Part VI
Determination of H_0

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Local Distance Indicators

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Abstract. A summary is given of the calibration of the Cepheid scale required in the derivation of distances from observations at V and I, as in the HST work on extragalactic Cepheids. There is some evidence that a small metallicity correction may be necessary in deriving distances in this way. The evidence for this comes both from observations of Cepheids of different metallicities and from a comparison of the LMC distance modulus derived from Cepheids and that derived by other methods.

1. Introduction

At the present time the value adopted for H_0 depends directly on the calibration of local distance indicators. These local calibrators should have a number of rather obvious characteristics.

1. Their absolute magnitudes should be derivable with good accuracy. The methods used to obtain these absolute magnitudes should be based on sound empirical results and be as free as possible from assumptions based on theory.

2. The absolute magnitudes of the calibrators should ideally be free from a dependence on either the age or the metallicity of the objects involved. But if there are age and metallicity effects, these must be known empirically and measurable in both the calibrating and programme stars.

3. The interstellar reddenings and absorptions of both calibrating and programme stars must be measurable with good accuracy.

Considerable emphasis has been put on point 1 in much of the current literature. However, points 2 and 3 are of equal importance, especially if one is hoping to establish scales to 5 or 10 percent. In fact, problems relating to these two latter points seem to account for some of the conflicting scales that have been recently proposed.

2. The Cepheid Scale

In the following it will be assumed that the primary interest at this symposium is the calibration of the scale to be used in the study of Cepheids; particularly the scale to adopt with the HST work on extragalactic Cepheids. The way

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in which the HST data are analysed differs slightly from one group of workers to another. However, the analysis is basically equivalent to using a period-luminosity relation at (Johnson) V, PL(V), with a measured V to obtain an apparent distance modulus. The reddening, and hence the absorption, A_V, is derived from the $(V - I)$ colour together with a period-$(V - I)_0$ relation, PC($V - I$).

A galactic PC($V - I$) relation can be obtained from local Cepheids with individual reddenings derived from three colour BVI photometry, e.g.

$$< V >_0 - < I >_0 = 0.297 \log P + 0.427 \tag{1}$$

This is derived from Caldwell & Coulson (1987) (see Feast 1999, appendix D, where a somewhat more accurate procedure is given). The zero-point of the BVI reddening system is set by the reddenings of Cepheids in open clusters whose reddenings are derived from non-Cepheid cluster members. However, it is important to note that in the most secure estimates of the Cepheid zero-point, the reddening zero-point is immaterial so long as one is consistently using the same zero-point for both calibrating and programme Cepheids. This is a major advantage of Cepheids over other distance indicators where this differential method cannot, or as yet has not been, applied.

The Cepheid PL(V) relation can be written:

$$M_V = -2.81 \log P + \rho_1 \tag{2}$$

The slope of the relation is taken from the Large Magellanic Cloud (LMC) (Caldwell & Laney 1991). This is the only use made of LMC data in deriving a Cepheid calibration. The slope may be estimated in a number of ways, none of which give significantly different values (see Feast 1999 for a discussion of this point and for a more detailed discussion of many of the points mentioned in the present paper). Values of ρ_1 can be obtained in a number of ways.

1. The most direct, empirical method is to use parallaxes of galactic Cepheids. A bias free analysis of Cepheid parallaxes from the Hipparcos catalogue (ESA 1997) gives,

   $$\rho_1 = -1.43 \pm 0.12$$

   (Feast & Catchpole 1997, Feast 1999). This result and its bias free nature has been confirmed either directly or through Monte Carlo simulations by several groups (Pont 1999, Lanoix et al. 1999, Groenewegen & Oudmaijer 2000).

2. Proper motions from Hipparcos can be combined with radial velocities in a statistical parallax type solution for ρ_1. This requires a galactic model. Both the proper motions (Feast & Whitelock 1997) and the radial velocities (e.g. Pont et al. 1994) show clearly and independently the dominant effect of differential galactic rotation on Cepheid motions and this is then the required model. In this way Feast, Pont & Whitelock (1998) obtained,

   $$\rho_1 = -1.47 \pm 0.13$$

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3. An estimate of ρ_1 can be obtained from pulsation parallaxes (The Baade-Wesselink method). In most current forms of this method a radius derived from radial velocities and photometry is combined with a colour-surface brightness relation to give an absolute magnitude. Laney (1998) recently obtained results which imply:

$$\rho_1 = -1.32 \pm 0.04 \quad \text{(internal)}$$

(see Feast 1999). If this method is applied consistently the internal errors can be very small. However, it is not yet possible to estimate realistically possible systematic errors in the derived radii or in the surface brightness estimates. Progress should be possible in this area when accurate interferometric observations of Cepheid radii (and their variation with phase) are obtained. Though even then systematic effects in the interpretation of the results may be difficult to estimate. Unlike the first two methods discussed above, the reddening zero-point is of importance when absolute magnitudes are derived in this way.

4. Cepheid luminosities can be calibrated somewhat less directly using those Cepheids that are members of open clusters. However, the direct determination of distances to some open clusters by Hipparcos has raised a number of problems (e.g. the large change in the distance of the Pleiades from the value inferred pre-Hipparcos). There are indications (see, e.g. Feast 1999, van Leeuwen 2000, Robichon et al. 2000) that these problems arise though a combination of photometric errors, errors in adopted reddenings and errors in assumed metallicity, all of which can have a significant effect because of the steepness of the main sequence. There is also a suggestion that the shape of the upper main sequence as a function of age may not agree entirely with theoretical predictions (van Leeuwen 2000). Evidently these questions will need to be sorted out, both for the nearby clusters with Hipparcos parallaxes and the clusters containing Cepheids before this method of obtaining Cepheid luminosities can be fully trusted. It seems best at the present time to base a cluster distance scale on the Hyades for which there is an excellent Hipparcos parallax (yielding $(\mathrm{m}-\mathrm{M})_0 = 3.33 \pm 0.01$, Perryman et al. 1998) and a metallicity ([Fe/H] = +0.13) which seems well accepted (e.g. Pinsonneault et al. 1998). The metallicity corrections of these latter authors then show that the Hyades main sequence in $V, (B-V)$ corresponds to that expected for a solar metallicity cluster at $(\mathrm{m}-\mathrm{M})_0 = 3.17$, or 3.12 if the metallicity corrections of Robichon et al. (2000) are used. A mean of 3.14 is adopted. Since most work on Cepheids in clusters is referred to Turner's (1979) Pleiades main-sequence we need to see how this is affected by this Hyades result. The Pleiades-Hyades magnitude difference in a $V, (B-V)$ diagram, corrected for reddening but not metallicity, is 2.52 mag. (Pel 1985). Thus the Turner sequence is that expected for a solar metallicity cluster at $(\mathrm{m}-\mathrm{M})_0 = 3.14 + 2.52 = 5.66$. If we assume that the clusters and associations containing Cepheids which are listed in Table 1 of Feast (1999) are in the mean of solar metallicity, then the results given there lead to:

$$\rho_1 = -1.43 \pm 0.05 \quad \text{(internal)}$$

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The external error of this result will be higher, partly due to the uncertainties in the metallicity correction. Note that, as with the Baade-Wesselink determinations, this result depends on the zero-point of the reddening scale adopted, unlike the first two results discussed in this section.

A straight mean of these four zero-point determinations gives:

$$\rho_1 = -1.41$$

This value is adopted here, although it should be noted that the two determinations which are most securely grounded (1 and 2 above) give a slightly brighter zero-point (–1.45) The real uncertainty in the adopted value is likely to be somewhat less than 0.1. The implied distance scale is about 7 percent greater than that used by the HST Cepheid workers. But this estimate may require revision when the details of the revised scale reported briefly by Freedman at this meeting, are available.

3. Tests for Metallicity Effects

Possible metallicity effects in deriving Cepheid distances from $V, V-I$ data were considered in some detail in Feast (1999). There are three possible causes of such effects.

1. A change of temperature at a given period.
2. A change of atmospheric blanketing at a given temperature.
3. A change in bolometric luminosity at a given period.

Items 1 and 2 affect the bolometric corrections at the wavelengths in question. Laney (1998, 1999 and private communication) discussed Baade-Wesselink radii and colours of Cepheids in the Galaxy ([Fe/H] ~ 0), the LMC ([Fe/H] ~ -0.3), and the SMC ([Fe/H] ~ -0.6), which lead (Feast 1999) to an effect in the derived distance moduli (in the $V, V-I$ system) of $\sim 0.09 \pm \sim 0.04$ mag $[\mathrm{Fe/H}]^{-1}$. Kennicutt et al. (1998) found the effect to be, 0.24 ± 0.16 mag $[\mathrm{Fe/H}]^{-1}$ from a study of Cepheids in regions of different metallicity in M101. Both these estimates are in the sense that without the correction the distance of a metal-poor Cepheid would be overestimated.

Further tests can be made by comparing the Cepheid distance modulus of the LMC, where the Cepheids have [Fe/H] ~ -0.3 (Luck et al. 1998), with independent estimates of the LMC modulus. In carrying out such a test one must bear in mind that none of the non-Cepheid distance indicators are free from problems of one kind or another. In addition the relative reddenings of these indicators and the Cepheids is a source of added uncertainty.

3.1. The RR Lyraes

Table 1 gives the distance modulus of the LMC as derived in different ways from RR Lyrae variables. The basic data on the (field) RR Lyraes in the LMC are taken from Clementini et al. (2000) including the reddenings and the mean metallicity ([Fe/H] $= -1.5$). The various absolute magnitude calibrations are as follows:

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Table 1. Non-Cepheid LMC Moduli

Method	Modulus
RR Lyraes	
Parallaxes	18.70 ± 0.22
Via HB parallaxes	18.50 ± 0.12
Via globular clusters	18.64 ± 0.12
Via δ Sct stars	18.62 ± 0.10
Statistical parallaxes	18.32 ± 0.13
Miras	
Parallaxes	18.64 ± 0.14
Via 47 Tuc	$18.60 \pm (0.09)$
SN1987A ring	18.58 ± 0.05
LMC globular clusters	18.52 ± 0.11
Red giant clump	$(18.55) \pm (0.05$ int.)
Eclipsing binary	$(18.40) \pm (0.07$ int.)

1. Trigonometrical parallaxes of RR Lyrae variables in the Hipparcos catalogue (Koen & Laney 1998). This is the most direct calibration but has a rather large standard error.

2. Hipparcos trigonometrical parallaxes of Horizontal-branch stars (Gratton 1998). This is somewhat less straight forward than using the parallaxes of RR Lyraes themselves (see Feast 1999).

3. At least three groups have discussed the calibration of RR Lyrae absolute magnitudes based on globular clusters with distances determined by main sequence fits to subdwarfs with Hipparcos parallaxes. A summary and revision of this method has recently been given by Carretta et al. (2000) and their result has been used here.

4. The Hipparcos parallaxes of δ Scuti stars can be used to derive distances to globular clusters and hence the luminosities of the RR Lyraes (McNamara 1997). At present this method is somewhat uncertain since it requires an extrapolation. Once δ Scuti stars themselves are observed in the LMC the method may prove rather valuable.

5. The last value in Table 1 is that derived from statistical parallaxes of galactic RR Lyrae variables by Gould & Popowski (1998). Such an analysis requires one to adopt a kinematic model. Gould and Popowski (along with other workers) adopt a classical model for the galactic halo in their work. However recent studies have shown how complex the halo actually is. The uncertainty in this result may thus be considerably larger than implied by the quoted standard error.

Estimates of RR Lyrae absolute magnitudes can also be made from Baade-Wesselink type analyses. There are a number of problems in doing this and a range of absolute magnitudes have been proposed (see Feast 1999 and references there). In view of these uncertainties the results of this method are not included here.

3.2. Miras

Mira variables show a good infrared period-luminosity relation (Feast et al. 1989) . This can be calibrated using Miras with Hipparcos parallaxes (Whitelock & Feast 2000). Table 1 gives the result using the PL relation at 2.2μm (K) which should be least affected by any metallicity differences between the LMC Miras of a given period and those used for the calibration. There is some evidence that at a given period the LMC Miras are metal-poor compared with galactic ones. If so, the theory of Wood (1990) indicates that the distance modulus shown is a lower limit (see the discussion in Feast & Whitelock 1999). The PL relation can also be calibrated using the infrared (K) magnitudes of the three Miras in the globular cluster 47 Tuc. The Table gives the result obtained when the distance of 47 Tuc is taken from the discussion of Carretta et al. (2000).

3.3. The Ring of SN1987A

The value quoted in Table 1 is for the distance of the LMC centroid as derived from the ring round SN1987A by Panagia (1998). This assumes the ring is circular. If the ring is elliptical the distance modulus derived would increase to a maximum of 18.64.

3.4. Main Sequence Fitting to LMC Globular Clusters

Johnson et al. (1999) fit main sequences of LMC globular clusters to that of M92 to obtain a distance modulus of the LMC. The tabulated value is based on the distance of M92 derived by Carretta et al. (2000). It should however be noted that these latter workers indicate that the derivation of the distance to this cluster is somewhat problematic.

3.5. The Red Giant Clump

The use of the red giant clump as a distance indicator has been much discussed in recent times. Using this method Udalski et al. (2000) and Stanek et al. (2000) obtained an LMC modulus of 18.24 ± 0.08. On the other hand Romaniello et al. (2000) found 18.59 ± 0.09. The difference between these estimates is mainly due to the adoption of different reddening corrections and different corrections for age and metallicity effects. An extensive study of this latter problem has recently been carried out by Girardi & Salaris (2000). They find, from models, that there are significant effects on the clump absolute magnitude due to both age and to metallicity. Coupling these results with population synthesis models of the LMC and adopting reddenings from Romaniello et al. (2000) and Zaritsky (1999) they derive the result given in Table 1. As Girardi and Salaris point out the significant age and metallicity effects reduce considerably the usefulness of the clump as a distance indicator. The result evidently depends strongly on both stellar evolutionary models and population synthesis work, making it less suitable as a primary distance indicator. For this reason the result in Table 1 is placed in brackets.

3.6. Eclipsing Binaries

Deriving distances from eclipsing binaries has much in common with the determination of pulsation parallaxes by a Baade-Wesselink type analysis. In both cases a stellar radius is combined with an estimate of the surface brightness to obtain a luminosity. In the case of eclipsing binaries the stellar radius derived depends amongst other things on the adopted limb darkening. Guinan et al. (1998) have studied the B-type binary HV2274 in the LMC. They combine HST spectrophotometry and optical photometry with a Kurucz model to deduce simultaneously, the law of reddening, the visual absorption (A_V), the metallicity ([Fe/H]), the surface gravity, the microturbulence, and the effective temperature. The result thus depends heavily on the model (as well of course on the accuracy of the spectrophotometry). They obtain a distance modulus of 18.35 for the star and from this estimate a distance modulus of the LMC centre of 18.30. Nelson et al. (2000) remeasured the optical photometry with Landolt standards and increase this later distance modulus to 18.40, the value give in Table 1. The value obtained is rather sensitive to the photometry. It can be roughly estimated that if Nelson et al. had used Cape rather than Landolt standards (see e.g. Menzies et al. 1991) they would have found an even larger distance modulus for the LMC ($\sim$ 18.47). As with the red clump distance, the eclipsing binary distance rests on a theoretical model and cannot, at least as yet, be considered an empirical determination. It is thus placed in brackets in Table 1.

3.7. Comparison of Cepheids and other Indicators

Table 2. Comparison of LMC Moduli

Non-Cepheid	
RR Lyraes	18.54
Miras	18.62
SN1987A	18.58
LMC Globulars	18.52
Red Clump	(18.55)
Eclipsing Binary	(18.40)
Cepheid	
V, I, no correction	18.66
with Laney correction	18.63
with Kennicutt correction	18.59

Table 2 contains mean LMC moduli as derived from each of the indicators in Table 1. Where several estimates for a given indicator are listed in Table 1, a straight unweighted mean has been taken except that the trigonometrical parallax result for RR Lyraes has been given half weight because of its large standard error. (Note that the statistical parallax result for the RR Lyrae stars has been given full weight although reasons were given in section 3.1 for regarding it with some suspicion.)

The first three entries of Table 2 are probably the most reliable and their mean is 18.58. A mean of all six entries is 18.54 which is negligibly different. These values may be compared with the Cepheid values which are also given in Table 2. These depend on the the use of $V, V-I$ photometry and the PL zero-point derived in section 2 ($\rho_1 = -1.41$). No metallicity correction has been applied to the first entry whilst the others have been correction according to the results of Laney or of Kennicutt et al. as discussed in section 3. These results suggest that the LMC test provides some additional evidence that the use of the Cepheid $V, V-I$ method is slightly metallicity dependent in the same sense as shown by the results of Laney and of Kennicutt et al. However, in view of the various uncertainties an effect in the LMC of about 0.1 mag must be considered marginal.

4. Conclusions

Galactic calibration of the Cepheid PL(V) and PC($V-I$) relations indicate that the scale used by HST workers (at least prior to mid-2000) needs increasing by about seven percent. Various tests suggests that there is a small metallicity effect when using V and I data in the manner adopted by the HST workers. The size of this effect is still rather uncertain. It is possibly ~ 0.1 or $0.2\,\mathrm{mag}\,[\mathrm{Fe/H}]^{-1}$ in the sense that the corrected distances of metal-poor Cepheids are smaller than the uncorrected ones.

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