A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
(08.04.1; 08.06.3; 08.12.1)

ASTRONOMY AND ASTROPHYSICS
November 17, 1998

The absolute magnitude of K0V stars from HIPPARCOS parallaxes

René D. Oudmaijer[1], **Martin A.T. Groenewegen**[2] & **Hans Schrijver**[3]

[1] Astrophysics Group, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, U.K.
[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85740 Garching, Germany
[3] SRON, Sorbonnelaan 2, NL-3584 CA Utrecht, The Netherlands

Accepted 1999. Received 1999; in original form 1999

Abstract. We investigate the properties of K0V stars with Hipparcos parallaxes and spectral types taken from the Michigan Spectral Survey. The sample of 200 objects allows the empirical investigation of the magnitude selection (Malmquist) bias, which appears clearly present. By selecting those objects that are not affected by bias, we find a mean absolute magnitude of $M_V = 5.7$, a downward revision from 5.9 mag. listed in Schmidt-Kaler (1982). Some objects have absolute magnitudes far brighter than $M_V = 5.7$, and it is suggested that these objects ($\approx 20\%$ of the total sample) are K0IV stars which may have been mis-classified as a K0V star. The presence of the Malmquist bias in even this high quality sample suggests that no sample can be expected to be bias-free.

Key words: Stars: distances - Stars: fundamental parameters - Stars: late-type

1. Introduction

The Hipparcos trigonometric parallax measurements of more than 100 000 stars (ESA, 1997) provide an excellent basis to determine the fundamental parameters of stars. Yet, some, not always trivial, problems arise which make the conversion from the measured parallax to intrinsic absolute magnitude of an object not straightforward. For example, the Lutz-Kelker effect (Lutz & Kelker, 1973), results in too faint magnitudes for large relative errors σ/π, while the Malmquist bias results in too bright mean absolute magnitudes, because at the observed magnitude limit, brighter objects will be included in a sample, while fainter objects will not. Additional complications are listed in Brown et al. (1997).

In a previous paper (Oudmaijer, Groenewegen & Schrijver 1998 - hereafter OGS98) we have shown empirically that the Lutz-Kelker bias is present in trigonometric parallaxes. This was done by comparing the best Hipparcos parallaxes ($\sigma/\pi < 5\%$ – defining a 'true' parallax sample) with lower quality ground-based parallaxes of a large sample of stars. The data showed that, for increasing σ/π, the derived absolute magnitude of an object indeed becomes too faint in a manner consistent with the Lutz-Kelker predictions (see also Koen 1992), but for even larger σ/π, the derived magnitudes became too bright by up to 2 magnitudes. The sample was evidently not hampered by only one type of bias, but by at least two. The first being the Lutz-Kelker bias, the second was called the 'completeness effect', which we now identify as the magnitude selection Malmquist bias.

To investigate this further, we tackle the problem in a similar way by analyzing a sample of stars for which it may be hoped that all have the same intrinsic magnitude. To this end, we have investigated a sample of stars with well-defined spectral types, the K0V stars.

2. Sample selection

To determine the absolute magnitudes of stars with the same spectral type, a coherent and homogeneous database of spectral types is needed. The Michigan Spectral Survey Volumes 1..4 (MSS, Houk & Cowley 1975; Houk 1978; Houk 1982 and Houk & Smith-Moore 1988, providing spectral types of the HD catalogue in Declination from –90° to –12°) is such a database. We chose to investigate K0V stars, as these objects are relatively close by and will not suffer much from interstellar extinction, while the number of objects is relatively large. The selection criteria from the Hipparcos Catalogue (ESA, 1997) were:

(i) Spectral type = 'K0V ' (Field H76, the sources for the spectral types are listed in Field H77)
(ii) Goodness-of-fit < 3 (Field H29)
(iii) Number of rejected data < 10% (Field H30)

563 objects in the Hipparcos catalogue have 'K0V ' listed in their spectral type entry, but the majority of the stars has the spectral type taken from other sources than the MSS or are listed as 'G8V/K0V'. These objects were rejected, leaving a sample of 201 objects. Only one of these

Send offprint requests to: René Oudmaijer

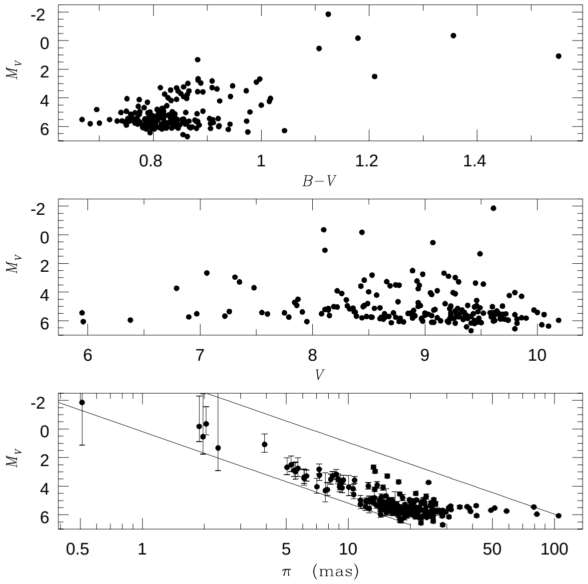

Fig. 1. Derived M_V as function of several parameters. Errorbars on the absolute magnitudes are for convenience only shown in the lower panel, and are often smaller than the plotsymbols. The solid lines are drawn according to Eq. 1 in OGS98, and explained in the text.

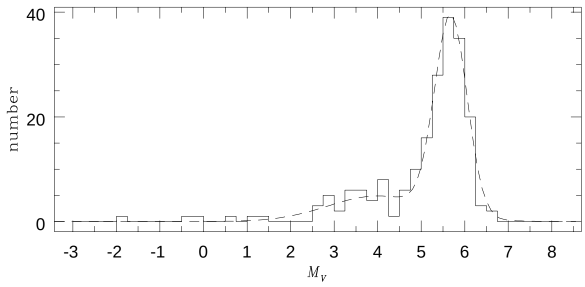

Fig. 2. The distribution of M_V, binned to 0.25 mag. bins. The dotted line represents a two component Gaussian fit to the data.

has a negative parallax (HD 219882), and was also rejected for further analysis, one object (HD 170132) has no *(B–V)* listed in the Hipparcos catalogue, its value was taken from the SIMBAD database.

The selection thus yielded 200 objects. The average error on the parallax and its scatter, are 1.4 ± 0.6 mas, and the bulk of the sample has parallaxes larger than 10 mas, probing the nearest 100 pc. The quality of the parallaxes is extremely high; the average σ/π is 11%, indicating a 9σ detection on average.

3. Properties of the sample

The absolute magnitude, derived from the parallax and the *V* magnitude, neglecting interstellar extinction, is plotted in Fig. 1. The upper panel shows M_V against *(B–V)*. The unweighted mean $M_V = 5.06 \pm 1.26$ (the r.m.s. deviation around the mean) is almost 1 magnitude brighter compared to what is expected for K0V stars ($M_V = 5.9$, Schmidt-Kaler 1982, hereafter SK82). Some objects are even 6 - 8 magnitudes brighter than a normal K0V star. A trend in (*B–V*) may be present, as the redder stars correspond to the intrinsically brightest objects. The relation between M_V and V (middle panel) shows a large scatter which seems to increase for fainter objects. There is a strong correlation between the derived M_V and the measured parallax (lower panel). For small parallaxes, the intrinsic magnitude becomes brighter and, interestingly, for the smallest parallaxes, no objects have intrinsic magnitudes that are even close to $M_V = 5.9$. A strong limit to the derived M_V as function of parallax is present, which is due to the 'completeness effect' mentioned in OGS98.

As discussed in OGS98, the difference between the derived absolute magnitude of an object from its parallax and the limiting observed *V* magnitude of a sample define a 'forbidden' region. The reason is that stars that would have been present in the fainter regions (the lower left hand corner of the lower panel) are simply too faint to be included in the sample. An upper bound is also present, reflecting the fact that fewer bright objects are present than faint objects. The solid lines in the figure indicate the regions where no data are expected, and are drawn according to Eq. 1 in OGS98, with limiting magnitudes corresponding to the faintest *V* magnitude in this sample, $V = 10.19$, respectively the brightest, $V = 5.95$.

We now identify this 'completeness effect' with the magnitude selection Malmquist bias, which is working on exactly the same principle, and effectively forbids the use of entire samples to derive their mean absolute magnitude, without correcting for it and/or investigating when the bias starts to dominate. It has been advocated to first plot luminosities as a function of distance, a parameter directly related to the distance such as the red-shift in the case of galaxies (e.g. Sandage 1994) or, in this case parallax, to assess the presence of selection biases. Such diagnostic plots, sometimes called Spaenhauer diagrams after Spaenhauer (1978), also serve to identify Lutz-Kelker type biases (see OGS98). Sandage (1994) showed that his sample of galaxies suffers from the Malmquist bias (with $\Delta \mathrm{M} = 1.386 \times \sigma^2$, for a uniform space distribution, with σ the assumed intrinsic scatter of the absolute magnitude distribution, see e.g. Hanson, 1979) when he compared the average with a sub-sample, easily identifiable in the diagrams, which is not affected.

Let us now derive the Malmquist correction for our sample, Fig. 1 shows that those objects with $\pi > 20$ mas are not affected – the unweighted mean of these objects returns a value of $M_V = 5.69$ with an (intrinsic) scatter of 0.4 mag. The entire sample returns an average of 5.06 ± 1.26 mag. The expected Malmquist correction is 0.22 mag for $\sigma = 0.4$, so the difference between the de-

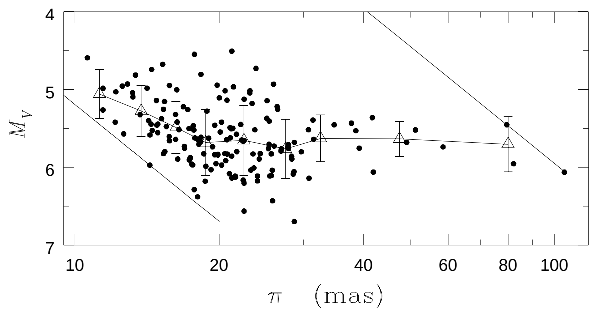

Fig. 3. The resulting K0V sample – 159 objects with $M_V > 4.5$. The solid lines are as in the previous figure. The triangles indicate the mean and its scatter in the parallax bins 10-12.5; 12.5-15; 15-17.5; 17.5-20; 20-25; 25-30; 30-35; 35-60 and > 60 mas.

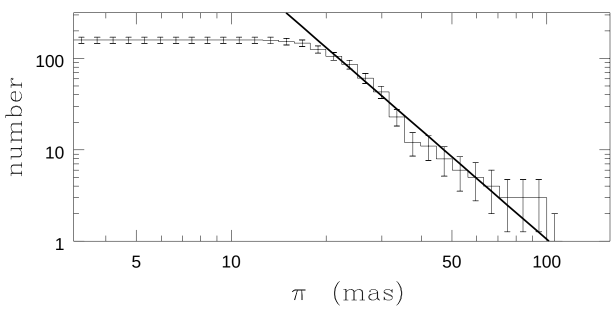

Fig. 4. Cumulative parallax distribution of the K0V sample. The solid line indicates a fit through the data points with $\pi > 20$ mas. The bins are 0.05 wide in $\log(\pi)$ units, the errorbars represent the statistical error ($\sqrt{N}$).

rived M_V for the entire sample and that of the unaffected sub-sample is much larger than what the Malmquist bias predicts. This is at first sight hard to understand, but may be related to the question why we would find K0V stars which are up to 6-8 magnitudes brighter than expected. Apart from the rather unlikely possibilities that parallax errors would result in such deviant values (these objects have very high signal-to-noise detections) or that the class of K0V stars can have such a large range of intrinsic magnitudes, it may be more likely that the discrepancy is due to spectral misclassification.

Some information may be gained from Fig. 2, where the distribution of the derived M_V values is shown. The distribution peaks close to 5.7, but is not symmetric around the mean; a secondary maximum appears close to $M_V = 3.5$. The presence of a secondary peak strongly suggests that an additional population of stars is present. These could be objects with a different spectral type as the peak roughly agrees with the magnitudes of K0IV stars ($M_V = 3.1$, SK82), while K0III giants may also be present ($M_V = 0.7$, SK82). It is hard to make a good distinction between the different groups, judging the gaps between the $M_V \approx 5.7$ and $M_V \approx 3.5$ objects in Figs. 1 and 2, the separation seems to be present for $M_V = 4.5$.

159 of the 200 objects are present in the 'faint' sample with $M_V > 4.5$, the remaining 41 stars have brighter intrinsic magnitudes. The average *(B–V)* of the faint (i.e. K0V) sample is 0.82 ± 0.05, consistent with the intrinsic colours for the group (0.81, SK82), also suggesting that our neglect of interstellar reddening is warranted. The remaining objects have a redder average *(B–V)* of 0.94 but with a large scatter of 0.16 mag. If we reject the 6 brightest objects in this sample, the scatter is reduced and the average *(B–V)* = 0.89 ± 0.08, with an average M_V of 3.5 ± 0.5, consistent with a K0IV nature of the sample. Although Schmidt-Kaler (1982) does not list the $(B{-}V)_0$ for K0IV objects, the interpolated value between K0V and K0III stars is 0.90, close to what is measured. The remaining 6 objects have even redder colours, *(B–V)* = 1.2 ± 0.2 with an average $M_V = 0.1 \pm 1$ mag, suggesting that these may be K0III stars.

The simplest explanation for the large range in absolute magnitudes then appears that the sample of K0V stars in the MSS survey is contaminated by K0IV objects (about 20% of the entire sample), and perhaps suffers from contamination from intrinsically even brighter objects.

4. The K0V subsample and the Malmquist bias

In the following, we will continue with the K0V sample, i.e. the 159 objects with inferred intrinsic magnitudes fainter than 4.5. Our interest is whether the 'completeness effect' or Malmquist bias affects the determination of the intrinsic magnitude of the sample under consideration. Fig. 3 shows the same figure as the lower panel of Fig. 1, but now only for the K0V sample. As before, there is a clear trend visible. The smaller the parallax, the brighter the mean is. We have binned the data in steps of π, and calculated the mean and its scatter. In the interval π = 10-12.5 mas (which are still 6-10σ detections), the mean is 0.7 mag brighter than in the interval 60-100 mas.

The change in mean absolute magnitude is easily understood. This can be learned from the volume completeness of the sample. Fig 4 shows the cumulative parallax distribution of the stars. The distribution flattens below $\pi < 20$ mas indicating that the sample is complete to ≈ 20 mas. The solid line represents a weighted least-squares fit to the data between 20 and 100 mas, with slope −3±0.15, implying a uniform space distribution, consistent with the small volume probed to 50 pc. The Malmquist bias only occurs for volume-incomplete samples, and indeed, for $\pi > 20$ mas, the mean magnitude in the bins does not change in Fig. 3, but it does for the lower parallax values.

What is the effect *in this particular case* on the derived absolute magnitudes of K0V stars if the Malmquist bias would not have been taken into account? The unweighted mean of the 159 objects is 5.59 ± 0.42 mag, while the unweighted mean for the unaffected sample (85 stars with $\pi > 20$ mas) is $M_V = 5.69 \pm 0.40$ mag. The scatter of ≈ 0.40 reflects the intrinsic scatter rather than errors arising from the measurement uncertainties, and may for example be due to variations in metallicity, rotation period or unseen binaries. The difference between the two values is more in agreement with the prediction that the Malmquist bias is of order 0.2 mag – this is dependent on the distinction between the K0V and the 'K0IV' samples, because a fainter cut-off value results in a slightly smaller scatter around the mean.

However, there is one significant difference with e.g. the situation of red-shifts as distance determinations: in the parallax case the relative observational error σ/π, is much larger than in the case of the red-shifts, so a straightforward averaging of the derived absolute magnitudes should be replaced by a weighting scheme. This will decrease the effect of the Malmquist bias somewhat: The objects that are more prone to the selection effects are further away, and have larger relative errors on the parallax, they will therefore have less weight. Since the error is asymmetric in magnitudes, we now have to calculate the weighted mean in 'reduced parallax' ($10^{0.2M_V}$). The weighting of all 159 objects now results in a mean $M_V = 5.65$, while the 85 objects with $\pi > 20$ mas have a weighted mean of 5.69 mag. So, for this sample, consisting of both high quality parallax measurements and spectral types, not taking into account the Malmquist bias would result in an unweighted mean too bright consistent with the expected value of the Malmquist bias, and a weighted mean absolute magnitude that is too bright by 0.04 mag.

The main result concerning the 'true' intrinsic magnitude of K0V stars is that the sample which is not affected by contamination by K0IV stars yields a value 0.2 mag brighter than has been listed in the literature so far (SK82). The existing calibrations apparently need a revision and this work illustrates the power of Hipparcos trigonometric parallaxes. An additional result is that the stars that we tentatively identify as K0IV objects seem to be 0.4 mag. fainter than expected. However, we do not put much weight to this result, as these by implication would be mis-classified K0V stars, and thus likely to be those K0IV objects that are on the fainter side of the distribution in the first place. A detailed study of this effect is beyond the scope of the present paper.

5. Final remarks

We have studied a sample of 200 K0V stars, taken from the best collection of spectral types available, the Michigan Spectral Survey, which have excellent trigonometric parallaxes from the Hipparcos mission. In our high quality data, the Malmquist bias occurs already when the measured parallax is 20 mas, the point where volume-incompleteness sets in. The presence of the Malmquist bias is readily seen, when the Spaenhauer diagram is used as a diagnostic tool. Only because K0V stars are intrinsically faint, the Malmquist bias starts to play a role this quickly. For intrinsically brighter objects, or samples with fainter limiting V magnitudes, the completeness limit will be pushed to lower observed parallaxes.

So far, we have not discussed the Lutz-Kelker (1973) effect – as shown in OGS98, this effect becomes important when the relative error on the parallax is still comparitively low (10-20%). Since the absolute errors on the parallaxes are almost all the same (≈ 1.4 mas in our sample), this corresponds to an observed π of 7-14 mas. In the case of the faint K0V stars, the Malmquist effect dominates at these parallaxes, so objects that otherwise would have had too faint derived absolute magnitudes are excluded from the sample, perhaps lowering the effect of the Malmquist bias. To assess such effects, one has to examine intrinsically brighter objects, as done in OGS98, or by Kaltcheva & Knude (1998) who investigated B stars. The latter authors showed that for well determined parallaxes ($\sigma/\pi < 10\%$), the absolute magnitudes of B stars derived from the parallax agree with the absolute magnitudes derived from Hβ photometric distances, but for less well determined parallaxes (σ/π between 10% and 20%), the individual objects are too faint, in agreement with the prediction for Lutz-Kelker bias.

As a final comment, it is expected that each sample of stars will prove to be sensitive to the Malmquist and Lutz-Kelker biases in its own unique way, and only careful examination of the data can make their, sometimes hidden, effects visible. An additional result of this work is that around 41 out of 200 K0V stars may be misclassified K0IV stars.

Acknowledgements RDO is funded by PPARC. This paper is based on data from the ESA Hipparcos satellite.

References

Brown A.G.A. Arenou F., van Leeuwen F., Lindegren L., Luri X., 1997, Hipparcos-Venice '97 Proceedings, ESA SP-402, p. 63
ESA, "The Hipparcos and Tycho Catalogues", 1997, ESA SP-1200
Hanson R.B. 1979, MNRAS 186, 875
Houk N. & Cowley A.P. 1975, "MSS, Vol 1", Univ. Michigan
Houk N. 1978, "MSS, Vol 2", Univ. Michigan
Houk N. 1982, "MSS, Vol 3", Univ. Michigan
Houk N. & Smith-Moore M. 1988, "MSS, Vol 4", Univ. Michigan
Kaltcheva N., Knude J. 1998, A&A 337, 178
Koen C. 1992, MNRAS 256, 65
Lutz T.E., Kelker D.H. 1973, PASP 85, 573
Oudmaijer R.D., Groenewegen M.A.T., Schrijver H. 1998, MNRAS 294, L41 (OGS98)
Sandage A. 1994, ApJ 430, 1
Schmidt-Kaler Th. 1982, in Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series Group VI, Vol. 2b, Springer-Verlag (SK82)
Spaenhauer A.M. 1978, A&A 65, 313