The Cepheid distance to the Local Group galaxy NGC 6822

Michael W. Feast, 1,2 Patricia A. Whitelock, 1,2 John W. Menzies 2* and Noriyuki Matsunaga 3

1 Astronomy, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, 7701 Rondebosch, South Africa
2 South African Astronomical Observatory, PO Box 9, 7935 Observatory, South Africa
3 Kiso Observatory, Institute of Astronomy, The University of Tokyo, 10762-30 Mitake, Kiso, Nagano 397-0101, Japan

ABSTRACT
Recent estimates of the Cepheid distance modulus of NGC 6822 differ by 0.18 mag. To investigate this we present new multi-epoch $JHK_s$ photometry of classical Cepheids in the central region of NGC 6822 and show that there is a zero-point difference from earlier work. These data together with optical and mid-infrared observations from the literature are used to derive estimates of the distance modulus of NGC 6822. A best value of 23.40 mag is adopted, based on a Large Magellanic Cloud (LMC) distance modulus of 18.50 mag. The standard error of this quantity is ~0.05 mag. We show that to derive consistent moduli from Cepheid observations at different wavelengths, it is necessary that the fiducial LMC period–luminosity relations at these wavelengths should refer to the same subsample of stars. Such a set is provided. A distance modulus based on RR Lyrae variables agrees with the Cepheid result.

Key words: stars: variables: Cepheids – galaxies: distances and redshifts – galaxies: individual: NGC 6822 – Local Group.

1 INTRODUCTION
Local Group galaxies, besides being of interest in their own right, are important test beds of Galactic and extragalactic distance indicators. For much extragalactic work classical Cepheids are of prime importance. It is somewhat disconcerting therefore that recent work 1 on Cepheids in NGC 6822, a Local Group dwarf galaxy, has led to distance moduli which differ by up to 0.18 mag, a 9 per cent range in distance. This is at a time when there is a general expectation that Cepheid distances to extragalactic systems can be obtained with very high precision (e.g. a distance with a 3 per cent uncertainty for M31; Riess, Fliri & Valls-Gabaud 2012). Uncertainties in the Cepheid distance to NGC 6822 have implications for the use of Cepheids generally.

For NGC 6822, Pietrzyński et al. (2004) found $(m - M)_0 = 23.34 \pm 0.04$ (statistical) $\pm 0.05$ (systematic) mag using a period–magnitude–colour relation in $VI$. Combining these results with new $JK$ observations, Gieren et al. (2006) found $23.31 \pm 0.021$ mag. On the other hand, Madore et al. (2009a) combined optical observations with mid-infrared (mid-IR) data to derive a modulus of $23.49 \pm 0.03$ mag. All these estimates are based on an assumed modulus of the Large Magellanic Cloud (LMC) of 18.50 mag and it was also assumed that any Cepheid metallicity corrections between the LMC and NGC 6822 were negligible. Madore et al. showed that it was difficult to combine their mid-IR data with the Gieren et al. $JK$ results, suggesting possible problems with these or the mid-IR data. In this paper we present new multi-epoch $JHK_s$ photometry of Cepheids in the central regions of NGC 6822 and compare this with earlier work. We then derive the distance modulus of the galaxy by combining these data with optical and mid-IR observations in a variety of ways and discuss the discrepancies noted above.

This work is part of a $JHK_s$ study of Local Group galaxies aimed primarily at asymptotic giant branch variables, but also dealing with other types of objects, and the structure of colour–magnitude diagrams.

2 OBSERVATIONS
Our survey of NGC 6822 is confined to the optical bar which is aligned nearly north–south. We used the Japanese–South African IRSF telescope equipped with the SIRIUS camera, which permits simultaneous imaging in the $J$, $H$ and $K_s$ bands. We defined three overlapping fields, with field 1 centred at $a(2000.0) = 19^h 44^m 56^s$ and $\delta(2000.0) = -14^\circ 48' 06''$. Fields 2 and 3 are centred 6.73 arcmin north and south, respectively, from field 1. The three fields, approximately 7.8 arcmin$^2$, were observed in $JHK_s$ at 19, 18 and 16 epochs, respectively, over a period of 3.5 yr. Typically 30 dithered exposures of 30 s each were combined at each epoch, though occasionally, depending on sky brightness at $K_s$, exposure times were reduced to 20 s.

Photometry was carried out with the DOPHOT program (Schechter, Mateo & Saha 1993) in ‘fixed-position’ mode. To allow for possible non-photometric nights, a set of bright reference stars was used to

*E-mail: jwm@sao.ac.za
1 Early work on the Cepheids in NGC 6822 is summarized by Madore et al. (2009a).
normalize the resultant magnitudes for the images in each band. The mean magnitudes of stars in common with Two Micron All Sky Survey (2MASS) were used to put our photometry on to the 2MASS system. Table 1 shows the number of 2MASS stars of quality AAA used in each field, together with the standard deviations (s.d.) of the comparisons with our magnitudes. The comparison stars cover the range 12.5–16.1 mag in J, 12.1–15.1 mag in H and 12.0–14.7 mag in KS. For each field, there is a different number of stars in each band following rejection of >3σ outliers.

The standard deviations are consistent with expectations, being almost entirely attributable to the quoted 2MASS errors. The residuals were investigated for colour equation, but none was found over the J–KS range, 0.4–1.5 mag, of the 2MASS stars. The implication is that our zero-points are accurate to 0.01 mag in all bands.

3 RESULTS

Table 2 lists our individual observations of the Cepheids (or possible Cepheids) in common with Pietrzyński et al. (2004). Intensity mean magnitudes for these stars are listed in Table 3. The mean magnitudes were determined by converting our JHKs magnitudes to intensities and then Fourier-fitting a sine curve. The mean intensity from the best fit was converted to a magnitude, which is listed in the table. Fourier fits of up to third order (i.e. using as many as two harmonics) were tried and the order that gave the best fit was used; for cep014 and fainter stars only first-order fits were made. Fig. 1 shows our intensity mean values of Ks plotted against log period.

In fitting a line to these data we have omitted cep001 (period = 123.9 d). Cepheids of such long periods are known to deviate from extrapolations of linear period–luminosity (PL) relations and these stars have been omitted by other observers on these grounds. In addition, we have omitted cep002 (log P = 1.82 d) since it is of longer period than the LMC stars in the OGLE survey we use (see below). We have also omitted the six stars with log P < 1.1. Of these stars cep026 was rejected by Pietrzyński et al. (2004) because it deviated from their optical PL relations. Their optical data also show that cep025, cep028 and cep101 are far too bright for their PL relations and they do not include them in their figs 9, 10 and 11. Our JHKs data are similarly too bright for our PL relations. Some or all of these stars may be overtone pulsators. Finally, cep022 and cep024 were omitted because the uncertainty of our KS is large for these stars. All the data of Table 3 are shown in the KS–log P plot of Fig. 1. For illustration the line in this figure is fitted to the Cepheids chosen above with a slope from the LMC (equation 7).

Table 1. Comparison with 2MASS.

| Band | Field | No. of stars | s.d. (mag) |
|------|-------|--------------|------------|
| J    | 1     | 86           | 0.053      |
|      | 2     | 89           | 0.044      |
|      | 3     | 84           | 0.035      |
| H    | 1     | 67           | 0.061      |
|      | 2     | 72           | 0.048      |
|      | 3     | 75           | 0.032      |
| K    | 1     | 75           | 0.074      |
|      | 2     | 69           | 0.084      |
|      | 3     | 71           | 0.051      |

Table 2. JHKs photometry for Cepheids observed in NGC 6822. This is a sample of the full table, which is available as Supporting Information with the online version of the article.

| HJD  | J   | σj  | H   | σH  | Ks  | σK  |
|------|-----|-----|-----|-----|-----|-----|
| −245000 | 2353.49644 | 15.781 | 0.009 | 15.271 | 0.010 | 15.056 | 0.017 |
| 2436.50394 | 15.352 | 0.008 | 14.866 | 0.008 | 14.616 | 0.012 |
| 2440.50422 | 15.359 | 0.009 | 14.925 | 0.013 | 14.721 | 0.016 |
| 2441.50423 | 15.386 | 0.008 | 14.865 | 0.008 | 14.683 | 0.021 |
| 2441.50423 | 15.382 | 0.008 | 14.883 | 0.008 | 14.705 | 0.013 |
| 2507.29760 | 15.883 | 0.009 | 15.439 | 0.012 | 15.225 | 0.014 |
| 2808.46756 | 15.310 | 0.009 | 14.871 | 0.010 | 14.652 | 0.017 |
| 2809.38435 | 15.383 | 0.006 | 14.899 | 0.008 | 14.685 | 0.008 |
| 2529.28608 | 15.509 | 0.008 | 15.075 | 0.009 | 14.903 | 0.010 |
| 2882.34804 | 15.759 | 0.008 | 15.356 | 0.009 | 15.167 | 0.014 |
| 3093.62506 | 15.844 | 0.008 | 15.335 | 0.009 | 15.125 | 0.016 |
| 3173.44424 | 15.410 | 0.006 | 14.917 | 0.007 | 14.706 | 0.008 |
| 3243.35845 | 15.785 | 0.007 | 15.349 | 0.007 | 15.178 | 0.008 |
| 3259.26118 | 15.583 | 0.007 | 15.171 | 0.008 | 15.004 | 0.009 |
| 3260.26279 | 15.517 | 0.006 | 15.165 | 0.008 | 15.002 | 0.009 |
| 3293.28920 | 15.451 | 0.009 | 14.963 | 0.008 | 14.750 | 0.010 |
| 3531.55302 | 15.419 | 0.006 | 14.951 | 0.006 | 14.747 | 0.008 |
| 3533.40996 | 15.445 | 0.006 | 14.960 | 0.007 | 14.727 | 0.008 |
| 3612.30425 | 15.884 | 0.007 | 15.446 | 0.008 | 15.256 | 0.009 |

4 DISCUSSION

Previous workers on the Cepheids in NGC 6822 have adopted PL relations derived for LMC Cepheids and applied these to the NGC 6822 Cepheids to find the difference between the distance moduli for the two galaxies. An absolute distance modulus then follows from an adopted LMC modulus of 18.50 mag. We follow the same general procedure here. As done previously by others we obtain an estimate of the true modulus of NGC 6822 from the relation between the apparent moduli at various wavelengths with the relative absorption coefficients at these wavelengths. A true modulus can also be obtained from the reddening-free parameter W_V = I − 1.55(V − I) (see e.g. Udalski 2000). This relation has the advantage that it also corrects, at least to first order, for the intrinsic spread in magnitude and colour at a given period (width of the instability strip). This width is particularly significant at optical wavelengths. We also use the IR reddening-free parameter W_Ks = Ks − 0.68(J − Ks) (see e.g. Persson et al. 2004). A brief discussion of the value of the LMC modulus and the question of metallicity dependence of PL relations are given later.

4.1 LMC period–luminosity relations

The most extensive study of LMC Cepheids in VI has been the work of the OGLE group (e.g. Sozzański et al. 2008). Pietrzyński et al. (2004) adopted OGLE relations in PL(V), PL(I) and PL(WVI), specifically those tabulated by Udalski (2000) (which are given in a form corrected for adopted reddenings). These results have been adopted by Gieren et al. (2006) and Madore et al. (2009a). The latter two papers also adopt LMC PL relations in JHK from Persson et al. (2004). Madore et al. (2009a) also adopt LMC PL relations in [3.6], [4.5], [5.8], [8.0] μm from Madore et al. (2009b).

These procedures have the disadvantage that a joint analysis of NGC 6822 at different wavelengths relies on LMC relations based on different samples of LMC Cepheids in the optical, near-IR and mid-IR. This is particularly so in that the near- and mid-IR Cepheid
Table 3. Flux-weighted mean $JHK_S$ for Cepheids in NGC 6822.

| $J$     | $\sigma_J$ | $H$     | $\sigma_H$ | $K$     | $\sigma_K$ | $J-H$  | $H-K$   | $J-K$  | $P$ (d) | Name*   | IRSF |
|---------|------------|---------|------------|---------|------------|--------|---------|--------|--------|---------|------|
| 15.585  | 0.015      | 15.117  | 0.013      | 14.919  | 0.013      | 0.468  | 0.198   | 0.666  | 123.900 | cep001  | 10170|
| 15.620  | 0.009      | 15.161  | 0.008      | 15.004  | 0.010      | 0.459  | 0.157   | 0.616  | 65.3200 | cep002  | 30131|
| 15.536  | 0.009      | 16.041  | 0.008      | 15.881  | 0.013      | 0.495  | 0.160   | 0.655  | 37.4610 | cep003  | 10463|
| 16.732  | 0.012      | 16.236  | 0.008      | 16.104  | 0.014      | 0.496  | 0.132   | 0.628  | 34.6630 | cep004  | 40353|
| 16.799  | 0.013      | 16.317  | 0.012      | 16.132  | 0.013      | 0.482  | 0.186   | 0.667  | 30.5120 | cep007  | 11214|
| 17.484  | 0.017      | 17.030  | 0.010      | 16.876  | 0.017      | 0.454  | 0.155   | 0.668  | 19.9600 | cep010  | 30518|
| 17.597  | 0.010      | 17.012  | 0.009      | 16.902  | 0.029      | 0.585  | 0.110   | 0.695  | 19.8870 | cep011  | 12406|
| 17.679  | 0.017      | 17.141  | 0.013      | 17.037  | 0.027      | 0.538  | 0.104   | 0.641  | 19.6020 | cep012  | 30994|
| 17.566  | 0.008      | 17.139  | 0.008      | 16.948  | 0.017      | 0.427  | 0.197   | 0.618  | 18.3390 | cep014  | 40553|
| 17.662  | 0.012      | 17.239  | 0.013      | 17.114  | 0.024      | 0.424  | 0.124   | 0.548  | 17.3440 | cep015  | 11791|
| 17.886  | 0.028      | 17.373  | 0.031      | 17.254  | 0.040      | 0.514  | 0.118   | 0.632  | 16.9600 | cep016  | 30954|
| 17.918  | 0.020      | 17.327  | 0.015      | 17.153  | 0.025      | 0.590  | 0.174   | 0.765  | 16.8550 | cep017  | 12137|
| 17.958  | 0.012      | 17.505  | 0.017      | 17.295  | 0.026      | 0.453  | 0.210   | 0.663  | 13.8720 | cep018  | 40491|
| 18.522  | 0.041      | 18.057  | 0.050      | 17.974  | 0.074      | 0.465  | 0.084   | 0.548  | 10.2770 | cep022  | 31807|
| 18.490  | 0.027      | 18.041  | 0.034      | 17.953  | 0.058      | 0.449  | 0.088   | 0.537  | 9.3660  | cep024  | 13520|
| 18.140  | 0.026      | 17.406  | 0.029      | 17.150  | 0.024      | 0.734  | 0.256   | 0.990  | 8.9367  | cep025  | 12507|
| 18.528  | 0.029      | 18.071  | 0.031      | 17.906  | 0.060      | 0.457  | 0.165   | 0.622  | 8.4670  | cep026  | 31757|
| 17.518  | 0.013      | 16.896  | 0.010      | 16.704  | 0.020      | 0.622  | 0.192   | 0.814  | 7.2085  | cep028  | 31048|
| 18.719  | 0.026      | 17.971  | 0.030      | 17.702  | 0.057      | 0.748  | 0.268   | 1.017  | 2.5937  | cep101  | 31703|

*Stars cep003 to cep018 used in solutions.

$J = -3.160(\pm0.202)(\log P - 1.2) + 12.703(\pm0.023)$, \hspace{1cm} (4)

$H = -3.218(\pm0.168)(\log P - 1.2) + 12.308(\pm0.019)$, \hspace{1cm} (5)

$K_S = -3.234(\pm0.155)(\log P - 1.2) + 12.202(\pm0.017)$, \hspace{1cm} (6)

$W_{JHKS} = 3.285(\pm0.132)(\log P - 1.2) + 11.862(\pm0.015)$, \hspace{1cm} (7)

$[3.6] = -3.244(\pm0.179)(\log P - 1.2) + 12.087(\pm0.020)$, \hspace{1cm} (8)

$[4.5] = -3.162(\pm0.183)(\log P - 1.2) + 12.099(\pm0.021)$, \hspace{1cm} (9)

$[5.8] = -3.308(\pm0.182)(\log P - 1.2) + 12.060(\pm0.021)$, \hspace{1cm} (10)

$[8.0] = -3.308(\pm0.189)(\log P - 1.2) + 12.037(\pm0.021)$. \hspace{1cm} (11)

The joint sample used to derive these equations contained 32 Cepheids. Table A1 in Appendix A lists the stars and their coordinates for future reference. A joint sample involving shorter period Cepheids and hence more stars could no doubt be constructed. However, by restricting the LMC sample to longer periods we avoid any problems connected with non-linearity of the relations. The difference between these results and earlier work is best seen by comparing $W_{VJ}$ and $W_{JHKS}$ relations which are free of the problems related to reddening corrections employed by earlier workers. In the case of the Persson et al. $W_{JHKS}$ this difference (at a mean $\log P = 1.4$, which is close to the mean period of the NGC 6822 sample) is 0.073 mag, our result being fainter. Much of this difference must be due to confining the sample to stars with OGLE data. This is shown by the fact that the difference between equation (3) for $W_{VJ}$ and that used by...
Pietrzyński et al. (based on an OGLE LMC relation from Udalski 2000) is only 0.014 mag (our result being brighter) at log $P = 4.4$. Similarly, our result (equation 3) is 0.019 mag brighter at this log $P$ than the latest OGLE III relation (Soszyński et al. 2008).

### 4.2 NGC 6822 $JHK_s$ Cepheid data

#### 4.2.1 Comparison with previous work

$JK_s$ observations of NGC 6822 Cepheids have been made by Gieren et al. (2006). These are in the United Kingdom Infrared Telescope (UKIRT) system. Since these authors had only a small number of observations per star they derive intensity mean magnitudes by a phase-correction method based on the optical data of Pietrzyński et al. (2004). These results need to be converted to the 2MASS system to be compared with our work. For this we have used the relations derived by Carpenter (2001, as updated on the 2MASS web page). The transformations are small, being $K_{s}^{2M} - K_{s}^{UK} = +0.005$ mag and $J^{2M} - J^{UK} = +0.030$ mag at the mean colour of the Cepheids compared. We use stars cep003 to cep018 of Table 3 for comparison. This omits stars which lie off the PL relation or have large photometric errors. For the chosen sample the differences, in the sense IRSF–Gieren, are $\Delta K_s = +0.061 \pm 0.014$ mag and $\Delta J = +0.126 \pm 0.022$ mag. The results for individual stars are plotted in Fig. 2. These differences evidently need further investigation. In view of them we restrict ourselves in the following to an analysis of our own $JHK_s$ data so far as the near-IR is concerned, since we have found no evidence for scale errors in our analysis.

#### 4.2.2 Conversion to Persson system

To compare our NGC 6822 results with the Persson results for the LMC discussed in Section 4.1, they have to be converted to the LCO (NICMOS) system. This was also done using the Carpenter transformations. At the mean colours of the NGC 6822 Cepheids we use for distance estimation, the corrections, LCO–IRSF (2MASS), are small: $+0.013$ at $J$, $+0.008$ mag at $H$ and $+0.014$ mag at $K_s$.

In calculating the difference in modulus between NGC 6822 and the LMC we have used the 11 stars, cep003 to cep018, in Table 3 as indicated previously. Including cep002 ($P = 65.3$ d) makes no significant difference to our conclusions.

### 4.3 NGC 6822 modulus from $VIJHK_s$

Assuming the slopes and zero-points given in equations (1)–(11) and a true mean distance modulus of 18.50 for the LMC Cepheid sample we derive the apparent distance moduli of NGC 6822 listed in Table 4. This table also contains relative absorption coefficients based on the Cardelli, Clayton & Mathis (1989) reddening law and as given by Indebetouw et al. (2005) for the mid-IR. Fig. 3 shows a plot of the $VIJHK_s$ as well as the mid-IR apparent moduli against the relative absorption.

A least-squares solution of the $VIJHK_s$ data with equal weight to each point yields a true modulus of 23.43 ± 0.02 (int.) mag and $A_V = 0.667$ mag for the amount that the mean visual extinction for the NGC 6822 stars is greater than that for the fiducial LMC sample. This modulus is entered in Table 5 together with the true moduli derived from $W_{VI}$ and $W_{JK}$. The errors given combine those of the LMC relations used (not including any error in the LMC distance modulus) with those of the NGC 6822 results except in the case of the least-squares fit to the results at the five wavelengths where the internal error is quoted. This latter result shows how closely the results are fitted by a linear relation.

An unweighed mean of the three values of the true modulus is 23.40 mag, which we take as our best estimate. It is difficult to see any significant difference to our conclusions.

![Figure 2. Comparison of present mean magnitudes with those of Gieren et al. (2006), corrected to the 2MASS system, plotted against our mean magnitudes. The lines show the mean differences of 0.126 mag in $J$ and 0.060 mag in $K_s$, respectively, for the Cepheids. Those used in our period-luminosity fitting are marked as black dots, the remainder as crosses.](image)

![Figure 3. Apparent $VIJHK_s$ and mid-IR distance moduli determined from NGC 6822 Cepheids plotted as a function of relative absorption as listed in Table 4.](image)

| Band | App. mod. | s.e. | s.e. | $N$ | $A_V$/3.1$^d$ |
|------|-----------|------|------|----|--------------|
| $V$  | 24.11     | 0.06 | 0.07 | 1.000 |
| $I$  | 23.81     | 0.04 | 0.05 | 0.600 |
| $J$  | 23.65     | 0.03 | 0.04 | 0.282 |
| $H$  | 23.55     | 0.02 | 0.03 | 0.190 |
| $K_s$ | 23.51    | 0.03 | 0.03 | 0.114 |
| $[3.6]$ | 23.40 | 0.06 | 0.06 | 14 | 0.067 |
| $[4.5]$ | 23.44 | 0.07 | 0.08 | 12 | 0.054 |
| $[5.8]$ | 23.40 | 0.14 | 0.14 | 6 | 0.048 |
| $[8.0]$ | 23.43 | (0.14) | (0.14) | 2 | 0.045 |

*a* s.e. is the standard error of the NGC 6822 result. 
*b* s.e. includes the uncertainty in the LMC relations (not considering any error in the adopted LMC modulus). 
*c* For the mid-IR data the number of stars used. 
*d* The adopted relative extinctions.
Table 5. True modulus of NGC 6822.

| Band     | Mod.  | Note |
|----------|-------|------|
| V        | 23.43 ± 0.02 | 1    |
| İ       | 23.34 ± 0.04 | 2    |
| Ks       | 23.42 ± 0.03 | 2    |
| Mean     | 23.40 |      |
| [3.6]    | 23.36 ± 0.06 | 2.3  |
| [4.5]    | 23.40 ± 0.08 | 2.3  |
| [5.8]    | 23.37 ± 0.14 | 2.3  |
| [8.0]    | 23.40 ± (0.14) | 2.3  |
| Mean (mid-IR) | 23.38 |      |

(1) s.e. is internal value, (2) s.e. includes uncertainty in LMC relation and (3) assumes AV = 0.667.

to estimate the true uncertainty of this value. Even with full light curves there must be some correlation between the deviations from mean PL relations for a given Cepheid at different wavelengths and this may have an effect when the number of Cepheids in a sample is relatively modest. The problem is, of course, worse when one relies on single measurements of a star taken simultaneously at different wavelengths (as in the mid-IR work). We estimate an uncertainty of ±0.05 mag, not taking into account any error in the adopted distance modulus of the LMC (see below).

4.4 The NGC 6822 mid-IR data

Table 4 also contains the apparent moduli derived from the mid-IR data of Madore et al. (2009a) in the same way as that described in the previous section. Here we have used all the Cepheids in Madore et al. (2009b) with log P < 1.7. We did not use these data in the least-squares solution of the last subsection for a number of reasons. (1) There are no mid-IR data for some of the Cepheids in our 11-Cepheid sample. It would have reduced the available data too much to confine the solutions to stars in common in the optical, near-IR and mid-IR samples. For instance, for [3.6] there are only seven stars in common with our adopted 11. (2) The mid-IR data are for single-phase measures only. The residuals at the various wavelengths are likely to be highly correlated (unless dominated by observational error). (3) A minor point is that the reddening law in the mid-IR is not very certain at present. The true moduli derived from these data are given in Table 5 assuming the difference in AV between NGC 6822 and the LMC to be 0.667 mag as derived above. An unweighted mean of the four values is given in Table 5. It agrees remarkably well (better than could have been expected) with the results from shorter wavelengths.

4.5 Distance modulus of NGC 6822

As already noted we adopt 24.40 mag as our best estimate of the NGC 6822 modulus. The results in Table 5 show that with our new JHKs data and revised discussion the range of derived moduli has been reduced by a factor of 2 to 0.09 mag. It is interesting to note that our W_V result agrees exactly with that of Pietrzyński et al. (2004), who included shorter period Cepheids in their NGC 6822 sample. As noted above their LMC relation is close to the one we use. The W_İ result is rather sensitive to any systematic errors in the photometry (a zero-point error of 0.02 mag in İ leads to a systematic error of 0.05 mag in W_İ). Errors of this amount are indeed possible as discussed by Pietrzyński et al. In view of this we do not consider the difference between the W_V and W_İ results of Table 5 to be significant.

4.6 A note on the adopted LMC modulus and metallicity effects

The derived distance modulus for NGC 6822 assumes an LMC modulus of 18.50 mag. Various distance indicators give values close to this (see for instance recent summaries by Feast 2012 and Walker 2011). With a zero-point based on a reduced parallax-type solution of the parallaxes of Galactic Cepheids (Benedict et al. 2007; van Leeuwen et al. 2007), an LMC modulus of 18.52 ± 0.03 mag was obtained for W_V from an OGLE Cepheid sample. Similarly, a modulus of 18.47 ± 0.03 mag was obtained using the Persson et al. (2004) Ks results for the LMC. The difference between these two estimates is not significant. However, it is interesting to note that a difference in this sense is expected in view of the discussion of Section 4.1. In neither case there was any correction made for metallicity differences between the LMC and Galactic samples. The metallicity of a young (i.e. Cepheid-like) population in NGC 6822 is intermediate between that of the LMC and the Small Magellanic Cloud (see Venn et al. 2001 for a discussion). No metallicity corrections have been applied to our derived NGC 6822 moduli. Whether there are significant metallicity effects on Cepheid relations at different wavelengths remains somewhat controversial. It should also be noted that whilst the relative distances of the LMC and NGC 6822 rest on a comparison of long-period Cepheids, the LMC Cepheid distance comes primarily from a comparison of short-period Cepheids with Galactic Cepheids of known parallax.

4.7 The RR Lyrae distance modulus of NGC 6822

An RR Lyrae distance modulus to NGC 6822 can be derived from the work of Baldacci et al. (2005) and Clementini et al. (2003). The 24 ab-type RR Lyraes in table 4 of Baldacci et al. have mean magnitude, V = 24.63 ± 0.04 mag. From a period–metallicity relation, Clementini et al. estimate that the NGC 6822 RR Lyraes have a mean [Fe/H] relation from the parallaxes of Galactic RR Lyrae variables (Benedict et al. 2011) gives M_V = 0.37 ± 0.04 mag and an apparent distance modulus of (m − M) = 24.26 mag. If we adopt V = 0.77 mag from Clementini et al., based on Schlegel, Finkbeiner & Davis (1998), then (m − M)_0 = 23.49 mag. (This differs from the Clementini et al. result, 23.36, almost entirely because their RR Lyrae zero-point is fainter than the Benedict et al. one used here.) The estimate of the absorption is for the foreground of NGC 6822 only and uncertainty in the absorption may be the main uncertainty in this result. Without taking this uncertainty or that in the metallicity estimate into account the standard error of the modulus is ±0.06 mag. The agreement with the Cepheids uncorrected for metallicity effects is evidently satisfactory.

5 CONCLUSIONS

NGC 6822 is a test case for the precision which can be achieved in practice in deriving extragalactic distances from classical Cepheids. As in most current extragalactic work the Cepheid distance to NGC 6822 is derived relative to the LMC Cepheids. The LMC is known to have significant depth and structure in the line of sight and reddenings vary from star to star. Complications can then arise, especially in combining results at different wavelengths. Fiducial PL relations were therefore derived for a common set of long-period Cepheids.
at wavelengths from the optical to the mid-IR. Appreciable differences exist between these relations and some used earlier. Using the new relations together with new multi-epoch observations of NGC 6822 Cepheids in JHKs reduces the spread of moduli derived in different ways by a factor of 2 compared to earlier work. Our best estimate of the true modulus of NGC 6822 is 23.40 mag.

The standard error of this quantity is estimated as ~0.05 mag (i.e. a 3 per cent distance scale uncertainty) not taking into account any metallicity effects on either the LMC or the NGC 6822 Cepheids.

A distance modulus of the galaxy from RR Lyrae variables and based on a recent calibration of the RR Lyrae scale is 23.49 mag, which agrees with the Cepheid result within the uncertainties.

Work is in progress on the Mira variables in NGC 6822 and on the IR colour–magnitude diagram. This will allow further comparison of distance estimates.

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APPENDIX A: LMC CEPHEIDS FOR PL RELATIONS

Table A1. Cepheids used for LMC PL relations.

| OGLE name | HV name     | α (2000.0) | δ       |
|-----------|-------------|------------|---------|
| OGLE-LMC-CEP-0070 | HV12724 | 04:46:01.08 | −69:38:55.8 |
| OGLE-LMC-CEP-0174 | HV12471 | 04:50:52.43 | −69:18:55.9 |
| OGLE-LMC-CEP-0467 | HV876 | 04:57:12.34 | −67:22:57.3 |
| OGLE-LMC-CEP-0500 | HV2244 | 04:57:50.87 | −67:50:18.9 |
| OGLE-LMC-CEP-0501 | HV878 | 04:57:51.03 | −69:57:29.7 |
| OGLE-LMC-CEP-0504 | HV12505 | 04:57:56.73 | −68:48:57.6 |
| OGLE-LMC-CEP-0648 | HV2270 | 05:00:48.36 | −69:31:54.7 |
| OGLE-LMC-CEP-0655 | HV2260 | 05:00:55.86 | −68:26:20.8 |
| OGLE-LMC-CEP-0683 | HV2282 | 05:01:24.94 | −70:04:18.3 |
| OGLE-LMC-CEP-0727 | HV887 | 05:02:10.24 | −69:32:23.7 |
| OGLE-LMC-CEP-0819 | HV2291 | 05:03:46.16 | −68:52:36.4 |
| OGLE-LMC-CEP-0821 | HV889 | 05:03:49.50 | −65:56:02.7 |
| OGLE-LMC-CEP-0844 | HV891 | 05:04:15.47 | −69:01:36.4 |
| OGLE-LMC-CEP-0848 | HV892 | 05:04:21.08 | −68:43:42.8 |
| OGLE-LMC-CEP-0935 | HV893 | 05:06:00.89 | −69:06:17.1 |
| OGLE-LMC-CEP-0986 | HV899 | 05:07:07.81 | −68:53:19.5 |
| OGLE-LMC-CEP-1001 | HV2324 | 05:07:21.69 | −68:20:18.3 |
| OGLE-LMC-CEP-1058 | HV904 | 05:08:18.27 | −68:46:47.1 |
| OGLE-LMC-CEP-1088 | HV2339 | 05:08:49.54 | −68:59:59.1 |
| OGLE-LMC-CEP-1184 | HV5655 | 05:11:05.41 | −70:30:34.4 |
| OGLE-LMC-CEP-1538 | HV2432 | 05:18:13.79 | −69:19:30.5 |
| OGLE-LMC-CEP-1578 | HV932 | 05:19:14.80 | −69:36:18.1 |
| OGLE-LMC-CEP-1954 | HV2527 | 05:25:39.09 | −71:06:39.9 |
| OGLE-LMC-CEP-2023 | HV2549 | 05:27:00.58 | −71:38:35.8 |
| OGLE-LMC-CEP-2030 | HV2538 | 05:27:07.76 | −68:29:42.9 |
| OGLE-LMC-CEP-2337 | HV997 | 05:33:00.98 | −69:11:27.6 |
| OGLE-LMC-CEP-2534 | HV1005 | 05:36:06.80 | −68:49:13.4 |
| OGLE-LMC-CEP-2636 | HV1006 | 05:37:22.45 | −69:28:59.4 |
| OGLE-LMC-CEP-2949 | HV2793 | 05:41:48.53 | −68:41:16.1 |
| OGLE-LMC-CEP-3013 | HV1019 | 05:42:51.05 | −70:08:12.3 |
| OGLE-LMC-CEP-3203 | HV12656 | 05:48:06.94 | −71:30:21.4 |

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 2. JHKs photometry for Cepheids observed in NGC 6822.

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