Hipparcos absolute magnitudes for metal rich K giants and the calibration of DDO photometry

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ABSTRACT

Parallaxes for 581 bright K giants have been determined using the Hipparcos satellite. We combine the trigonometric parallaxes with ground based photometric data to determine the K giant absolute magnitudes. For all these giants, absolute magnitude estimates can also be made using the intermediate band photometric DDO system (Janes 1975, 1979). We compare the DDO absolute magnitudes with the very accurate Hipparcos absolute magnitudes, finding various systematic offsets in the DDO system. These systematic effects can be corrected, and we provide a new calibration of the DDO system allowing absolute magnitude to be determined with an accuracy of 0.35 mag in the range $2 < M_V < -1$. The new calibration performs well when tested on K giants with DDO photometry in a selection of low reddening open-clusters with well-measured distance moduli.

1 INTRODUCTION

K giants are bright and ubiquitous, occurring in a wide range of Galactic populations, and are convenient tracer objects for examining the structure and kinematics of the Galaxy. The chief difficulty with these objects has been the uncertainty in their absolute magnitudes, which arises from the fact that stars on the giant branch form from a wide range of mass and age, as well as the giant branch being rather steep as a function of colour. K giants span a broad range of absolute magnitude $M_V$ from about $2 < M_V < -3$.

In some studies accurate distances to the tracer objects are required such as in Bahcall, Flynn and Gould (1991) and Flynn and Fuchs (1994), who used the kinematics of K giants to constrain the amount of dark matter present in the Galactic disc. In these studies the absolute magnitudes and hence distances of the giants were estimated using David Dunlop Observatory (DDO) photometry. This is an intermediate band photometric system of six filters, four of which can be used to estimate physical parameters for late type giants (McClure 1976). The four filters are called 41, 42, 45 and 48 and are at the wavelengths 4166, 4257, 4517 and 4886 Å and have passbands of 83, 73, 76 and 186 Å respectively. Three colours, C4142, C4548 and C4245 are formed from these four filters. C4245 is primarily sensitive to effective temperature, C4548 to luminosity and C4142 can be used in combination with the other two colours to estimate stellar metallicity, [Fe/H]. Janes (1979) describes the measurement of absolute magnitude and abundance using these filters. His absolute magnitude scale was based on distances determined by means of the Wilson-Bappu effect, and was later adjusted slightly when DDO photometry had been obtained of K giants in open clusters. Janes’ calibration applies to metal rich disc stars ([Fe/H] > $-$1), although the system has been extended to metal weak populations (e.g. Norris, Bessell and Pickles 1985, Morrison, Flynn and Freeman 1990, and Claria et.al. 1994). In this paper we are concerned with metal rich K giants only, [Fe/H] > $-$0.5.

The European Space Agency’s Hipparcos satellite has observed all bright (apparent $V < 8.0$) K giants, which are included in the all sky part of the Hipparcos Input Catalogue (HIC), so that very high accuracy trigonometric parallaxes are now available in the Hipparcos Catalogue (ESA 1997). Before Hipparcos, only a handful of giants had accurate parallax measurements, whereas Hipparcos has now measured accurate parallaxes for around 600 giants. In this paper, we use the parallaxes of local K giants from Hipparcos to check the DDO system’s absolute magnitude calibration. Our sample is described in section 2. A number of systematic offsets are found in the DDO absolute magnitudes, particularly for the redder ($B – V > 1.2$) giants and around the clump giants. In section 3 we develop a new calibration of the DDO system, tied to the Hipparcos results. In addition to remov-
ing the systematic errors in the old system, the new calibration is a good deal simpler to use. Absolute magnitudes of K-giants can thus be determined photometrically over the range \(2 < M_V < -1\) with an accuracy of 0.34 magnitudes. In section 4 the new calibration is found to be satisfactory when checked with K giants in old open clusters for which DDO photometry is available in the literature. The calibration developed here can be applied in a wide range of Galactic structure studies, one of which is the measurement of the amount of dark matter in the Galactic disc. We draw our conclusions in section 5.

2 K GIANT SAMPLE AND ANALYSIS

Our specific purpose was to calibrate the distance scale for metal rich K giants, \([\text{Fe/H}] > -0.5\), since it is these giants which are of particular interest in the examination of the mass density of the local disc. Accordingly, we selected all G and K giants in the Bright Star Catalog brighter than \(V=6.5\) and for which DDO photometry is available from Mclure and Forrester (1981). We selected stars in the colour range \(0.85 < C4245 < 1.15\), which corresponds closely to the \(B-V\) range \(1.0 < B-V < 1.35\) (Flynn and Freeman 1993) and isolates (approximately) G8 to K3 giants. All the chosen objects are well within the magnitude limit of Hipparcos (which is complete over the whole sky to \(V = 7.3\)), so all were measured by the satellite. The parallaxes \(\pi\) obtained by the satellite have errors \(\sigma_\pi\) of typically 0.8 mas (mas = milliarcsec). There were 676 giants in this basic sample. We obtained Hipparcos data for the sample in the first PI release, in August 1996. For each object, we used the Hipparcos measurement of the parallax \(\pi\), the parallax error \(\sigma_\pi\) and the apparent \(V\) magnitude to calculate the absolute magnitude \(M_V\) and error in the absolute magnitude \(\delta M_V\). Figure 1 we show the distribution of parallaxes \(\pi\), the distribution of the relative parallax error \(\sigma_\pi/\pi\) and the distribution of absolute magnitude error \(\delta M_V\). These figures demonstrate the very high quality of the Hipparcos data. A typical giant in this sample has a parallax of 10 mas, a relative parallax error of 8% and an absolute magnitude error of 0.15 mag. We used the apparent \(V\) magnitudes in the Hipparcos Input Catalog, which are accurate to 0.01 mag., and hence the parallax error completely dominates the absolute magnitude error.

Most of these stars are closer to the Sun than 120 pc so that the reddening to each star is expected to be small. We checked this by calculating the reddening to each star using the method of Janes (1975) from the DDO photometry and \(B-V\) colour. The mean reddening of the sample was found to be \(E(B-V) = 0.01\) with a scatter of 0.03 dex. A histogram of the reddening values is shown in Figure 2. The scatter is consistent with the accuracy of the method of 0.03 dex (Janes 1975). For a handful of stars a small amount of reddening was indicated, and so stars with \(E(B-V) > 0.05\) were removed from the sample. For the remaining stars the mean reddening reduces to \(E(B-V) = 0.00\) so no reddening corrections were deemed necessary.

Finally we confined ourselves to stars with a relative parallax error of less than 0.15 (or an absolute magnitude error of less than 0.32 mag — see Figure 1). This reduces the sample to 581 giants and places a distance limit on the sample of approximately 120 pc.

The colour magnitude diagram (CMD) of our selected giants is shown in Figure 3(a), where \(B-V\) colour from the Hipparcos Catalogue is plotted versus the absolute magnitude, \(M_V\) (Hipp), determined from the Hipparcos parallaxes and the \(V\) magnitude in the Hipparcos catalogue. The prominent features are the steeply rising giant branch and the clump stars near \(M_V = 0.8\). The typical error in absolute magnitude is 0.15 mag.

For each giant an absolute magnitude \(M_V\) (DDO) was estimated using Janes (1979) calibration. Figure 3(b) shows the CMD using this method for the same giants as Figure 3(a). Hipparcos clearly reveals that there are two main problems in the DDO calibration. Firstly, \(M_V\) (DDO) for the redder giants \((B-V > 1.2)\) is underestimated (i.e. Hipparcos reveals that they are brighter than previously thought). Secondly, the position of the clump stars (the core He burning giants in the field equivalent of the Horizontal Branch) is estimated too bright (by approx 0.3 mag) with the DDO system. Note that the clump stars show up as a much sharper feature in the Hipparcos diagram because the typical errors in the absolute magnitudes are much smaller.

\(\text{Figure 1. The Hipparcos results for the basic sample of 676 metal rich K giants. Lower panel: distribution of parallax } \pi \text{ in mas (milliarcsec). A typical giant has a parallax of 10 mas. Middle panel: distribution of the relative standard error in the parallaxes } \sigma_\pi/\pi. \text{ Upper panel: distribution of the absolute magnitude standard error } \delta M_V \text{ for the giants. A typical giant has a standard error of 0.15 mag.}\)
2.1 Malmquist bias and Lutz-Kelker corrections

In any sample of parallaxes which is magnitude limited like this one, there are potentially biases in the derived absolute magnitudes due to Malmquist bias and the Lutz-Kelker (1973) effect.

The simplest method to determine the size of these biases was to carry out a Monte-Carlo simulation of our selection procedure on simulated catalogs of stars. The results show that for this particular sample such biases are smaller than 0.01 mag, and can be safely ignored. This is primarily due to the high accuracy of the Hipparcos parallaxes and the very small number of stars rejected because of a large relative parallax error.

We carried out simulations in which we distributed 10000 stars at random with uniform density in a sphere around the Sun to a radius of 400 pc; this being beyond the most distant stars in the observed sample. The stars were assumed to have the same absolute magnitude \( M_V \). We know the true distance and true parallax \( \pi \) for each star, and we simulate the measured parallax \( \pi(\text{obs}) \) for each star from \( \pi \) by adding an error drawn from a Gaussian distribution of dispersion \( \sigma_\pi = 0.8 \) mas.

The main selection criteria of the real sample of stars are that \( V < 6.5 \) and that the relative parallax error \( \sigma_\pi/\pi < 0.15 \). For all stars meeting these selection criteria in the simulation, we compare the true absolute magnitude \( M_V \) and the absolute magnitude \( M_V(\text{obs}) \) we would derive from the observed parallax \( \pi(\text{obs}) \). We find that, over the range in absolute magnitude of interest, \( 2 \gtrsim M_V \gtrsim -1 \), the mean difference between true and measured absolute magnitudes is less than 0.01 mag.

We assumed the stars are uniformly distributed in space, which is a reasonable first approximation since most of the stars in the sample are closer than 120 pc. The stars will actually have some vertical density falloff, and we tested the effect of an exponential falloff where the density \( \rho \) of the stars falls with height \( z \) above the Galactic plane like \( \rho(z) = \rho(0)e^{-z/h} \), with the scale height \( h \) ranging between 100 and 300 pc, typical values for the Galactic disk. As expected, no systematic differences between true and measured absolute magnitude were found. We conclude from our simulations that our estimates of the stellar absolute magnitudes based on \( 1/\pi \) require no corrections for Malmquist or Lutz-Kelker bias.

3 DDO2 : AN METAL RICH K-GIANT ABSOLUTE MAGNITUDE ESTIMATOR

3.1 The initial calibration

The DDO absolute magnitudes clearly show several systematic differences relative to the Hipparcos data. We decided
Figure 4. Residual abundance dependence of the fit to the Hipparcos absolute magnitudes. The line shows the adopted correction (Equation 2) for this residual dependence with [Fe/H].

We investigated the possible systematic effects as follows: we divided the colour-magnitude diagram into a grid of boxes 0.1 mag. wide in colour and 0.5 to 1.0 mag. wide in $M_V$. There were typically 30 giants in each box with which to check for systematic differences in the estimated and true (Hipparcos) absolute magnitude as functionos of colour or abundance. No systematics were found in the areas dominated by the first ascent giants (in particular the region $B - V > 1.15$). A clear trend was found in the horizontal branch ($B - V < 1.15$) region. Hence, in the region $B - V < 1.15$ there is a correction to the absolute magnitudes of

$$
\Delta M_V(2) = b_0 + b_1 \times [\text{Fe/H}] \quad \text{for} \quad B - V < 1.15
$$

This leads to our DDO2 absolute magnitude estimator:

$$
M_V(\text{DDO2}) = M_V(1) + \Delta M_V(1) + \Delta M_V(2).
$$

Figure 5 shows the CMD of the giants using this transformation $M_V(\text{DDO2})$, including the metallicity corrections. Comparing this with the Hipparcos measured CMD (Figure 3a) one sees that with the new system the positions of the clump stars and the redder giants, as well as the CMD magnitude in general, are more satisfactory than with the old DDO system. In Figure 6 we show the residuals between $M_V(\text{Hipp})$ and $M_V(\text{DDO2})$ as functions of $B - V$, [Fe/H] and $M_V(\text{DDO2})$, to illustrate that no significant residual trends are apparent.

### Table 1. Best fit coefficients of the surface fit to $M_V$ and the residual [Fe/H] dependence (Equations 1, 2 and 3)

| Coefficient | Value     |
|-------------|-----------|
| $a_1$       | -3.5185187|
| $b_1$       | 31.6767174|
| $c_1$       | 5.3719567 |
| $d_1$       | -28.1707768|  
| $e_1$       | -27.7136769|
| $f_1$       | 29.6306218 |
| $a_2$       | 0.058910365|
| $a_3$       | 1.12501061 |
| $a_4$       | 0.85962826 |
| $b_0$       | 0.051     |
| $b_1$       | 0.897     |

Equations (1) and (2) lead to an absolute magnitude estimator for which no residuals remain as a function of colour or metallicity for the 581 giants as a whole. However, since the evolutionary state of the giants varies significantly over the colour-magnitude diagram (in particular we have both clump and first ascent giants in the sample), it remained possible that interplay between colour and metallicity could lead to measurable systematic offsets in particular regions of the colour-magnitude diagram. For example in the clump region, metal poor giants tend to be bluer and the metal rich ones redder, while on the Giant Branch, metal poor giants are bluer and brighter than metal rich giants.

We investigated the possible systematic effects as follows: we divided the colour-magnitude diagram into a grid of boxes 0.1 mag. wide in colour and 0.5 to 1.0 mag. wide in $M_V$.
In summary, the new calibration of DDO photometry can be used to derive absolute magnitudes for metal rich ([Fe/H] > -0.5) K giants with an accuracy of 0.34 dex over the absolute magnitude range $2 > M_V > -1$ and in the colour range $0.85 < C_{4245} < 1.15$.

4 CHECKING THE CALIBRATION USING K GIANTS IN OPEN CLUSTERS

Our new DDO calibration (DDO2) is based on the Hipparcos absolute magnitudes for local K giants. Younger giants will therefore be overrepresented in the calibration sample since they remain closer to the plane than older giants. To check that this age bias has not led to systematic effects for older giants, we can check the calibration by examining K giants with DDO photometry in old open clusters, for which ages are known. The cluster distance moduli, if based on main sequence fitting, allow the absolute magnitudes of the giants to be found independently. This provides a general check on the calibration and so is useful in any case.

We choose almost the same set of clusters as analysed by Flynn and Mermilliod (1991). These authors checked the absolute magnitude zero point of the DDO system, confirming the Janes (1979) analysis, by using much improved distance estimates (based on main sequence photometry) to open clusters than were available to Janes in 1979. Distance estimates to these clusters have improved still further since 1991, and we list the clusters and the adopted parameters in Table 2. Two clusters, NGC 2423 and NGC 2099 have been dropped, since DDO data are now available for it. In Table 2 we show the cluster name (column 1), the adopted distance modulus and its source (columns 2 and 3), the log of the age in years, (column 4, log($T$)), the adopted reddening $E(B - V)$ in column 6 and the number of giants $N$ with DDO photometry in column 7. The data for these clusters were obtained from the General Catalogue of Photometric Data maintained by J.-C. Mermilliod, B. Hauck and M. Mermilliod. Their website (http://obswww.unige.ch/gcpd/gcpd.html) enabled us to search for all available DDO data in open clusters. We obtained DDO and broadband $V$ and $B - V$ photometry for the cluster giants from this site. We de-reddened the DDO photometry using the Janes (1975) method, using the mean cluster reddening rather than individually determined reddenings, as this was judged a more stable process. Cluster giants with de-reddened colours in the range $0.85 < C_{4245} < 1.15$ were then selected (the colour range of the Hipparcos sample) and this is the number of giants $N$ seen in column 7 of Table 2. For each giant the absolute magnitude was calculated from the apparent magnitude and the apparent distance modulus, which we denote $M_V$(distmod), and was also calculated from the de-reddened DDO photometry using the new calibration in the previous section and this we denote $M_V$(DDO2). For the giants in each cluster the mean difference between these was calculated (and shown in column 8 of Table 2)
Table 2. Open clusters used to check the absolute magnitude calibration

| Name       | $(M - m)_V$ | Sourcea | log(Age) | [Fe/H] | $E(B - V)$ | $N$ | $\Delta M_V$ |
|------------|-------------|---------|----------|--------|------------|----|-------------|
| IC 4651    | 10.32       | 1       | 9.28     | 0.10   | 0.14       | 9  | 0.119       |
| Melotte 66 | 12.69       | 2       | 9.69     | -0.51  | 0.13       | 2  | -0.110      |
| NGC 188    | 11.71       | 1       | 9.82     | -0.05  | 0.12       | 9  | 0.201       |
| NGC 752    | 7.94        | 1       | 9.25     | -0.25  | 0.02       | 4  | -0.165      |
| NGC 2287   | 9.18        | 1       | 8.38     | -0.06  | 0.01       | 5  | 0.356       |
| NGC 2360   | 10.52       | 2       | 9.27     | -0.28  | 0.08       | 3  | 0.343       |
| NGC 2420   | 11.85       | 2       | 9.47     | -0.42  | 0.02       | 5  | -0.141      |
| NGC 2506   | 12.60       | 2       | 9.36     | -0.52  | 0.02       | 3  | 0.395       |
| NGC 2548   | 9.12        | 3       | 8.50     | -0.13  | 0.04       | 3  | -0.195      |
| NGC 2682 (M67) | 9.58 | 2       | 9.70     | -0.09  | 0.05       | 25 | 0.136       |
| NGC 3114   | 9.99        | 4       | 7.89     | -0.13  | 0.04       | 9  | -0.461      |
| NGC 3532   | 8.47        | 1       | 8.50     | -0.15  | 0.04       | 3  | -0.192      |
| NGC 3680   | 10.33       | 2       | 9.60     | -0.16  | 0.06       | 9  | 0.735       |
| NGC 3960   | 12.03       | 2       | 9.03     | -0.34  | 0.30       | 2  | 0.033       |
| NGC 5822   | 9.68        | 2       | 9.08     | -0.21  | 0.12       | 6  | 0.127       |
| NGC 6791   | 13.60       | 5       | 10.0     | 0.20   | 0.20       | 7  | -0.697      |
| NGC 7789   | 12.04       | 2       | 9.26     | -0.24  | 0.24       | 9  | -0.276      |

a Sources for apparent distance moduli, $(M - m)_V$
1: Meynet, Mermilliod, Maeder (1993)
2: Friel (1995)
3: Janes, Tilley, Lyngå (1988)
4: Sagar, Sharples (1991)
5: Tripicco, Bell, Dorman, Hufnagel (1995)

These results are shown in Figure 7 where for each of the 17 clusters the mean difference in the methods is shown as a function of cluster abundance [Fe/H], age and reddening. One can see that there are no significant trends with age, abundance or reddening. It is satisfying to see no significant trend with reddening or abundance, although these are only self-consistency checks on the method. Most important in this plot is that there is no significant trend with age. Since the calibration was derived from local K giants, amongst which young K giants will be overrepresented, there was a potential for a systematic difference in the older clusters, but this is not seen. We conclude that the method can be applied to disc K giants over a full range of age, and further that there are no significant systematic differences between our absolute magnitude calibration and the absolute magnitudes of giants in well studied open clusters. We expect an improvement in the near future in the distance moduli to some of these clusters, since Hipparcos has made direct parallax measurements for a large number of stars in open clusters.

5 DISCUSSION AND CONCLUSIONS

We have used very accurate Hipparcos data for a sample of 581 local K giants to measure their absolute magnitudes. These stars were used to check the absolute magnitudes derived using intermediate band DDO photometry. A number of systematic offsets in the DDO system emerged from this comparison. The Hipparcos data were then used to derive a new calibration of absolute magnitude in the DDO system. We have checked our new calibration satisfactorily against K giants with DDO photometry in 17 open clusters. Our calibration is appropriate for K giants in the colour range $0.85 < C4245 < 1.15$ or approximately $0.95 < B - V < 1.3$,
and with $[\text{Fe/H}] > -0.5$, (i.e. metal rich stars) with an accuracy of 0.35 mag.

The quality of the Hipparcos data enable a great improvement to be made in the estimation of K giant $M_V$ by photometric methods. With the release of the full data set in mid-1997, it should be possible to extend the calibration presented here to giants with $[\text{Fe/H}] < -0.5$ and to subgiants. K giants have a venerable tradition in Galactic structure studies, such as tracing inner and outer disc kinematics, measuring the disc scale length, properties of the Bulge, and the disc dark matter problem. The latter was our primary motivation for this study, since the work of Bahcall, Flynn and Gould (1992), Flynn and Fuchs (1994) used K giants to trace the scale height and kinematics of the disc and place limits on its dark matter content. This new calibration will provide an improved measure of the distances of K giants and we are looking forward to using it to reanalyse the disc dark matter problem.

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