A new LMC K-band distance from precision measurements of nearby red clump stars

C. D. Laney\textsuperscript{1, 2}\textsuperscript{*}, M. D. Joner\textsuperscript{1} and G. Pietrzyński\textsuperscript{3, 4}

\textsuperscript{1}Dept. of Physics and Astronomy, N283 ESC, Brigham Young University, Provo, UT 84601, USA
\textsuperscript{2}South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
\textsuperscript{3}Universidad de Concepción, Departamento de Astronomía, Casilla 160-C, Concepción, Chile
\textsuperscript{4}Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warsaw, Poland

ABSTRACT
High-precision ($\sigma_{\text{mag}} < 0.01$) new JHK observations of 226 of the brightest and nearest red clump stars in the solar neighbourhood are used to determine distance moduli for the LMC. The resulting K- and H-band values of 18.47 $\pm$ 0.02 and 18.49 $\pm$ 0.06 imply that any correction to the K-band Cepheid PL relation due to metallicity differences between Cepheids in the LMC and in the solar neighborhood must be quite small.

Key words: distance scale – Magellanic Clouds – infrared: stars – stars: variables: Cepheids

1 INTRODUCTION
In principle, the helium-burning red clump stars as defined by Paczyński & Stanek (1998) offer real advantages as distance indicators. They are a relatively numerous, well-defined population, and hundreds of red clump stars with quite accurate parallaxes can be found in the Hipparcos catalog. At first, attention centred on distance determination using the I band (Paczyński & Stanek 1998, Stanek & Garnavich 1998, Udalski et al. 1998, Udalski 2000), but the effects of stellar population differences on the mean V-band or I-band red clump magnitude can be considerable (Alves et al. 2002, Grocholski & Sarajedini 2002, Girardi & Salaris 2001, Groenewegen 2008, Pietrzyński et al. 2010). In the K band, the effects of stellar population differences and reddening are generally less (Salaris & Girardi 2002, Alves et al. 2002, Grocholski & Sarajedini 2002, Pietrzyński et al. 2010), although not always negligible. In particular, the estimated corrections are predicted to be much smaller when comparing the red clump populations in the solar neighborhood and in the LMC field (Salaris & Girardi 2002), and the data suggest that this is indeed the case (Alves et al. 2002, Pietrzyński et al. 2010).

But ever since Alves (2000) first determined a mean K-band absolute magnitude for nearby red clump stars, a fundamental weakness of this approach has been the quality of the infrared photometry available for nearby red clump stars. As pointed out by Alves, the stars with the best Hipparcos parallaxes are all saturated in the 2MASS survey data, and modern IR array detectors are too sensitive for stars with K$<5$. Indeed, a typical IR telescope/array combination like the InfraRed Survey Facility (IRSF) in South Africa has a bright limit of K=8 despite a telescope aperture of only 1.4m. The catalog data used by Alves were therefore a miscellaneous collection on no well-defined system, and the more modern data used by Groenewegen (2008) (giving a rather different result) were restricted to fainter stars.

Here it may be useful to quote Groenewegen: To settle the issue on the importance of the bias and the absolute K-magnitude of RC stars would require accurate NIR magnitudes of a 100 to a few hundred (cf. Table 2) bright (K $\sim$ 5) RC stars. Given the brightness, this represents a challenge to modern instrumentation because of saturation.

For this study we have determined accurate K-band magnitudes for 226 bright, nearby red clump stars with magnitudes brighter than K $\sim$ 5. With these data we have determined the mean K-band absolute magnitude for red clump stars in the solar neighbourhood to within 2%.

2 OBSERVATIONS AND ERRORS
JHK observations for 226 nearby red clump stars with K magnitudes between -0.3 and 4.9 were obtained with the 0.75m telescope at the South African Astronomical Observatory (SAAO), using the Mk. II infrared photometer and the same filter set used (Carter 1990) to define the SAAO JHKL standard system. Program stars were chosen from those identified by Paczyński & Stanek (1998), selecting for declinations observable from SAAO. As pointed out by a referee, it should perhaps be noted that the list of red clump stars...
stars given in Paczyński & Stanek (1998) excluded any objects with more than 10% error in their (original) Hipparcos parallaxes. As our selection from their list was not based on parallax, our subsample of 226 stars shares this cutoff. Our sample also necessarily shares their definition of the red clump in colour and absolute magnitude.

Standard stars from the Carter list were observed frequently, with preference given to observing standard and program stars at comparable airmass, while minimising the angular distance between standard and program stars on the sky. The resulting mean JHK magnitudes (transformed to the 2MASS system) can be found in Table 1 (complete version online), where the transformations from the Carter (1990) system to 2MASS have been taken from the 2MASS website (Carpenter 2003). Of the 226 program stars, 85 were observed more than once. From this subsample we have calculated the internal standard deviation of a single observation to be 0.008 in J and 0.006 in H and K, while the internal mean standard error for the 85 stars with multiple observations is 0.005 in J and 0.004 in H and K. The mean standard error for the entire sample (including stars observed only once) is thus about 0.007 in J and 0.005 in H and K.

The error introduced by standardisation is largely included in the above, since the second and any additional observations of a particular red clump star will in general not have been standardised using exactly the same choice of standards as for the first observation of that star.

How large is the error introduced by random errors in the standards used? A comparison of the Carter (1990) and CIT standards can be used to estimate the error introduced by standardisation. Assuming equal errors in both standard sets, the transformation equations given by Laney & Stobie (1993) imply a mean error in H and K of approximately 0.006. In general, there will be two standards involved in standardising a given programme star, thereby reducing the standardisation error to roughly 0.004, which suggests that random errors and standardisation errors are of about the same magnitude. Our precision and accuracy should be more than adequate for the present purpose.

3 DERIVING MEAN ABSOLUTE MAGNITUDES FOR THE HIPPARCOS SAMPLE

The absolute magnitudes given in Table 1 for our sample of nearby red clump stars were derived using the current Hipparcos parallaxes (van Leeuwen 2007), assuming as did Paczyński & Stanek (1998) and Alves (2000) that reddening-
A new LMC K-band distance from precision measurements of nearby red clump stars

Figure 2. $K_{2MASS}$ absolute magnitude vs. parallax. Symbols as in Figure 1. The horizontal line is the mean absolute magnitude for parallaxes $\geq 12$ mas.

Table 1

| HIP   | J    | H    | K    | par  | err  | type | H       | K       | [M/H]** |
|-------|------|------|------|------|------|------|---------|---------|---------|
| 671   | 4.282| 3.757| 3.653| 10.16| 0.42 | 5    | -1.208  | -1.312  | -0.07   |
| +765  | 2.182| 1.675| 1.561| 22.62| 0.45 | 1    | -1.552  | -1.667  |         |
| 814   | 3.579| 3.080| 2.968| 12.81| 0.19 | 5    | -1.383  | -1.494  |         |
| 966   | 4.776| 4.269| 4.151| 8.41 | 0.38 | 5    | -1.107  | -1.225  | -0.12   |
| 3137  | 4.150| 3.612| 3.485| 10.62| 0.43 | 5    | -1.258  | -1.385  | 0.03    |

*Star not used in calculating mean absolute magnitudes (see text)

**[M/H] on the scale of Liu et al. (2007)

ing is of negligible importance in the near-infrared for these nearby stars (average distance less than 70 pc). Examination of the figures in Marshall et al. (2006) also suggests that extinction in K is likely to be negligible. As a further test, we looked for a trend with parallax in H-K and J-K. No significant trend with parallax was found for J-K, while the trend in H-K suggests a K-band extinction only 0.003 greater for the most distant stars in our sample (about 180 pc) compared to the nearest (less than 20 pc), which is not too surprising given that almost all the stars in our sample lie within the 'local bubble' radius given by Jones, West & Foster (2011).

Some of the 226 stars observed were not used in deriving mean absolute magnitudes. It can be seen from Fig. 1 that the 29 stars for which Hipparcos parallaxes with 5-parameter fits (type 5) are not available (van Leeuwen 2007) tend to
Figure 3. \( K_{2\text{MASS}} \) absolute magnitudes as a function of metal abundance on the scale of Liu et al. (2007). Stars with 5-parameter parallax fits and metal abundances are represented by filled circles, and other red clump stars with measured metal abundances by open circles. Note the tendency for the stars without 5-parameter fits to be slightly fainter.

have parallaxes with substantially larger error bars. These 29 stars have therefore been omitted. Of the remaining 197 stars, six were also omitted from our final ‘good’ list – one with the reddest J-H color (and hence possibly reddened), one with a less than optimal parallax fit in the original Hipparcos reduction, two with low metal abundances outside the range of the rest of the sample, one whose absolute magnitude was clearly an outlier for its colors, and one with an abnormally large parallax error. Including these stars would decrease the mean absolute magnitude in both \( H_{2\text{MASS}} \) and \( K_{2\text{MASS}} \) by about 8 mmag.

The sample we actually used in determining mean absolute magnitudes therefore includes 191 of the 226 stars observed. Among these stars, there is a slight (2\( \sigma \)) tendency (Fig. 2) for the stars with parallaxes lower than about 12 mas to give fainter absolute magnitudes, which is in the expected sense for a sample with a cutoff determined either by parallax or by percentage error in parallax. Note that below 12 mas the parallax error begins to increase markedly (Fig. 1). If we define \( f \) to be 1 for parallaxes less than 12 mas and 0 for parallaxes \( \geq \) this value, we can write

\[
M_K = -1.605 \pm 0.022 + 0.062 \pm 0.030 f \quad (1)
\]

\[
M_H = -1.481 \pm 0.022 + 0.062 \pm 0.029 f \quad (2)
\]

\[
M_J = -0.974 \pm 0.020 + 0.057 \pm 0.027 f \quad (3)
\]

where K, H and J are on the 2MASS system.

Calculation of the effects of Lutz-Kelker correction (Smith 1999) for the 86 stars with parallaxes (van Leeuwen 2007) of 12 mas or greater gives a very small mean correction, which raises the mean K, H and J absolute magnitudes for this 'large parallax' subset to \(-1.607 \pm 0.022, -1.484 \pm 0.022\) and \(-0.976 \pm 0.020\), respectively.

Since Lutz-Kelker bias is a selection effect, and we selected stars with revised (i.e. 2007) Hipparcos parallaxes less than 12 mas, our calculation of the Lutz-Kelker corrections was likewise based on the revised Hipparcos parallaxes and errors. But our complete sample (191 stars) shares the cutoff in the original list of Paczyński & Stanek (1998), of which our observing list was a southern subset. This cutoff was based on the original (1997) Hipparcos results, and our calculation of the Lutz-Kelker corrections for our sample of 191 stars must likewise be based on the original Hipparcos parallaxes and errors. Such a calculation gives

\[
M_K = -1.613 \pm 0.015 \quad (4)
\]

\[
M_H = -1.490 \pm 0.015 \quad (5)
\]

\[
M_J = -0.984 \pm 0.014 \quad (6)
\]

on the 2MASS system. Reassuringly, these results differ from
those derived using our 'large parallax' subset (see above) by only 6-8mmag. Likewise reassuring is the fact that a comparison of these results with those including only the nearer stars shows no sign whatever of extinction effects.

4 TRENDS WITH METAL ABUNDANCE

Given past interest in the effect of metal abundance on red clump absolute magnitudes, we examined our data to see if any trend was apparent.

From our sample, 101 stars had metal abundances either from McWilliam (1990) or Liu et al. (2007). A comparison of 24 stars in common showed that the abundances from these two sources had different zero points, and that the McWilliam metallicities could be placed on the scale of Liu et al. simply by adding 0.12±0.02. For the stars with abundances from both sources, the two values have been averaged.

Absolute magnitudes in K$_{2MASS}$ and H$_{2MASS}$ have been plotted against metallicity (on the Liu et al. scale) in Figs. 3 and 4. As is evident from these figures, there is no strong, significant trend in either absolute magnitude with metallicity (at least for stars with [M/H] greater than -0.6), in agreement with the result found by Alves (2000).

5 LMC DISTANCE MODULUS

To derive an LMC distance modulus, we need a mean K$_{2MASS}$ value for LMC red clump stars. The two most comprehensive studies of LMC red clump stars in the field give dereddened mean K$_{2MASS}$ magnitudes of 16.887±0.009 (Alves et al. 2002) and 16.897±0.009 (Szewczyk et al. 2008), while an extensive recent survey of LMC red clump stars in clusters (Grocholski et al. 2007) yields a mean of 16.891±0.032. These are in extremely good agreement, and have been averaged to give

$$K_{2MASS} = 16.892 \pm 0.011$$  \hspace{1cm} (7)

We have followed Grocholski et al. (2007) in using the reddening law of Cardelli et al. (1989). The mean K magnitudes from Alves et al. (2002) and Grocholski et al. (2007) have been corrected to the LMC center as described in those papers, while the mean K magnitude from Szewczyk et al. (2008) has been left uncorrected for reasons cited by the authors of that paper. In all cases the K magnitudes from these three papers have been transformed to the 2MASS system using the transformations on the 2MASS website (Carpenter 2003). The mean K magnitudes for red clump stars in individual LMC clusters as given in Grocholski et al. have not been corrected for age and metallicity according to the formulation given by those authors, as this actually increases the dispersion in distance modulus.
Combining the mean $K_{2MASS}$ magnitudes for the solar neighbourhood and the LMC gives an uncorrected LMC distance modulus of 18.505±0.019. Applying K-band corrections for the age and metallicity differences between LMC and solar-neighbourhood red clump populations of -0.03 (Salaris & Girardi 2002) gives a ‘true’ LMC K-band distance modulus of 18.475±0.021, where we have somewhat arbitrarily allowed for an uncertainty of 0.01 mag in the population correction.

The only H-band mean magnitude for LMC red clump stars currently available in the literature is $H_{2MASS} = 17.03 ± 0.06$ from Koerwer (2009). On the assumption that H-K is about equal in LMC and solar neighborhood red clump stars (given that H-K is insensitive to both temperature and metallicity), we apply the same population correction as for K to get an H-band LMC modulus of 18.49±0.06, in good agreement with the K-band value but much less tightly constrained.

For LMC red clump stars in the J band, we have used the values given by Szewczyk et al. (2008), as neither Alves et al. (2002) nor Grocholski et al. (2007) provide J-band measurements. We get a mean $J_{2MASS}$ for LMC red clump stars of 17.40±0.02, and hence an uncorrected LMC distance modulus of 18.38±0.03. The discrepancy between this and the corrected K-band modulus is unsurprising, since the mean J-K for red clump stars in the LMC is about 0.13 bluer than in the solar neighbourhood, indicating that a substantial population correction would be required. Our results suggest that this correction would lie roughly halfway between the value for I (0.2, Girardi & Salaris 2001) and K (-0.03, Salaris & Girardi 2002).

6 COMPARISON WITH OTHER RESULTS

The mean red clump absolute magnitude in K derived above is consistent with that of Alves (2000), although an exact comparison is difficult given the absence of a well-defined standard system in the data used there. Our result is, however, somewhat brighter than that derived by Groenewegen (2008). This is not surprising in view of the trend toward fainter absolute magnitude with decreasing parallax seen in our own data. Alves’ sample included a range of parallaxes similar to that used here, while Groenewegen’s sample included only stars more distant than those we observed. The hypothesis considered by Groenewegen, that a bias might be present in his result because of a lack of data for bright nearby red clump stars, is thus confirmed. As all three studies use the same definition of the red clump (i.e. Paczyński & Stanek 1998), this is not a factor in the comparison.

The corrected distance to the LMC derived above is in good agreement with the K-band red clump distance derived by Alves et al. (2002) (18.49±0.03), which includes the same Salaris & Girardi (2002) population correction. Our uncorrected distance is in excellent agreement with Pietrzyński, Gieren and Udalski (2003) (18.50±0.01), who applied no correction for population differences. Red clump LMC distances derived using V and I magnitudes would need much larger and more uncertain corrections for abundance and age effects, and are best excluded from comparison (Pietrzyński et al. 2010). While the K-band correction undoubtedly has some uncertainty attached, the correction itself is quite small.

The uncorrected K-band Cepheid distance moduli of 18.48±0.04 (Benedict et al. 2007) and 18.47±0.03 (van Leeuwen et al. 2007) are likewise in excellent agreement, especially with our corrected distance. The uncorrected V-band and $W_{VI}$ distance moduli from Benedict et al. (2007), 18.50 ±0.03 and 18.52±0.06, and the $W_{VI}$ modulus from van Leeuwen et al. (2007), 18.52±0.03, are slightly larger, but LMC Cepheids have long been known to be bluer at a given period than Cepheids in the solar neighbourhood (Gascoigne & Kron 1965, Laney & Stobie 1986, 1994), so this small difference is in the expected sense, though hardly significant.

Agreement with the Cepheid moduli apparently also implies good agreement with the most recent RR Lyrae results from HST parallaxes (Benedict & McArthur 2011). For Type II Cepheids, the latest results (Matsunaga, Feast & Menzies 2009) give 18.46±0.10, which is in very good agreement although considerably less precise. This supersedes the earlier result (Feast et al. 2008), which gave a rather smaller modulus.

Results from LMC eclipsing binaries are rather sparse, and only one result is available for a binary where empirical surface brightnesses are available (Pietrzyński et al. 2009). Agreement between their value for the LMC modulus (18.50±0.06) and ours is reasonable enough, but a final comparison will have to wait until results for the remaining seven binaries in that phase of the Araucaria Project are available.

7 CONCLUSIONS

Near-IR observations of 226 red clump stars as bright as $K = -0.3$ have resulted in a determination of the local mean absolute magnitude in $H_{2MASS}$ and $K_{2MASS}$ accurate to ±0.02 mag. A comparison with K-band absolute magnitudes for LMC red clump stars from the literature implies an LMC distance modulus of 18.50±0.02 (uncorrected), or 18.47±0.02 (corrected by the value given in Salaris & Girardi 2002).

Comparison of this result to uncorrected Cepheid PL-relation distance moduli in the K-band (van Leeuwen et al. 2007, Benedict et al. 2007) suggests that metallicity corrections to distance moduli derived from near-IR Cepheid PL relations may not be very significant, at least for abundances between those in the solar neighbourhood and in the LMC.

In addition, the agreement between our distance modulus and those derived from Cepheid $W_{VI}$ PL relations (van Leeuwen et al. 2007, Benedict et al. 2007) suggests that Bonfanti et al. (2010) may be correct in arguing that metallicity corrections to distances from Cepheid Wesenheit (VI) PL relations may be fairly negligible.

Much the same holds for the V-band PL relation (Benedict et al. 2007), and these conclusions are strengthened by the recent results from RR Lyraes, Type II Cepheids, and (on a preliminary basis) one late-type double-line eclipsing binary as mentioned above.

In turn the results found here and in other recent papers strengthen the conclusions reached by Bresolin (2011), who found such a shallow oxygen abundance gradient in NGC
A new LMC K-band distance from precision measurements of nearby red clump stars

4258 HII regions that abundance differences could not realistically explain the difference in brightness between Cepheids in the outer and inner regions of that galaxy.

8 ACKNOWLEDGEMENTS

We would like to thank the South African Astronomical Observatory for generous allotments of observing time with what may be the world’s last instrument capable of high-precision IR observations of bright objects. Travel funding for this project has been provided by the Brigham Young University Department of Physics and Astronomy. Support from the FOCUS and TEAM subsidies of the Foundation for Polish Science (FNP) is also acknowledged. We extend our thanks to Dr. Benjamin J. Taylor for his comments on our original manuscript. We also thank Lisa Joner for her careful proofreading of several different versions of this paper. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France.

REFERENCES

Alves D.R., 2000, ApJ, 539, 732
Alves D.R., Rejkuba M., Minniti D., Cook K. H. 2002, ApJ, 573, L51
Benedict G.F., McArthur B.E., 2011, DDA mtg. 42, 3.06, Bull. Am. Ast. Soc., 43
Benedict G.F., McArthur B.E., Feast M.W., Barnes T.G. Harrison, T.E., Patterson R.J., Menzies, John W., Bean J.L., Freedman W.L., 2007, AJ, 133, 1810
Bresolin F., 2011, [arXiv:1101.0369v1]
Cardelli J.A., Clayton G.C., Mathis J.S., 1989, ApJ, 345, 245
Carpenter J., 2003, [http://www.astro.caltech.edu/~jmc/2mass/v3/transformations/]
Carter B.S., 1990, MNRAS, 242, 1
Feast M.W., Laney, C.D., Kinman, T.D.; van Leeuwen, F., White- lock, P.A., 2008, MNRAS, 386, 211
Gascoigne S.C.B., Kron G.E., 1965, MNRAS, 130, 333
Girardi L., Salaris M., 2001, MNRAS, 332, 109
Grocholski A.J., Sarajedini A. 2002, AJ, 123, 1603
Grocholski A.J., Sarajedini A., Olsen K.A.G., Tiede G.P, Mancone C.M., 2007, AJ, 134, 680
Groenewegen M.A.T., 2008, A&A, 488, 935
Koerwer J.F., 2009, AJ, 138, 1
Jones D.O., West A.A., Foster J.B., 2011, AJ, 142, 44
Laney C.D., Stobie R.S., 1986, MNRAS, 222, 449
Laney C.D., Stobie R.S., 1993, MNRAS, 263, 92
Laney C.D., Stobie R.S., 1994, MNRAS, 266, 441
Liu Y.J., Zhao G., Shi J.R., Pietrzyński G., Gieren W., 2007, MNRAS, 382, 553
Marshall D.J., Robin A.C., Reylé, Schultheis M., Picaud S., 2006, A&A, 453, 635
Matsunaga N., Feast M.W., Menzies J.W., 2009, MNRAS, 397, 933
Matsunaga N., Feast M.W., Soszyński I., 2011, MNRAS, 413, 223
McWilliam A., 1990, ApJS, 74, 1075
Paczynski B., Stanek K.Z., 1998, ApJ, 495, L219
Pietrzyński G., Gieren W., Udalski A., 2003, AJ, 125, 2494
Pietrzyński G., Thompson I., Graczyk D., Gieren W., Udalski A., Soszyński O., Minniti D., Kaluzkowsi Z., Bresolin F., Kudritzki R.P., 2009, ApJ, 697, 862
Pietrzyński G., Górski M., Gieren W., Laney D., Udalski A., Ciechanowska A., 2010, AJ, 140, 1038
Salaris M., Girardi L., 2002, MNRAS, 337, 332
Smith H., 1998, in "Modern Astrometry and Astrodynamics", R. Dvorak, H. F. Haupt, and K. Wodnar eds., Austrian Academy of Sciences Press, p. 139 (www.astro.ufl.edu/~hsmith/Vienna4.pdf)
Szewczyk O., Pietrzyński G., Gieren W., Storm J., Walker A., Rizzi L., Kinemuch, K., Bresolin F., Kudritzki R.P., Dall’Ora M., 2008, AJ, 136, 272
Stanek K.Z., and Garnavich P. M., 1998, ApJ, 503, L131
Udalski A., Szymański M., Kubíak M., Pietrzyński G., Woźniak P., and Zbieruś K., 1998, Acta Astron., 48, 147
Udalski A., 2000, ApJ, 531, L25
van Leeuwen F., 2007, "Hipparcos, The New Reduction", [http://vizier.ustrasbg.fr/cgi-bin/Vizier-I]
van Leeuwen F., Feast M.W., Whitelock P.A., Laney C.D., 2007, 379, 723