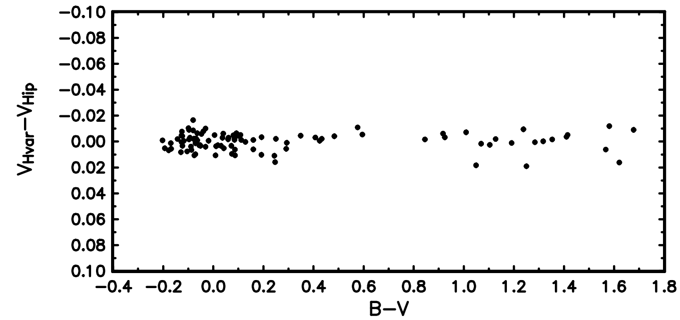

Fig. 20. A plot of the $O-C$ deviations vs. $(B-V)$ from the least-square fit of formula (1) to the final data set

all stars (row "all") and an intermediate result (row "med") after deletion of 46 Lib and 21 Sgr. One can see that the differences of the coefficients are very small, showing that the result is quite robust.

The result is very encouraging not only for its practical applicability but also for the fact that is shows the quality of Hipparcos and also Hvar and Skalnaté Pleso reductions. The stars used for the final transformation are recommedable as standards also for other photometric programs.

It is also important to note that the accuracy of the determination of the standard Johnson V and B magnitudes for a given star is essentially given by the accuracy with which one knows the $(B-V)$ colour index for that star. It is seen that an error of $0.^{\mathrm{m}}03$ in $(B-V)$ would result in a $0.^{\mathrm{m}}01$ error in V and less than $0.^{\mathrm{m}}02$ error in B. Very fortunately, the dependence on $U-B$ is a very weak one. Therefore, even a very approximate knowledge of the $(U-B)$ index suffices for a reliable calculation of V and B magnitudes from the Hipparcos H_p magnitude.

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