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The Distance to the Large Magellanic Cloud; A Critical Review

Michael Feast

Department of Astronomy, University of Cape Town, Rondebosch, 7700, South Africa

Abstract. Five independent methods of deriving the distance modulus of the Large Magellanic Cloud are reviewed and compared. A value in the range 18.60 to 18.80 is presently preferred.

1. Introduction

A remarkable range of distance moduli has been proposed for the LMC in very recent times. These moduli range from 18.06, from red clump stars, to 18.70 and greater from some discussions of Cepheids, Miras and RR Lyrae stars. This paper will briefly review five methods of determining the distance to the LMC and examine their strengths and weaknesses. These five methods are all independent of one another at least so far as their basic calibrations are concerned. Some methods have been omitted because they are not independent of the ones discussed. For instance the use of the luminosity of the red giant tip involves a calibration using horizontal branch or RR Lyrae luminosities.

2. Cepheids

The Hipparcos parallaxes of Cepheids can be used to determine the zero-points of the period - luminosity (PL) and period - luminosity - colour (PLC) relations (Feast & Catchpole 1997; Feast & Whitelock 1997). These parallaxes are mostly quite small and it is essential to analyse them in a way that avoids statistical bias. Such a method was used in the above two references (see also Feast, Pont, & Whitelock 1998, Feast 1998, and Koen & Laney 1998). Other authors have used methods which introduce bias and either ignore it (e.g., Madore & Freedman 1998) or attempt to correct for it in an approximate way (e.g., Oudmaijer, Groenewegen, & Schrijver 1998). In using a PL relation it is important to realize that even the relatively nearby (Hipparcos) stars on which the zero-point is based are generally significantly reddened. This will not cause problems so long as the systems for dereddening the programme and calibrating stars are equivalent.

In applying a PL relation to the LMC one has to take into account that the metallicity of the Cepheids there is lower than in the solar neighbourhood. This has some effect on the PL zero-point (depending on the wavelength at which one is working) and also on most methods of determining the interstellar absorption. Feast & Catchpole (1997) adopt a metallicity depletion of a factor

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1.4 for the LMC, LMC reddenings from *BVI* photometry (Caldwell & Coulson 1985; Caldwell & Laney 1991) and PL metallicity corrections from Laney and Stobie (1994). They then derive an LMC modulus of 18.70±0.10. If they had adopted a metal deficiency of a factor of two as suggested by some work (see V. Smith this volume) they would have obtained a distance modulus of 18.76.

The Hipparcos proper motions of Cepheids can be used to estimate PL and PLC zero-points. The most satisfactory way to do this is to compare the value of the Oort constant of differential galactic rotation (A) derived from the proper motions (this is almost independent of distance scale) with that derived from radial velocities (this varies inversely with the distance scale) (Feast & Whitelock 1997; Feast, Pont, & Whitelock 1998). In this way one derives a zero-point which is 0.04 brighter than that derived above and an LMC modulus of 18.74±0.13 for a metal deficiency of a factor 1.4.

Until the availability of the Hipparcos results the best PL zero-point came from Cepheids in galactic open clusters. The distance scale for the clusters most commonly used was based on the parallaxes of nearby main-sequence stars using the shape of the Pleiades main sequence as a template. Using this scale Laney & Stobie (1994) obtained an LMC modulus of 18.53. A later discussion using more parallax data (Feast 1995) increased this to 18.64. Obviously there is now a great deal of data from Hipparcos which could be used to update this result. The steepness of the main sequence makes the cluster method rather sensitive to systematic errors in the photometry and the reddening correction.

One can also estimate the PL zero-point from Baade-Wesselink type analyses of Cepheids. One of the most recent such estimates has been made by Gieren, Fouqué, & Gómez(1998). They derive a steeper slope for the PL relation from their galactic stars than is observed in the LMC. If this were significant it would raise questions regarding the use of Cepheids as distance indicators. Putting this possibility on one side (i.e., attributing the difference to the selection of stars and the method of analysis), the best proceedure is probably to calibrate the LMC PL relation at the mean log P of the galactic calibrating stars. This leads to an LMC modulus of 18.55. Gieren et al. quote an uncertainty of $\sim 0\overset{m}{.}02$ for their zero-point. However this appears to be essentially an internal error. In addition there may be systematic uncertainties in the radii determinations and in the colour - surface brightness calibration (there are few suitable calibrating stars in the colour and luminosity range of the Cepheids).

3. Miras

Miras in the LMC show good PL relations in the infrared (at K) or in M_{bol} (e.g. Feast et al. 1989). van Leeuwen et al. (1997) calibrated these relations using some initial results on the Hipparcos parallaxes of Miras.This has been extended by Whitelock et al. (1997) and further work is in progress. As with the Cepheids care was taken to avoid bias in the analysis (see also Feast & Whitelock 1998). van Leeuwen et al. obtained in this way LMC moduli of 18.60 ± 0.18 (PL at

K) [1] and 18.47 ± 0.17 (PL at M_{bol}). The difference between these two estimates (which is of much higher accuracy than that of the individual values) is real and expected. This is because it is known that the period - infrared colour relations in the LMC and the Galaxy differ significantly (Whitelock et al. 1994; Glass et al. 1995). This is plausibly a metallicity effect. In that case Wood (1990) predicts that the PL(K) relation should be the least affected. Taking these results and Wood's theory at their face value, one deduces that at a given period the LMC Miras are metal deficient by Δ[Fe/H] ~ -0.4 compared with those in the Galaxy and that the LMC modulus is 18.77. Obviously the metallicity correction is quite uncertain but it does suggest that the Mira modulus of the LMC is more likely to be greater than 18.6 than less.

It is also possible to calibrate the Mira PL relations using Miras in globular clusters containing Miras, provided the cluster distances are known. Reid (1998) has recently derived a distance modulus for the globular cluster 47 Tuc using Hipparcos parallaxes of subdwarfs. Using this modulus with infrared photometry of the three Miras in the cluster, Feast, & Whitelock (1998) obtain a PL(K) zero-point which leads to an LMC modulus of 18.79 ± 0.17.

4. RR Lyraes

Reid (1997,1998) obtained distances to galactic globular clusters of various metallicities using Hipparcos parallaxes of subdwarfs. He thus derived the absolute magnitudes of RR Lyraes (or the level of the horizontal branch (HB) at the position of the RR Lyraes) in these clusters and applied these results to RR Lyraes in LMC clusters. The strength of this method is that it is based on trigonometrical parallaxes, deals exclusively with cluster RR Lyraes (or HBs) and compares cluster RR Lyraes (or HBs) in the Galaxy with those of the same metallicity in the LMC. Reid (1998) found an LMC modulus of 18.71 ± 0.13 in this way. McNamara (1998) has used Hipparcos parallaxes of SX Phoenicis stars to determine distances of some clusters and galaxies and has inferred RR Lyrae luminosities in this way. His results lead him to an LMC modulus of 18.56 ± 0.10. This is an interesting approach but depends on the parallaxes of two stars and a number of intervening steps and should therefore probably be given a lower weight than Reid's determination.

One can estimate the luminosities of field RR Lyrae variables as a function of metallicity using their Hipparcos parallaxes. The results obtained by Koen & Laney (1998) in this way lead to an LMC modulus of 18.68 ± 0.22 when applied to RR Lyraes in LMC clusters. Gratton (1998) suggested that the Hipparcos parallaxes of field HB stars could be used to infer RR Lyrae luminosities. His results have been slightly revised by Koen & Laney (1998) and lead to an LMC modulus of 18.45 ± 0.11, again using the RR Lyraes in LMC clusters. The true uncertainty of this result may well be greater than that shown since large corrections are necessary to some of the HB star results to take into account the fact that the HB is far from horizontal at the wavelength of the V band.

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[1] Further work by Whitelock (private communication) on more extensive data give an LMC modulus of 18.64 ± 0.13 (PL(K))

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Considerable interest has been aroused by the results of statistical parallax analyses of field RR Lyraes based on radial velocities and Hipparcos proper motions. The statistical parallax analysis of Tsujimoto et al. (1998) leads to an LMC modulus of 18.37 ± 0.10 when their results are applied to RR Lyraes in LMC clusters. An analysis by Fernley et al. (1998) of basically the same data leads to an LMC modulus of 18.25 ± 0.17.

The difference in the RR Lyrae moduli of the LMC obtained via the galactic globular clusters (18.71 ± 0.13) and via the statistical parallaxes (18.25 or 18.37) is rather striking. One possibility is that field RR Lyraes differ from those in clusters in some way (see Reid 1998, Sweigart 1997) in which case one cannot apply the statistical parallax results to the RR Lyraes in LMC globular clusters. The result from the trigonometrical parallaxes of field RR Lyraes (Koen & Laney 1998, see also above) is unfortunately not of quite high enough accuracy to decide clearly on this point, although this result too, favours a high value for the LMC modulus and suggests at least tentatively that there is little difference between the luminosities of the field and cluster RR Lyraes of the same metallicity.. Another possibility is that the model of the galactic halo adopted in the statistical parallax work is too simple. It is now widely believed that the halo contains a significant number of infalling streams. If the RR Lyrae populations observed in different directions contain differing proportions of stars from the various streams then the statistical parallax result might well be significantly affected. The recent work of Gould & Popowski (1998) on the statistical parallax method does not deal with this problem. It would appear best therefore to regard the statistical parallax result with reserve at the present time.

5. SN1987A

A discussion of the LMC modulus to be derived from the ring around SN1987A in the LMC is given by Panagia in the present volume. He gives reasons for adopting 18.58 ± 0.05 rather than the lower value which has sometimes been suggested.

6. Red Clump Stars

The large data bases from the microlensing surveys in the direction of the Clouds open up the possibility of using the red giant clump in the c-m diagram as a distance indicator. Because of the large number of stars involved the internal precision of the method is potentially high, though systematic errors may be introduced by uncertainties in the adopted interstellar reddenings. The LMC distance modulus is obtained by comparing the apparent magnitude of the LMC clump with an absolute magnitude derived from Hipparcos parallaxes of galactic clump stars. In this way Stanik et al. (1998) obtained $18.065 \pm 0.031 \pm 0.09$ and Udalski et al. (1998) found $18.08 \pm 0.03 \pm 0.12$, where the first uncertainty in each case is statistical and the second systematic.

However evolutionary models indicate that the absolute magnitude of the clump depends on age and metallicity. Also the colour distribution of the LMC clump stars differs from that of the Hipparcos sample. Some of these problems have been discussed by Cole (1998) and Beaulieu and Sackett (1998). Cole obtained an LMC modulus of 18.36 ± 0.17 on a model of the age and metallicity distribution of the LMC stars and using evolutionary models. According to the models the luminosity of clump stars of a given metallicity changes only modestly with age for ages greater than 10^9 years, but is a strong function of age for younger stars (changing by 0.4 mag between $10^{8.7}$ and $10^{8.6}$ years (Bertelli et al. 1994)). In view of the fact that the relative ages and metallicities of LMC and Hipparcos clump stars are not known and that the interpretation of the data depends on models which among other things have to adopt some parameterization of the mass loss on the giant branch as a function of mass and metallicity, it would appear unsafe to place too much confidence in the present results of this method. The red clump may in fact be more useful as an indicator of stellar population than as a distance indicator.

7. Conclusions

The Cepheids, Miras and cluster RR Lyraes all indicate an LMC modulus near 18.70 or slightly greater. SN1987A gives a value near 18.6. Some other methods (e.g., red clump stars, statistical parallaxes of halo RR Lyraes) give lower values. Reasons can be advanced for regarding these low values with reserve. Thus at the present time a high value is to be preferred. The most likely value being in the range 18.60 t0 18.80.

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Discussion

Nolan Walborn: Sometimes a long journey brings us back to where we started. When I started working on the Magellanic Clouds in 1973, I looked up the moduli and found 18.6 for the LMC in a paper by Sandage & Gascoigne, the value I have used consistently every since. Recently I studied 100 OB stars in 30 Doradus and found an average difference between derived and (galactic) calibration M_v's of 0.05 mag. In the meantime, there was a "revision" to 18.1 - 18.3 based on cluster main sequences, which has evidently gone away due to ambiguities among reddening, metallicity, and age, and was not even mentioned today. I've been annoyed by some of the writing about the current red clump "revision", claiming a real result or at least a long-short distance controversy. Those who obtain such results should be more critical about their uncertainties and be required to address the host of other problems they would create if real. It seems clear the LMC modulus is 18.6 ± 0.1, or at most ± 0.2, on a firmer basis than 25 years ago due to the extensive intervening work.

Serge Demers: Why did you not mention main sequence fitting as a distance indicator for the MCs? A number of clusters and associations in the LMC have already been observed.

Feast: As I said at the start of my talk I could not cover all methods. As regards main sequence fitting there are three points I can make. 1. No one has yet produced a fiducial main sequence band on Hipparcos parallaxes of field stars. 2. The main sequence fitting method is sensitive to abundance which must be known quite accurately. 3. The main sequence fitting method is sensitive to the adopted reddening (because of the steep slope of the main sequence). Nevertheless, I would expect this valuable method to be used increasingly in the future.

Nino Panagia: The study by Romaniello et al. (these proceedings) of the stellar populations around SN 1987A shows that once one can correct for reddening individually for each star, a fit of the observations with a theoretical MS for $Z = 0.3\ Z_\odot$ is perfectly consistent with a distance modules of 18.55 as determined for SN 1987A itself. This suggests that MS fitting may be able to provide meaningful distance determinations but that a large sample of stars, with high quality photometry and individual reddening corrections, is required.

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