Optical Gravitational Lensing Experiment.
Distance to the Magellanic Clouds
with the Red Clump Stars:
Are the Magellanic Clouds 15% Closer
than Generally Accepted?

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ABSTRACT

We present a new distance determination to the Large and Small Magellanic Clouds using the newly developed red clump stars method (Paczyński and Stanek 1998). This new, single-step, Hipparcos calibrated method seems to be one of the most precise techniques of distance determination with very small statistical error due to large number of red clump stars usually available.

The distances were determined independently along four lines-of-sight located at opposite sides of each Magellanic Cloud. The results for each line-of-sight are very consistent. For the SMC we obtain the distance modulus: $m - M = 18.56 \pm 0.03 \pm 0.06$ mag (statistical and systematic errors, respectively) and for the LMC: $m - M = 18.08 \pm 0.03 \pm 0.12$ mag where systematic errors are mostly due to uncertainty in reddening estimates. Both distances will be refined and systematic errors reduced when accurate reddening maps for our fields are available.

Distance moduli to both Magellanic Clouds are $\approx 0.4$ mag smaller than generally accepted values. The modulus to the LMC is in good agreement with the recent determinations from RR Lyrae type stars and upper limit resulting from the SN1987A echo. We suspect that the distance to the LMC and SMC is shorter by about 15% than previously assumed: 42 kpc and 52 kpc, respectively. Calibrations of the period-luminosity relation for Cepheids which give overestimated distances to the LMC and SMC are probably incorrect and require urgent reanalysis.

\textsuperscript{*}Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.
We also present our color-magnitude diagrams around the red clump for the LMC and SMC. We identify vertical red clump, first noted by Zaritsky and Lin (1997), in the color-magnitude diagram of both Magellanic Clouds and we interpret it as an evolutionary feature rather than unknown stellar population between the LMC and our Galaxy.

**Key words:** Magellanic Clouds – Galaxies: distances and redshifts – Hertzsprung-Russel (HR) diagram

1 Introduction

Two of our closest neighboring galaxies from the Local Group – the Magellanic Clouds – belong to the most important objects of the modern astrophysics. Hosting many objects commonly used as standard candles at practically the same distance they serve as ideal targets for calibrating the distance scale in the Universe. Therefore it is crucial to have well established distances to both Magellanic Clouds.

Until recently, that is in the pre-Hipparcos era, it was generally accepted that the distance modulus to the Large Magellanic Cloud was in the range of $m-M=(18.5\div 18.6)$ mag based mostly on the calibration of the period-luminosity (P–L) relation for Cepheids (e.g., Laney and Stobie 1994, Gieren et al. 1997 and references therein) and measurements of the supernova SN1987A echo (cf. Panagia et al. 1991, Sonneborn et al. 1997). In 1992 Walker (1992) noted $\approx 0.3$ mag discrepancy between absolute magnitudes of RR Lyrae type stars from the Galaxy and the LMC at distance of 18.5 mag. Based on the new statistical parallax solution for RR Lyrae, Layden et al. (1997) recalibrated the absolute magnitude-metallicity relation for these stars and found that the resulting distance modulus to the LMC might be significantly lower: $m-M = 18.28 \pm 0.13$ mag.

The latest determinations of the distance to the LMC come from Hipparcos recalibration of the P–L relations for different type of pulsating stars. Both Cepheid and Mira recalibrations lead to larger distance moduli: Cepheids – $18.70 \pm 0.1$ mag (Feast and Catchpole 1997) or $18.57 \pm 0.11$ mag (Madore and Freedman 1998) and Miras – $18.54 \pm 0.18$ mag (van Leeuven et al. 1997). The value $m-M = 18.50 \pm 0.10$ mag has been adopted by the HST Extragalactic Distance Scale Key Project team (e.g., Rawson et al. 1997 and other papers of the series) as the distance to the LMC to which extragalactic, Cepheid-based distance scale is tied.

On the other hand Hipparcos recalibration for RR Lyrae based both on direct parallax determination and statistical parallaxes gives results fully confirming Layden et al. (1997) determination: $18.26 \pm 0.15$ mag (Fernley et
Similar results from statistical parallaxes were recently obtained by Popowski and Gould (1998). Thus it seems very likely that the RR Lyrae stars give \( \approx 0.25 \text{ mag} \) shorter distance scale to the LMC. Meanwhile, recent reanalysis of the supernova 1987A echo by Gould and Uza (1998) also suggests smaller distance modulus than previously derived (cf. Sonneborn et al. 1997, Lundquist and Sonneborn 1997) with the upper limit as low as \( m - M < 18.37 \pm 0.04 \text{ mag} \).

The distance to the Small Magellanic Cloud is poorly known. The distance modulus to the SMC is assumed to be about 18.9 mag (Westerlund 1990). Massey et al. (1995) obtained 19.1 \( \pm 0.3 \) mag from spectroscopic parallaxes. The most recent determination based on the Cepheid period-luminosity relation gives similar value: \( m - M = 18.94 \text{ mag} \) (Laney and Stobie 1994).

Summarizing this short review, the distance to the Large Magellanic Cloud is at least controversial and the generally accepted value \( m - M \approx 18.5 \text{ mag} \) cannot be now treated as established beyond any doubt. The distance to the Small Magellanic Cloud is assumed to be \( m - M \approx 18.9 \text{ mag} \), still poorly known, and therefore any new, independent information about both distances is of the greatest importance.

Recently Paczyński and Stanek (1998) proposed a new, single step method of distance scale determination to the objects in the Galaxy and neighboring galaxies. The method bases on the fact that the red clump giant stars seem to be a very homogeneous group of objects and their mean magnitude in the \( I \)-band is practically independent of their color. Therefore the red clump stars might be considered as excellent standard candle candidates. The red clump stars are very numerous compared with other objects used as standard candles so far (typically several orders of magnitude more numerous than e.g., pulsating stars). Thus, their mean magnitudes can be obtained very precisely with small statistical error making the method very attractive for precise determination of distances in the Universe.

The mean absolute magnitude of the red clump stars from the solar vicinity was determined by Paczyński and Stanek (1998) who analyzed luminosities of about 600 such stars with precise parallaxes (accuracy better than 10\%) measured by Hipparcos \( (M_{I_0}^{\text{loc}} = -0.185 \pm 0.016 \text{ mag}) \). Paczyński and Stanek (1998) applied the method for determination of the distance to the center of the Galaxy comparing \( M_{I_0}^{\text{loc}} \) with the mean \( I \)-band magnitude of the red clump stars from the Baade’s Window obtained from photometry of the first phase of the Optical Gravitational Lensing Experiment (OGLE). The new method was also applied by Stanek and Garnavich (1998) for deter-
mination of the distance to M31. Stanek and Garnavich (1998) also refined the maximum of the local red clump stars luminosity function by limiting the Hipparcos sample of the red clump stars to be volume rather than luminosity limited and derived $M_{I_{0}}^{\text{loc}} = -0.23 \pm 0.03$ mag from 228 red clump stars located within the distance $d < 70$ pc. Very large number of red clump stars in the Hipparcos sample makes the calibration very sound comparing with calibrations of other standard candles. It should be noted that this calibration might be even more precise in the future when good $VI$ photometry is derived for more Hipparcos stars.

Although employing the red clump stars as distance indicator seems to be very attractive and can be possibly one of the most precise methods of distance determination one should be aware of potential systematic errors which can lead to errors in determined distance scale. The most important is proper determination of the interstellar extinction which can affect both target red clump luminosity as well as the local Hipparcos sample. However, the latter sample is very likely extinction free for $d < 70$ pc or it is affected negligibly, e.g., that one analyzed by Stanek and Garnavich (1998). Nevertheless precise determination of extinction to the target stars is very important to avoid large systematic errors.

The second source of errors can be the differences in populations – ages, chemical composition etc., between the red clump stars of the target object and those in the solar neighborhood. This is, however, a common problem of any other method of distance determination when similar objects from different locations of the Universe are compared. In case of the red clump stars theoretical models predict that their luminosity is very weakly dependent on chemical composition and age (Castellani, Chieffi and Straniero 1992, Jimenez, Flynn and Kotoneva 1998). Nevertheless, the empirical fact of the very small dispersion of $I$-band magnitudes of the red clump stars as observed in the solar vicinity, Baade’s Window and M31 (Paczyński and Stanek 1998, Stanek and Garnavich 1998) should find theoretical explanation which could also answer the question about uncertainties introduced by comparison of different populations of the red clump stars.

The natural consequence of the successful application of the red clump method for determination of distances to the Galactic center (Paczyński and Stanek 1998) and M31 (Stanek and Garnavich 1998) is a distance determination to other objects in the Local Group. The most natural candidates are the Magellanic Clouds, which are targets of the microlensing surveys providing huge databases of photometric data for millions of stars in both Magellanic Clouds.
The OGLE project is a long term microlensing survey which second phase – OGLE-II started at the beginning of 1997 (Udalski, Kubiak and Szymański 1997). The Magellanic Clouds are the new targets of the OGLE-II phase. Unlike other microlensing surveys the OGLE project observations are carried out with the standard $BVI$-bands with majority ($\approx 75\%$) observations obtained in the $I$-band. Thus, the data can be precisely transformed to the standard $BVI$ system and applied directly to many projects unrelated to microlensing. In particular the OGLE observations are very well suited for the above mentioned red-clump method as the most of data is collected in the $I$-band.

In this paper we apply the red clump stars method for determination of distances to both Large and Small Magellanic Clouds. Although OGLE-II data cover large fractions of both Magellanic Clouds we present here distance determination for two most west- and eastward lines-of-sight toward both Clouds where we assume extinction to be constant in the first approximation. Thus, the results should be considered as preliminary and will be refined when accurate maps of extinction based on the OGLE-II data are derived.

2 Observational Data

All observations were collected with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. The telescope and instrumentation as well as the data pipeline has been described by Udalski, Kubiak and Szymański (1997).

The photometric data for the SMC come from the just released ”$BVI$ color maps of the SMC” which will be publicly available after June 1, 1998 from the OGLE-II archive (Udalski et al. 1998). The maps provide three band photometry for eleven driftscan strips covering large part of the SMC ($\approx 2.5$ square degree). For this study we limited ourselves to the two most westward scans: SMC,SC1, and SMC,SC2 and two eastward scans: SMC,SC10 and SMC,SC11 (Table 1). They are the least dense regions of the SMC, where we believe the extinction is small and constant. Each strip covers $\approx 14'2 \times 57'$ on the sky, and about 100 000–150 000 stars were detected in each of them. Photometric reduction procedure is described in detail in Udalski et al. (1998). The magnitudes of stars are the average of about 100–115 and 20–25 observations in the $I$ and $V$-bands, respectively. Observations span the period from Jun. 26, 1997 through Feb. 11, 1998. The data were reduced to the standard system based on observations of standard
stars from selected Landolt’s fields (Landolt 1992) obtained on 20–22 and 5–8 nights for the $I$ and $V$-bands, respectively. The accuracy of the zero point is better than 0.01 mag for both bands. Comparison of the photometry with some previous measurements showing very good agreement can be found in Udalski et al. (1998).

Table 1

| Field  | RA$_{2000}$ | DEC$_{2000}$ |
|--------|------------|--------------|
| SMC_SC1 | 0$^h$37$^m$50$^s$.9 | -73$^\circ$29$'$.42$''$ |
| SMC_SC2 | 0$^h$40$^m$53$^s$.1 | -73$^\circ$17$'$.29$''$ |
| SMC_SC10 | 1$^h$04$^m$50$^s$.5 | -72$^\circ$24$'$.47$''$ |
| SMC_SC11 | 1$^h$07$^m$45$^s$.4 | -72$^\circ$39$'$.32$''$ |
| LMC_SC15N | 5$^h$01$^m$18$^s$.0 | -68$^\circ$45$'$.52$''$ |
| LMC_SC14N | 5$^h$03$^m$47$^s$.3 | -68$^\circ$45$'$.39$''$ |
| LMC_SC19S | 5$^h$43$^m$47$^s$.1 | -70$^\circ$53$'$.33$''$ |
| LMC_SC20S | 5$^h$46$^m$16$^s$.9 | -71$^\circ$03$'$.40$''$ |

Also for the LMC only the most east- and westward scans were selected: LMC_SC20, LMC_SC19, LMC_SC14 and LMC_SC15 (Table 1). All these fields were added to the main LMC targets of the OGLE-II search in the 1997/98 observing season and are still being extensively observed. Full, three band photometry of these fields will be released in the future, when at least 100 observations in the $I$-band and 30 in the $B$ and $V$-bands are collected. Mean magnitudes used in this paper were obtained from about 50 and 5 observations in the $I$ and $V$-bands, respectively. Thus, accuracy of individual stellar magnitudes is somewhat lower than that of the SMC data. Calibrations of the data to the standard system come from 9 and 2 nights only for the $I$ and $V$-bands, respectively. However, accuracy of the zero point for the $I$-band is about 0.01 mag and 0.015 mag for the $V$-band. The data cover the period of Oct. 5, 1997 through Feb. 13, 1998. Selected fields are located at the edge of the LMC bar and about 200 000 stars were detected and measured in each of them.

We browsed through literature and compared our LMC photometry with already published, reliable CCD photometries. Unfortunately, dense, central regions of the LMC where OGLE-II fields are located were very rarely
observed with the CCD technique, in particular in the $I$-band. We found only one reliable CCD photometry of regions overlapping with our fields: NGC 1850 (Sebo and Wood 1995). Unfortunately, Sebo and Wood (1995) do not provide their photometry of constant stars, only photometry of detected variable stars is available. Therefore, we extracted light curves of a few "stable" variable stars from our database, namely Cepheid variables, and compared our light curves with those of Sebo and Wood (1995). Fig. 1 presents sample $I$-band light curves of two Cepheids. We do not see any significant shifts in the magnitude scale fully confirming that our zero points are determined correctly.

3 Red Clump in the Magellanic Clouds

Figs. 2 and 3 present part of the $I$ vs. $V - I$ color-magnitude diagram (CMD) around the red clump for all SMC and LMC fields, respectively. Because of larger and non-uniform extinction in the LMC fields we decided to analyze only the least dense 1/3 part of the whole driftscan strip of each field. We designate such subfields with the letter added in the field name describing location of the subfield on the strip: N – northern part, S – southern part. Size of such trimmed subfield is $14'2 \times 19'$ and equatorial coordinates of the center are given in Table 1. Figs. 2 and 3 indicate that at least in the first approximation extinction is more or less constant in so selected fields, although in some fields, in particular LMC_SC19S, some non-uniformities of extinction are still present. Direction of the reddening is given by an arrow in each Figure.

The color-magnitude diagrams of the SMC and LMC fields show all the features characteristic for CMDs of the Magellanic Clouds and resemble nicely synthetic CMD of the LMC obtained by Gallart (1998). Superimposed on the red giant branch, the red clump is very compact similarly as M31, Baade’s Window and Hipparcos red clumps. There is no trace of the horizontal branch stars strip extending blueward from the red clump what differentiates Magellanic Clouds from M31 and suggests somewhat different stellar population content in these galaxies.

Two additional features in the CMDs are clearly recognizable. First, the asymptotic giant branch bump brighter by about 1 mag and redder than the red clump (Gallart 1998). The second feature is vertical extension of the red clump called vertical red clump (VRC) by Zaritsky and Lin (1997) and interpreted by them as a new, unknown stellar population located along
the line-of-sight between the LMC and our Galaxy. However, it should be noted that this feature is not always present in our CMDs of the LMC fields (e.g., LMC\_SC19S, but in those cases it could be smeared by differential extinction). It shows up in all SMC diagrams however, but there it bends a little blueward. It is also noticeable in the CMD of the Hipparcos local stars (cf. Paczyński and Stanek 1998, Fig. 2). Therefore Zaritsky and Lin (1997) interpretation seems to be incorrect – the VRC is more likely an evolutionary feature (cf. Beaulieu and Sackett 1998, Gallart 1998).

4 Distance Determination

To derive distances to the Magellanic Clouds, we followed the procedure described in Paczyński and Stanek (1998) and Stanek and Garnavich (1998). In the first step, we dereddened our CMDs. Unfortunately, the extinction maps for our fields derived from the OGLE-II photometry are not yet available. Therefore, we decided to estimate extinction based on extinction determination from the literature. We limited ourselves to papers with direct determination of the reddening for the Magellanic Clouds rather than to all-sky maps as complexity of the Magellanic Clouds extinction makes former determination more reliable. As our fields cover relatively large area on the sky (0.075 and 0.22 square degrees for the LMC and SMC, respectively) which smooths reddening, we decided to use the mean extinction values adjusted to the general trends resulting from available extinction maps.

In case of the SMC the situation is relatively simple. All determinations show that extinction toward the SMC, except for its central parts, is small. Our fields selected for distance determination are located outside the densest regions, therefore the reddening should be rather uniform which is confirmed by our CMDs. A direct extinction estimate toward our field SMC\_SC11 has been published. Mighell, Sarajedini and French (1998) derived $E(B-V) = 0.08 \pm 0.03$ mag toward the globular cluster NGC 416 which is located in this field. This is close to the mean reddening of the SMC given by Grieve and Madore (1986) or Massey et al. (1995): $E(B-V) = 0.09$ mag, and in general agreement with the extinction map of Grieve and Madore (1986). Therefore we adopted that value for both eastward SMC fields – SMC\_SC10 and SMC\_SC11. On the opposite side of the SMC – in the fields SMC\_SC1 and SMC\_SC2, there are no measurements available. However this region is also far from the central bar and we can safely adopt the same value for both westward fields.
The situation is much more complicated in our LMC fields. Available maps of extinction show that reddening in the LMC is much more clumpy and the mean $E(B - V)$ estimates range from 0.13 to 0.20 mag (cf. Harris, Zaritsky and Thompson 1997). The most recent maps (e.g., Harris, Zaritsky and Thompson 1997, Oestreicher and Schmidt-Kaler 1996) show that extinction can vary significantly from place to place in the LMC. Our westward fields LMC_SC14N and LMC_SC15N are located relatively close to the Harris, Zaritsky and Thompson (1997) map which shows a trend of smaller extinction in the direction of our fields. Thus we adopt $E(B - V) = 0.17$ mag for these fields, also in reasonable agreement with the map of Oestreicher and Schmidt-Kaler (1996). Our eastward fields are located about two degrees south from the region of larger extinction (Oestreicher and Schmidt-Kaler 1996) and therefore we adopt there a little larger reddening: $E(B - V) = 0.20$ mag.

As we already mentioned, the extinction uncertainty is the main source of the distance determination error. Therefore, to be on the safe side, in both cases we adopted relatively large error of reddening $\sigma_{E(B-V)} = 0.06$ mag which represents mostly uncertainty in absolute extinction estimate rather than differential extinction in the field (compactness of the red clumps in the LMC, see below, suggests small differential extinction). It should be stressed here that for more accurate distance determination, in particular to the LMC, we need much more precise reddening values which we hope to obtain for our fields from the OGLE-II photometric databases. Another possibility is to analyze the fields in the halo of the LMC, less affected by extinction and we plan to add such fields to the OGLE-II program in the future.

Adopted reddening for all our fields with its error and corresponding extinction in the $I$-band as well as $E(V - I)$ (assuming standard extinction curve $A_I = 1.96 \times E(B - V)$ and $E(V - I) = 1.28 \times E(B - V)$, Schlegel, Finkbeiner and Davis 1998) are listed in Table 2.

In the second step, we selected the red clump stars in the magnitude range $16.8 < I_0 < 18.8$ mag for the LMC and $17.3 < I_0 < 19.3$ mag for the SMC, and color range $0.8 < (V - I)_0 < 0.95$ mag. We limited the color range from the blue side to have exact overlap with the local Hipparcos sample of the red clump stars and from the red side to cut the tail of more reddened stars and background red giant branch stars. Total number of stars selected in these ranges for each field is given in Table 3.

Then, we prepared histograms of the magnitude distribution of the red clump stars with 0.02 mag bins and fitted a function given by Stanek and
Table 2
Assumed reddening

| Field       | $E(B-V)$ [mag] | $A_I$ [mag] | $E(V-I)$ [mag] |
|-------------|---------------|-------------|---------------|
| SMC_SC1     | 0.08 ± 0.03   | 0.16 ± 0.06 | 0.10 ± 0.04   |
| SMC_SC2     | 0.08 ± 0.03   | 0.16 ± 0.06 | 0.10 ± 0.04   |
| SMC_SC10    | 0.08 ± 0.03   | 0.16 ± 0.06 | 0.10 ± 0.04   |
| SMC_SC11    | 0.08 ± 0.03   | 0.16 ± 0.06 | 0.10 ± 0.04   |
| LMC_SC15N   | 0.17 ± 0.06   | 0.33 ± 0.12 | 0.22 ± 0.08   |
| LMC_SC14N   | 0.17 ± 0.06   | 0.33 ± 0.12 | 0.22 ± 0.08   |
| LMC_SC19S   | 0.20 ± 0.06   | 0.39 ± 0.12 | 0.26 ± 0.08   |
| LMC_SC20S   | 0.20 ± 0.06   | 0.39 ± 0.12 | 0.26 ± 0.08   |

Garnavich (1998):

$$n(I_0) = a + b(I_0 - I_0^{\text{max}}) + c(I_0 - I_0^{\text{max}})^2 + \frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp \left[ -\frac{(I_0 - I_0^{\text{max}})^2}{2\sigma_{RC}^2} \right] \quad (1)$$

which describes distribution of the red giant branch stars (three first terms) with superimposed Gaussian distribution of the red clump stars. Maxima of distribution and standard deviations $\sigma_{RC}$ are given in Table 3. One should note small values of $\sigma_{RC}$ (0.13–0.16 mag for the LMC and 0.16–0.17 mag for the SMC) confirming compactness of the red clumps in our fields. Figs. 4 and 5 present histograms of the luminosity function of the red clump stars in our fields with the best fit function given by Eq. (1).

To check if our limitation of the $(V-I)_0$ color of the red clump stars does not affect derived maxima of luminosity function we repeated calculations including all red clump stars: $(V-I)_0 > 0.7$ mag. No statistically significant difference was found.

Finally, we derived the distance moduli $m - M$ to our eight fields assuming the mean absolute magnitude of the red clump stars that of the local Hipparcos sample: $M_{I_0}^{\text{loc}} = -0.23 \pm 0.03$ mag (Stanek and Garnavich 1998). Results with corresponding errors are given in Table 3. We distinguish between errors from two sources: statistical – resulting from uncertainties of the mean magnitudes of target and the local Hipparcos sample, and systematic – resulting mostly from uncertainties of extinction determination.
As can be noted for all four lines-of-sight to both Magellanic Clouds, which are located at different sections of these galaxies, results of distance determination are very consistent. For the SMC the distance is determined with better accuracy. For the LMC the uncertainty is larger but it will certainly be improved in the future when better reddening information is available. Thus results should be considered as preliminary. Consistent results from the east- and westward locations of both Magellanic Clouds indicate that our extinction approximation was reasonable.

### Table 3
Distance determination to the SMC and LMC

| Field     | Number of stars | $I_0^{\text{max}}$ | $\sigma_{RC}$ | $m - M$ | $\sigma_{m-M}^{\text{stat}}$ | $\sigma_{m-M}^{\text{syst}}$ |
|-----------|-----------------|---------------------|---------------|----------|-----------------------------|-----------------------------|
| SMC_SC1   | 13845           | 18.302 ± 0.003      | 0.16          | 18.53    | 0.03                        | 0.06                        |
| SMC_SC2   | 17852           | 18.326 ± 0.003      | 0.16          | 18.56    | 0.03                        | 0.06                        |
| SMC_SC10  | 12603           | 18.332 ± 0.003      | 0.17          | 18.56    | 0.03                        | 0.06                        |
| SMC_SC11  | 11370           | 18.342 ± 0.003      | 0.16          | 18.57    | 0.03                        | 0.06                        |
| LMC_SC15N | 5600            | 17.860 ± 0.003      | 0.13          | 18.09    | 0.03                        | 0.12                        |
| LMC_SC14N | 6489            | 17.865 ± 0.004      | 0.13          | 18.10    | 0.03                        | 0.12                        |
| LMC_SC19S | 5641            | 17.871 ± 0.004      | 0.16          | 18.10    | 0.03                        | 0.12                        |
| LMC_SC20S | 4938            | 17.812 ± 0.004      | 0.15          | 18.04    | 0.03                        | 0.12                        |

5 Discussion

Results of distance determination to the Magellanic Clouds with the red clump stars method (Table 3) lead to the surprising conclusion. All of our determinations are consistently $\approx 0.4$ mag smaller than generally accepted distance moduli to the Magellanic Clouds.

There might be a few reasons of the discrepancy:

- error of the zero point of the OGLE photometry. This is, however, extremely unlikely. In Section 2 we discussed accuracy of the OGLE photometry and showed comparison with other reliable CCD photometries of the Magellanic Clouds (e.g., Fig. 1). The OGLE mean magnitudes are the average of tens of individual observations and were tied with the standard system based on observations collected on many nights with hundreds of...
observations of standard stars. We believe that our photometry constitutes a huge set of secondary $BVI$ standards in both Magellanic Clouds and large systematic errors are excluded.

- errors in reddening estimates for our fields. Certainly overestimating of the reddening leads to smaller distance moduli. However, one should note that even with the zero reddening the distance moduli derived with the red clump method are smaller than generally accepted for the Magellanic Clouds (by at least 0.1 mag). But extinction to the Magellanic Clouds does exist and for the LMC the foreground extinction is at least $E(B - V) = 0.075$ mag, $A_I = 0.15$ mag, and to the SMC $E(B - V) = 0.037$ mag, $A_I = 0.07$ mag, (Schlegel, Finkbeiner and Davis 1998). Reddening to the SMC is much smaller and our distance determination is less affected by the reddening estimate. But consistently the distance modulus to the SMC is also smaller by $\approx 0.4$ mag.

- the red clump stars method. We addressed this possibility in the Introduction. It seems unlikely from our present understanding of the red clump stars, but in principle, the mean $I$-band magnitude of the red clump stars might be a function of stellar population (although it shows very small dispersion in all objects investigated so far: local sample, Galactic bulge, M31 and Magellanic Clouds). We stress here once again that this problem must be carefully investigated both theoretically and observationally to answer potential questions.

As any of the above reasons does not seem to be satisfactory, we come to the very tempting conclusion that the distance determination to the Magellanic Clouds with the red clump method is correct, the distance moduli are $\approx 0.4$ mag smaller than those generally accepted and both Magellanic Clouds are located about 15% closer to our Galaxy than previously assumed: the LMC at 42 kpc, and the SMC at 52 kpc.

Our conclusion seems to be a strong argument in favor of the shorter distance to the LMC. Our determination is based on the independent, very straightforward, single-step method with minimum possibilities for the potential error sources. The new technique is calibrated with Hipparcos data with much better accuracy than calibration of any other standard candle (orders of magnitude more stars, very close objects with precise parallaxes). Independent determinations for four lines-of-sight located at different sides of each Magellanic Cloud yield very consistent results which makes them very sound. If we underestimated the reddening, the Magellanic Clouds are even closer to us. On the other hand if we assume only minimum, foreground reddening, which is certainly an underestimate, $E(B - V) =$
$0.075 \pm 0.015$ mag for the LMC and $E(B-V) = 0.037 \pm 0.015$ mag for the SMC, Schlegel, Finkbeiner and Davis (1998) the upper limits for distance moduli are: $m - M < 18.29 \pm 0.03 \pm 0.03$ mag for the LMC and $m - M < 18.65 \pm 0.03 \pm 0.03$ mag for the SMC. Still a few sigma gap between distance moduli resulting from the red clump method and presently accepted values remains.

Brocato et al. (1996) presented the CCD photometry of selected globular clusters in the LMC. We find there that one of the CMDs, showing the region around NGC 1786, contains a neat red clump. Unfortunately Brocato et al. (1996) do not provide their photometry, but even visual inspection of their Fig. 1 indicates that the mean magnitude of the red clump stars is $I = 18.2 \pm 0.1$ mag. NGC 1786 is located only one degree north from our field LMC_SC15N so it is comparably affected by extinction (it falls almost into the extinction map of Harris, Zaritsky and Thompson 1997). Thus resulting distance modulus from NGC 1786 field and independent photometry is in perfect agreement with our red clump determinations in Table 3.

As we mentioned in the Introduction, RR Lyrae-based distance determination also seems to favor smaller distance modulus to the LMC. All recent determinations from statistical parallaxes and Hipparcos calibrations of RR Lyrae stars are within one sigma agreement with our determination. Also the upper limit for the distance to the LMC from the SN1987A light echo by Gould and Uza (1998) is compatible with our determination.

The only arguments for the larger distance to the LMC come then from the Cepheid P–L calibration (and the Mira variables but because of much lower accuracy this determination is much less reliable). However, because of its complex nature, the calibration might be simply incorrect. An incorrect account of possible population effects, mainly metallicity, could result in overestimated distances obtained with that method (cf. Sekiguchi and Fukugita 1998, Sasselov et al. 1997). Our SMC distance determination also confirms this thesis: our distance modulus to the SMC is $\approx 0.4$ mag smaller than that derived from Cepheid P–L (Laney and Stobie 1994). It should be also noted that there exists $\approx 0.3$ mag discrepancy between Hipparcos calibrated Cepheid P–L distance to M31 (Feast and Catchpole 1997) and recent determination with the red clump stars (Stanek and Garnavich 1998) and globular clusters (Holland 1998). Thus we would like to stress at this point the necessity of urgent reanalysis of the Cepheid P–L relation. Very precise, BVI light curves of hundreds of Cepheids from both Magellanic Clouds will be provided by the OGLE project to the astronomical community later during this year and can be of great importance for such a project.
Concluding, it seems very likely that Cepheid P–L relation gives distance moduli overestimated by about \( \approx 0.4 \) mag (at least toward the Magellanic Clouds) with all astrophysical consequences – distances beyond M31, up to several Mpc rely mainly on Cepheids and the LMC distance. Our independent distance measurement to the LMC confirms the recent calibrations of the absolute magnitude–metallicity relation for RR Lyrae stars giving fainter absolute magnitudes contrary to results of Chaboyer et al. (1998) and therefore leading to older ages of globular clusters (Layden et al. 1996). On the other hand shorter distance to the LMC means shorter distance to Cepheid-based galaxies and in turn larger Hubble constant and shorter age of the Universe. The "age problem" gap increases.

We believe that there exists at least one crucial test which can verify our present findings. Paczyński (1997) proposed detached eclipsing binaries as an excellent method of distance determination. Having precise light curve and spectroscopic data one can determine the distance to the eclipsing, well detached system with accuracy of a few percent. The catalog of eclipsing stars in the Magellanic Clouds suitable for such a distance determination with three color light curves, periods etc. will be released by the OGLE project in a few months. Faintness of the Magellanic Cloud stars will require the largest, 10-m class telescopes to collect good quality spectroscopic data and a lot of telescope time. However, importance of the problem makes such a project the one of the highest priority and we hope it will be undertaken soon.

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**Note:** Based on theoretical isochrones fitting to the main sequence and the red clump in four fields in the LMC, Beaulieu and Sackett (1998, revised version of their paper) found significantly better fit assuming smaller distance modulus to the LMC \((m – M = 18.3)\) providing thus, additional argument in favor of the shorter distance to the LMC.
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**Figure captions**

Fig. 1. Comparison of light curves of two Cepheids from NGC1850 field obtained by Sebo and Wood (1995) and OGLE-II project.

Fig. 2. Observed color-magnitude diagrams around the red clump for four fields in the SMC selected for distance determination. Arrow indicates reddening direction.

Fig. 3. Observed color-magnitude diagrams around the red clump for four fields in the LMC selected for distance determination. Arrow indicates reddening direction.

Fig. 4. Luminosity function of the red clump stars for four fields in the SMC. Bins are 0.02 mag wide. Solid line is the best fit obtained with the function given by Eq. (1).

Fig. 5. Luminosity function of the red clump stars for four fields in the LMC. Bins are 0.02 mag wide. Solid line is the best fit obtained with the function given by Eq. (1).
Sebo & Wood (1995)
Variable #9 P=30.40 d

Sebo & Wood (1995)
Variable #269 P=7.010 d
This figure "fig2.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803035v2
This figure "fig3.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803035v2
$I_0^{\text{max}} = 17.865$

$\sigma_{\text{RC}} = 0.13$

$A_I = 0.33$

\hfill

$I_0^{\text{max}} = 17.860$

$\sigma_{\text{RC}} = 0.13$

$A_I = 0.33$

\hfill

$I_0^{\text{max}} = 17.871$

$\sigma_{\text{RC}} = 0.16$

$A_I = 0.39$

\hfill

$I_0^{\text{max}} = 17.812$

$\sigma_{\text{RC}} = 0.15$

$A_I = 0.39$