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Distance Scales and the Local Group

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Abstract. A review is given of a number of basic distance indicators as applied to some members of the local group. Particular attention is given to galaxies whose distances have been determined by more than one method. This allows one to test the internal consistency of the indicators.

1. Introduction

Establishing distances to local group galaxies is of obvious importance for the study of their composition and internal dynamics as well as for the dynamics of the group as a whole. But the local group galaxies are also of great importance in calibrating and testing distance scales and this paper is primarily concerned with this latter problem. The whole area of distance determination is a very active one at the present time. This is in a large measure due to the stimulus provided by the Hipparcos mission to the subject. Concerns have arisen that there might be serious discrepancies between various basic distance indicators such as the Cepheids and the RR Lyrae variables which would then lead to uncertainties in distances on all scales; in our own Galaxy, in the local group, and at cosmologically significant distances. The distance to the Large Magellanic Cloud (LMC) has generally been taken as the standard measuring rod against which other distances are calibrated. The distance to the LMC will therefore be discussed first and then the paper will concentrate on those other members of the local group whose distances have been estimated by more than one method. This is important since it allows us to test the consistency of the various distance indicators.

2. The Large Magellanic Cloud

2.1. Introduction

The determination of the distance to the LMC has recently been reviewed (Feast 1999) and here the main results of that discussion are summarized. Various estimates of the LMC modulus (throughout the true modulus, correct for reddening, will be meant) are given in Table 1 and the following comments refer to these estimates.

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Table 1. LMC Distance Modulus

Method	Modulus
Cepheid Parallaxes	18.70 ± 0.10
Cepheid Proper Motions	18.74 ± 0.13
Cepheids in Clusters	(18.64)
Cepheids (Baade-Wesselink)	(18.55)
Mira Parallaxes	> 18.64 ± 0.13
Miras in 47 Tuc	18.79 ± 0.17
RR Lyrae Parallaxes	18.68 ± 0.22
HB Star Parallaxes	18.45 ± 0.11
RR Lyraes + NGC 6397 (Reid)	18.71 ± 0.15
RR Lyraes + M92, M15, M68 (Reid)	18.65 ± 0.1
RR Lyraes + M92 (Pont et al.)	18.50 - 18.61
RR Lyrae Statistical Parallaxes (Fernley)	18.25 ± 0.17
RR Lyrae Statistical Parallaxes (Tsujimoto)	18.37 ± 0.10
SN 1987A Ring	18.58 ± 0.05
Red Clump Parallaxes	18.06 ± 0.10

2.2. Cepheid Parallaxes

Hipparcos allows us, for the first time, to calibrate the Cepheid period-luminosity (PL) and period-luminosity-colour (PLC) relations directly from the parallaxes of Cepheids themselves. However, these parallaxes are small and it is essential to analyse the data using a method which is free of statistical bias. This was done by Feast & Catchpole (1997) (see also Feast, Pont & Whitelock 1998, Feast 1998; Koen & Laney 1998) who used their calibration to derive an LMC modulus of 18.70 ± 0.10. This assumes that LMC Cepheids are metal deficient with respect to those in the solar neighbourhood by a factor of 1.4. A change in metallicity affects the PL relation (in a minor way only in the V band) and also any correction for interstellar absorption which uses the Cepheid colours. Table 2 shows the results obtained with metal deficiencies of 1.4 and 2.0 for the LMC Cepheids. The latter value has been suggested by recent spectroscopic work (see, e.g. Smith 1999). The results in Table 2 were obtained as follows:

(a) Metallicity corrections to BVI reddenings follow the discussion of Caldwell & Coulson (1985) and depend only on differential blanketing effects. The (minor) metallicity corrections to the PL(V) relation are from Laney & Stobie (1994).

(b) BVI reddenings determined as in (a) and a metallicity-corrected PL(K) relation from Laney & Stobie (1994), with a zero point adjusted to be consistent with the Feast & Catchpole (1997) PL(V) zero-point.

(c) VI reddenings obtained using a galactic $(<V> - <I>)_0$ - log P relation derived from data in Caldwell & Coulson (1987), together with the Feast & Catchpole PL(V) relation and with the resulting modulus corrected for metallicity according to the results of Kennicutt et al. (1998). These metallicity corrections should be considered rather tentative since the authors themselves chose not to employ them. Furthermore the galactic $(<V> - <I>)_0$ - log P relation is not yet definitive.

Table 2. Effect of Cepheid Metallicity on LMC Modulus

Method	LMC Modulus [Fe/H] = −0.15	LMC Modulus [Fe/H] = −0.30
(a) BVI, PL(V)	18.70	18.76
(b) BVI, PL(K)	18.68	18.67
(c) VI, PL(V)	18.62	18.60

2.3. Cepheid Proper Motions

Comparison of the Oort constant A derived from Hipparcos proper motions of Cepheids with that derived from Cepheid radial velocities (the latter from Pont et al. 1994) leads (with the same metallicity assumptions as in Feast & Catchpole 1997) to the LMC modulus in Table 1 (Feast & Whitelock 1997, Feast, Pont & Whitelock 1998).

2.4. Cepheids in Clusters

The LMC modulus in Table 1 is from Feast (1995) and is based on cluster distances derived using pre-Hipparcos parallaxes of main-sequence stars in the main-sequence fitting procedure. This work needs repeating using Hipparcos parallaxes of main-sequence stars.

2.5. Baade-Wesselink Type Analyses

A recent analysis of Baade-Wesselink results (Gieren et al. 1998) leads to an LMC modulus of 18.55 (Feast 1999). Whilst the internal error of this determination is small, the true external error of this type of analysis is not known and the value in Table 1 is thus put in brackets.

2.6. Mira Parallaxes

The result in Table 1 was obtained from a PL(K) relation calibrated using Hipparcos parallaxes of Miras (Whitelock, in preparation). There are indications of a metallicity effect (see Feast & Whitelock 1998) which would increase the derived value of the modulus, possibly to about 18.8.

2.7. Miras in 47 Tucanae

Reid (1998) has derived a distance modulus of 13.59 ± 0.15 for the metal rich globular cluster 47 Tuc using subdwarf parallaxes from Hipparcos. Infrared observations of the three 200-day Miras in the cluster can then be used to calibrate the Mira PL(K) relation and this leads to the LMC modulus in Table 1 (Feast & Whitelock 1998).

2.8. RR Lyrae Parallaxes

The Hipparcos parallaxes of field RR Lyrae variables have recently been analysed by Koen & Laney (1998). When their result is used with the reddening corrected apparent magnitudes of RR Lyraes in LMC clusters (Walker 1992) one obtains the modulus shown in Table 1. Here and throughout this paper any metallicity difference between programme and calibrating RR Lyraes has been taken into account using the relation,

$$M_V = 0.30[Fe/H] + const. \quad (1)$$

The value of the coefficient of [Fe/H] in this equation has been much debated. In the present applications, changing this coefficient within a reasonable range will not affect the conclusions of this paper significantly.

2.9. Horizontal-Branch Star Parallaxes

Gratton (1998) suggested that the Hipparcos parallaxes of horizontal-branch (HB) stars could be used to determine the absolute magnitude of the HB at the position of the RR Lyrae stars. Using a rediscussion of Gratton's results by Koen & Laney (1998) together with the RR Lyraes in LMC clusters leads to the LMC modulus in Table 1. Perhaps the main uncertainty in this result comes from the large corrections that need to be applied to some of the HB stars to take into account the fact that the HB is far from horizontal, especially at its blue end.

2.10. RR Lyraes and Horizontal Branches in Globular Clusters

It is possible to derive distances to galactic metal-poor globular clusters from main-sequence fitting to field subdwarfs with Hipparcos parallaxes. This gives the absolute magnitude of the cluster RR Lyraes (or the absolute magnitude of the HB at the colour of the RR Lyraes). Comparison with RR Lyraes in LMC clusters then gives the LMC modulus. The method compares RR Lyraes in clusters of known distance in our Galaxy with those in LMC clusters and avoids having to assume that RR Lyraes of a given overall metallicity are the same in clusters as in the field. Perhaps the most reliable modulus is obtained by comparing the cluster NGC 6397 (Reid 1998) with LMC clusters of about the same metallicity ([Fe/H] ~ -1.8, see, Walker 1992). One can also use the mean result from the galactic metal-poor clusters, M92, M15 and M68 together with the LMC cluster data as was done by Reid (1997). Pont et al. (1998) obtain a slightly lower modulus than Reid for M92. Depending on the way they treat their data this leads to an LMC modulus in the range 18.61 - 18.50. The various values obtained by this method are given in Table 1.

2.11. Statistical Parallaxes of RR Lyraes

Considerable interest has been aroused by the faint absolute magnitudes inferred from statistical parallaxes for (galactic) field RR Lyraes using Hipparcos proper motions. The results by two different groups of workers (Fernley et al. 1998, Tsujimoto, Miyamoto & Yoshii 1998) lead to the values in Table 1 when applied to the RR Lyraes in LMC globular clusters. These values (~ 18.3) are considerably lower than those obtained by several other methods. In carrying out the statistical parallax solution it is necessary to adopt a model for the galactic halo. Both groups of workers adopt a simple classical halo model. However, recent work suggests that there are a significant number of streams in the halo (possibly due to infalling satellite galaxies). If particular streams are seen preferentially in certain directions then the statistical parallax result might be significantly affected. Until this matter is clarified it seems advisable to regard the statistical parallax result with caution.

2.12. SN1987A

One of the few results on the LMC modulus which is not dependent on Hipparcos data is that from the ring round SN1987A. The modulus implied by observations of the ring has been a matter of some debate. Panagia (1999) has recently given reasons for preferring the value in Table 1.

2.13. Red-Clump Stars

The red giant clump with an absolute magnitude based on Hipparcos parallaxes would seem at first sight an attractive distance indicator (e.g. Stanek, Zaritsky & Harris 1998). A very low LMC modulus was derived in this way (see Table 1). However, the age and metallicity dependence of this distance indicator is not known empirically. Furthermore the relative ages and metallicities of the LMC clump stars and those in the Hipparcos sample are not known with any certainty. The result would therefore seem to need to be treated with great reserve at the present time (for a further discussion see Feast 1999).

2.14. Summary of LMC Modulus Determinations

A consideration of the above subsections suggests that the most reliable results for the LMC modulus are in the range 18.6 to 18.8. Plausible reasons can be advanced for regarding the low values discussed above with some suspicion though clearly these results require further study. In the following an LMC modulus of 18.7 will be adopted.

3. The SMC–LMC Difference in Moduli

Table 3. SMC–LMC Modulus Difference

	Δ (Mod)
1 Cepheids	(i) 0.41
	(ii) 0.36
2 Cepheids	(i) 0.45
	(ii) 0.48
3 Miras	~0.4
4 Red Clump	0.48

Notes:
1 $[Fe/H]_{SMC} = -0.60$ $[Fe/H]_{LMC} = -0.15$
2 $[Fe/H]_{SMC} = -0.60$ $[Fe/H]_{LMC} = -0.30$

(i) Metallicity correction as in 2.2(a)
(ii) Metallicity correction as in 2.2(c)

Table 3 gives the difference in the moduli of the SMC and the LMC from various distance indicators. In the case of the Cepheid moduli the result is given for two different LMC metallicities and the metallicity corrections discussed under (a) or (c) of section 2.2. For the Miras the estimate comes from Feast

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(1988) and Wood (1995). The red clump result is from Udalski et al. (1998). The Cepheids and Miras suggest a modulus difference of about 0.4 mag, whereas the red clump result is slightly greater.

4. The LMC - Galactic Centre Difference

Table 4 shows the distance to the galactic centre (R_o) derived in various ways and the LMC modulus derived from the same type of objects and based on the same calibration. The differences in the derived moduli of the LMC and the galactic centre are also shown.

Table 4. LMC-Galactic Centre Difference

Method	R_o (kpc)	LMC (Mod)	Δ (Mod)
(a) RR Lyrae	9.6 ± 0.6	18.71	3.80
	9.0 ± 0.6		3.94
(b) Cepheids	8.5 ± 0.5	18.70	4.05
(c) Miras	8.6 ± 0.5	18.79 or >18.64	4.13 or >3.97
	9.1 ± 0.5		3.99 or >3.84
(d) Red Clump	8.05 ± 0.2	18.13	3.60

H_2O Masers (SgrB2)	$R_o = 7.1 \pm 1.5$ kpc
H_2O Masers (W49)	$R_o = 8.1 \pm 1.1$ kpc

(a) Reid (1998) determined these values of R_o from RR Lyrae in the galactic bulge on the basis of two slightly different reddening laws. The LMC result is also based on his RR Lyrae calibration (see section 2.10).

(b) The value of R_o is the kinematic value of Pont et al. (1994) adjusted to the Hipparcos parallax scale of Feast & Catchpole (1997) (see Feast & Whitelock 1997).

(c) Catchpole et al. (1999) have recently redetermined R_o from Mira variables in the galactic bulge. Using the Mira PL(K) zero-point of Whitelock (see section 2.6), values in the range shown are derived.

(d) The red clump values are from Udalski (1998).

The LMC - Galactic Centre modulus differences are in the range 3.8 to 4.1 mag except for the red clump derivation which is smaller.

At the bottom of Table 4 values of R_o derived from H_2O masers are given (see Reid et al. 1988, Gwinn, Moran & Reid 1992). These are smaller than those derived from RR Lyraes, Cepheids and Miras. However, the quoted uncertainties in the maser results are large.

5. M31

Table 5 shows various estimates of the distance modulus of M31.

(a) Two estimates are given based on Cepheids. The first is the estimate of Freedman & Madore (1990) which makes no correction for metallicity differences between M31 and the LMC. The second is from Gould (1994) who derived and applied a metallicity correction. Both moduli have been adjusted to an LMC modulus of 18.70.

Table 5. M31 Modulus

Method	Modulus
(a) Cepheids (i) Freedman/Madore	24.64 ± ~0.1
(ii) Gould	24.77 ± ~0.1
(b) 3 Clusters + NGC 6397	24.81 ± 0.15
(c) G1 + 47 Tuc	24.72 ± 0.15
(d) 4 Clusters + RR Lyrae Parallaxes	24.81 ± 0.22
(e) 4 Clusters + HB Parallaxes	24.58 ± 0.11
(f) 4 Clusters + Statistical Parallaxes	24.43 ± 0.15
(g) Red Clump	24.47 ± 0.07
(h) Clusters + Isochrones	24.47 ± 0.07

(b) This result comes from a comparison of the HB at the position of the RR Lyrae stars in the galactic globular cluster NGC 6397 with that in three M31 clusters of about the same metallicity. The M31 data are for the clusters, Bo358, Bo405 from Fusi Pecci et al. (1996) and G302 from Holland et al. (1997). The distance adopted for NGC 6397 is from Reid (1998) and is based on Hipparcos parallaxes of subdwarfs.

(c) The modulus in the table is from a comparison of the HB in the metal-rich cluster G1 in M31 (Rich et al. 1996) with that of 47 Tuc and adopting Reid's (1998) modulus for the latter.

(d) (e) (f) (g) (h) These entries give distance moduli derived from the HBs of M31 clusters (data from Fusi Pecci et al. (1996) and Holland et al. (1997)) together with RR Lyrae absolute magnitudes derived in the various ways discussed in section 2. A straight mean of the statistical parallax determinations has been taken. As expected from the discussion in section 2, the HB parallaxes and particularly the RR Lyrae statistical parallaxes give low values of the M31 modulus. The red clump distance (Stanek & Garnavich 1998) is low as is a value based on theoretical isochrone fits to globular cluster colour-magnitude diagrams (Holland 1998).

As in the previous discussion, there seem reasons at the present time for regarding the low values with some reservation, though clearly further work is required on this problem. The current best estimate of the M31 modulus is probably near 24.75.

6. The Difference in Moduli of M31 and the LMC

A comparison of the relative modulus of M31 and LMC again gives an opportunity to compare distance indicators independent of their absolute calibration. Table 6 includes data from Table 8 on the red giant tip (RGB tip) distances which are discussed in section 8. The other data can be deduced from Table 1 and 5. It will be seen that there is good agreement between the different indicators except for the red clump. If the red clump modulus of the LMC is corrected on the model of age and metallicity distribution suggested by Cole (1998) this would become 18.36 ± 0.17 and the M31 - LMC difference would be 6.11 (assuming no correction is necessary to the M31 red-clump modulus). This would then agree with the other differences. It however also shows the sensitivity of

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the red clump to age and metallicity and suggests (as discussed above) that the absolute calibration may be quite uncertain.

Table 6. M31-LMC Modulus Difference

Method	Δ (Mod)
(a) Cepheids (i)	5.94
(ii)	6.07
(b) Clusters HB/RR Lyraes	6.10
(c) RGB Tips	5.98
(d) Red Clumps	6.40

7. The Satellites of M31

Table 7 gives the relative moduli of And I, And III and M31 based on the use of the RGB tip. The data are from Mould & Kristian (1990), Da Costa et al. (1996) and Armandroff et al. (1993) and the calibration is that of Salaris & Cassisi (1998). The close agreement of the moduli suggests that the RGB tip is a useful distance indicator if properly calibrated.

Table 7. RGB Tip Distances to M31 and its Satellites

Galaxies	Δ (Mod)
And I – M31	+0.10
And III – M31	+0.03

8. A Comparison of Cepheid and RGB Tip Moduli

The use of the RGB tip as a distance indicator and its correction for metallicity effects has been recently discussed by Salaris & Cassisi (1998). Their absolute calibration is based on evolutionary models. Table 8 compares their moduli for various galaxies with Cepheid moduli. This table is similar to their Table 2 except that the Cepheid moduli have been adjusted to the Feast & Catchpole (1997) zero-point. Data on NGC 6822 from Gallart et al. (1996) have been added, as well as Gould's (corrected) distance to M31 (see section 5). The general agreement of the Cepheid and RGB moduli is remarkably good. The scatter in the difference (σ) is only 0.08 mag. This again suggests that the RGB tip is a robust distance indicator at least in the relative sense. It might however be thought that its absolute calibration was best determined through an empirical comparison with Cepheid distances rather than through the use of models. The results of Table 8 also suggest that there are no large relative errors in the Cepheid moduli. The agreement between the Cepheids and the RGB tip distances would be unlikely unless the Cepheids provided a scale which was internally consistent at about the 0.1 mag level. It is unlikely therefore that errors in the corrections for reddening or metallicity effects have introduced any errors larger than about 0.1 mag in the Cepheid distance to these galaxies.

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Table 8. Cepheid and RGB Tip Comparison

Galaxy	Modulus		Δ (Mod)
	Cepheids	RGB Tip	
LMC	18.70	18.64	+0.06
NGC 1613	24.62	24.45	+0.17
M31	24.64	24.62	+0.02
	24.77		+0.15
M33	24.83	24.92	−0.09
WLM	25.12	25.03	+0.09
Sex A	26.05	25.92	+0.13
Sex B	25.89	25.81	+0.08
NGC 3109	25.80	25.69	+0.11
NGC 6822	23.69	23.58	+0.11
		Mean	+0.09±0.02
			$\sigma = 0.08$

9. Conclusions

The conclusions of the present paper may be summarized as follows.

(1) Within the local group the distance scales of Cepheids, RR Lyraes, Miras and the RGB tip are consistent at least in the relative sense. This suggests that corrections for relative reddening or metallicity effects from galaxy to galaxy are satisfactory, at least at the 0.1 mag level.

(2) The red clump moduli are not consistent with other moduli, even in a relative sense, at least not without major adjustments for age and metallicity effects. This suggests that the the red clump might in the future be more useful as a population indicator than a distance indicator.

(3) There is good agreement in the absolute distance scale in the local group from Cepheids, Miras and RR Lyraes in globular clusters. There is no significant inconsistency of this scale with the LMC modulus derived from the ring round SN1987A.

(4) The theoretical calibration of the RGB-tip scale by Salaris & Cassisi agrees well with the Cepheid scale.

(5)The absolute magnitudes of field RR Lyrae stars given by recent statistical parallax work are fainter than those derived in other ways, particularly from RR Lyraes in globular clusters of known (Hipparcos-based) distance. One possible reason for this is that the galactic halo may depart significantly from the model adopted in the statistical parallax work.

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Discussion

Lynden-Bell: There has always been a problem that the statistical and secular parallaxes disagree. Was there such a difference in the analysis of Hipparcos stars?

Feast: What I have referred to as "statistical parallax" is a combination of what were often in the past described as "statistical parallaxes" and "secular parallaxes". In the past solutions for these two types of parallax were carried out separately (with the resulting disagreement you mention). Nowadays simultaneous solutions using maximum likelihood methods are generally carried out. It would be interesting to separate the two types of parallax as you suggest to see if there are still differences in the results.

Laney: You mentioned the subdwarf analysis by Reid. Pont has analysed much the same data, but gets a quite different result.

Feast: The results I quote are from Reid's second paper which discusses the Pont et al. paper. Note that one difference between Reid and Pont et al. concerned the isochrones used to derive the ages of globular clusters once their distances were determined. That is an important issue but not one relevant to the present discussion.

Cannon: I won't defend the use of the clump; clearly it is giving anomalous results. However, since all stars with ages from less than 1 Gyr to about 10 Gyr go through the clump phase of evolution, if you want to explain shifts in clump luminosity as due to differences in ages or metallicity you have to say that there are very significant differences in mean population. In that case, it's not clear to me that the RR Lyraes or Cepheids are necessarily any more reliable. What I would have expected is that the clump should become smeared out in galactic systems, rather than shift bodily in luminosity, if there are significant changes dependent on age or metallicity.

Feast: One reason why the Cepheids and cluster RR Lyraes should be more reliable than the clump stars is that we have estimates of their metallicities (direct spectroscopic evidence for the Cepheids and indirect evidence for the RR Lyraes from the metallicities of the LMC globular clusters to which they belong). In the case of the LMC clump the observations do show a considerable spread in luminosity. However, there is a strong concentration at one luminosity. This presumably indicates a dominant population of a particular age and metallicity. However, I think it fair to say that we have as yet no very strong evidence of what that age and metallicity is.

Mighell: One reason to be concerned about the short "clump" distance modulus for the LMC is that it implies – at face value – that the LMC ancient globular clusters are older than the ancient globular clusters of the Milky Way galaxy. Recent HST observations of LMC globular clusters must be considered when such short distances to the LMC are proposed.

Zijlstra: The most luminous carbon star in the LMC has $M_{bol} \sim -6.9$. Assuming it fits the core-mass luminosity relation, as carbon stars should, the upper limit to the core-mass of 1.7 $M_{\odot}$ gives an upper limit of the distance to the LMC. This gives a limit in the range 18.8 to 18.9.

Maeder: Do your metallicity corrections implicitly account for the possible helium differences between the LMC and the galaxy? It should be significant if the $\Delta Y/\Delta Z$ is of the order of 3 or thereabouts.

Feast: Robin Catchpole and I use *BVI* photometry for the reddening. Metallicity corrections to this are due to differential blanketing and should not be sensitive to helium differences. We then use a PL relation at V. The discussion of Laney & Stobie (MNRAS 266, 441, 1994) shows that changing $\Delta Y/\Delta Z$ from 0 to 2.8 changes the LMC modulus by only about 0.01 mag. This is essentially a change to the bolometric correction and assumes that the PL relation at M_{bol} is independent of abundance. This is a fundamental assumption which still requires observation confirmation (though the recent work of Kennicut et al. goes someway to providing this).