Calibration of the Cepheid Distance Scale

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Abstract

The absolute calibration of the Cepheid period-luminosity (PL) relation with galactic Cepheids is discussed. Various methods, most importantly the cluster ZAMS-fitting scale and the Baade-Wesselink scale are found to yield PL zero points which agree within $\sim \pm 0.1$ mag. The present Cepheid calibration sets the Large Magellanic Cloud at μ_o (LMC) = 18.6 ± 0.1 mag, in good agreement with the distance derived from SN 1987A and other methods except RR Lyrae stars which seem to give a shorter distance scale.

1. Introduction

Cepheid variables continue to be the most important calibrators of the extragalactic distance scale. This is so because they are intrinsically bright, easy to detect and obey a period-luminosity (PL) relation for which we have reasons to believe that it is universal.

In order to derive *absolute* distances to galaxies one has to calibrate the *local* distance scale using Cepheids in our Galaxy. This is a complicated problem and has occupied researchers for some 80 years now without full confidence in the results being attained even today.

Recent reviews dealing with Cepheids as standard candles have been given, among others, by Madore and Freedman (1991), Walker (1988), and Feast and Walker (1987). In the past few years, progress has been made in several respects. Improved Cepheid distances to a number of nearby galaxies have been measured using multicolor CCD photometry (reviewed elsewhere in this volume), and there has been important work on improving our knowledge of the absolute magnitudes of galactic Cepheids using a variety of methods, which will be reviewed here.

It is clear that Cepheid observations in infrared passbands have attained increasing importance in recent years for distance determinations of extragalactic Cepheids, mainly because of less problems with reddening corrections and reduced light amplitudes in the infrared. Still, work on the galactic calibrators has mainly involved observations in the B and V passbands, and for this reason this review will concentrate on the calibration of the PL(V) relation.

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Infrared Cepheid PL relations have been discussed elsewhere (e.g. Madore and Freedman 1991; Feast and Walker 1987; Laney and Stobie 1986).

2. The metallicity dependence of the PL and PLC relations

Theory predicts (e.g. Stothers 1988) that the slope of the PL(V) relation is practically metallicity independent. Observations of Cepheids in the Galaxy and the Magellanic Clouds, as well as in some Local Group galaxies seem to confirm this, yielding PL slopes close to -2.9. Different slopes which have occasionally been found can probably be attributed to selection effects due to the observations of only the *brightest* Cepheids in a galaxy which produces a bias of the Malmquist type (Sandage 1988), or to calibration errors in photographic photometry near the plate limit.

Theoretical work also shows that the zero point of the *bolometric* PL relation is metallicity independent (Stothers 1988). The bolometric correction BC is a weak function of metallicity (Laney and Stobie 1986) but since BC is very small in the V band no appreciable metallicity effect on the PL(V) zero point is expected. This has recently been confirmed by the work of Freedman and Madore (1990) on M31 Cepheids which has shown that there are no significant zero point shifts of the PL relations obeyed by Cepheids in fields of widely different radial distances from the center of M31 having metallicities ranging over a factor of ~ 5.

The basic problem in the use of a PLC relation for distance determinations is its strongly increased sensitivity to metallicity differences in the Cepheids (e.g. Stothers 1988). Caldwell and Coulson (1986) have found a PLC zero point offset of 0.51 mag between our Galaxy (at $z = 0.02$) and the SMC (at $z = 0.005$). For galaxies for whose Cepheids accurate metallicities and reddenings are available the use of a PLC relation may be as good or even preferable to the use of a PL relation, but in practice this information is only available in the Magellanic Clouds. Another problem which is still with us is the true size of the color coefficient in the PLC relation which is difficult to determine due to the necessity for disentangling the effects of differential reddening. This is briefly discussed in Section 7 of this review.

3. Calibration on the galactic Cepheid PL(V) relation

There are at least four observational methods to find Cepheid absolute magnitudes. These are:

a) ZAMS-fitting to the color-magnitude diagrams of clusters containing Cepheids

b) Baade-Wesselink methods

c) Statistical parallaxes

d) Binary systems containing Cepheids

The cluster method has traditionally been considered as the most reliable means to obtain Cepheid luminosities. However, there are a number of severe difficulties with

this method. There are few rich and nearby clusters containing Cepheids; most clusters are distant and sparse, and Cepheid membership is sometimes quite controversial due to the lack of additional membership information such as radial velocities of the cluster stars. Most clusters have high and variable reddening due to their low galactic latitudes, and have high field star densities contaminating the observed CMD's. The ZAMS is sensitive to the cluster metallicity (e.g. VandenBerg and Bridges 1984) and this is often not known, and there is the problem of the true distance of the standard cluster. The Pleiades are now generally used for this purpose rather than the Hyades cluster because of less problems with evolved stars on the upper main sequence due to its younger age, and of its solar metallicity. Since van Leeuwen's (1983) trigonometric parallax study a value of μ_o(Pleiades) = 5.57 mag has been favored but more recent evidence (e.g. Gatewood et al. 1990; Feast 1991) suggests a slightly larger value of ∼ 5.70 which carries directly over into the ZAMS-fitting Cepheid distance scale.

Baade-Wesselink (BW) methods have the advantage of yielding Cepheid luminosities which are *independent* of any of the other methods. BW distances can be found to any Cepheid having the necessary data (photometry and radial velocities) available allowing the PL relation to be calibrated with a large number of stars. Problems with uneven filling of the Cepheid instability strip and a very limited range in period and color of the calibrating Cepheids, as inherent in the cluster method, can be largely avoided in BW studies, but there are possibly severe sources of systematic error, mainly regarding the color indices appropriate to those studies.

The statistical parallax method has most recently been used by Wilson et al. (1991) to derive Cepheid luminosities. The resulting Cepheid magnitudes have relatively large errors but serve as a valuable check on the other methods.

Analyses of Cepheid companions detected in the ultraviolet by the IUE satellite have yielded absolute magnitudes of binary Cepheids in several cases (Evans 1991; Böhm-Vitense 1985) and a typical error in the best studied cases seems to be ± 0.3 mag (see reviews by Evans and Böhm-Vitense in this volume). The binary method is valuable as an additional means to obtain luminosity information on Cepheids, but it is still quite limited regarding the number of studied cases and the accuracy of the results.

4. The ZAMS-fitting Cepheid distance scale

Recent calibrations of the galactic Cepheid PL relation using the ZAMS-fitting method have been given by Gieren and Fouqué (1992)(=GF), Turner (1992), Fernie (1992), Walker (1988), and Feast and Walker (1987). The coefficients of least-squares solutions to the respective data sets used by these authors are given in Table 1. Since the slopes are all close to -2.90 and their mean value is -2.903 ± 0.019, GF argue that -2.90 ± 0.02 should be *adopted* as the appropriate slope of the PL(V) relation. Redetermining the PL zero points of the different data sets with the slopes forced to -2.90 then yields the following results:

FW 87:   -1.251 ± 0.038 $\sigma = 0.203$ N = 28 stars
Wa 88:   -1.228 ± 0.036 $\sigma = 0.191$ N = 28
Fe 92:   -1.203 ± 0.029 $\sigma = 0.26$ N = 28 (+28 δ Sct)
Tu 92:   -1.192 ± 0.022 $\sigma = 0.068$ N = 10
GF 92:   -1.292 ± 0.049 $\sigma = 0.275$ N = 32

There seems to be a strong selection effect in the small Turner sample (10 stars) which further exhibits an unrealistically low dispersion. GF find a zero point of -1.204 ± 0.077 from *their* absolute magnitudes if they restrict their sample to the 10 Cepheids studied by Turner, in agreement with his result, but with a $\sigma = 0.243$ comparable to other studies.

The GF study yields a PL zero point ~ 0.07 mag *brighter* than the other ZAMS-fitting studies. This is essentially due to the fact that they use Cepheid color excesses as given in Fernie (1990) and determined from the Cepheids themselves, rather than calculating the Cepheid color excesses from the cluster OB star reddenings, as done in the other studies. Another improvement in the work of GF, besides of including the most recent data on true cluster distance moduli, is a homogeneous treatment of R, the ratio of total to selective absorption. GF use the values of R for the clusters as given in the original references *if these were measured*; in other cases they standardize the cluster R values to

$$R = 3.06 + 0.25(<B>_o - <V>_o) + 0.05E(OB) \qquad (1)$$

using $<B>_o - <V>_o = -0.2$. The coefficients in (1) are from Olson (1975) and the zero point is chosen so that the value of R agrees with the mean value found for 51 galactic clusters by Turner (1976). All μ_o (cluster) values given in the original references were adjusted to the corrected R (cluster) values and to μ_o(Pleiades) = 5.57. The values of R appropriate to the Cepheids were also calculated from (1) but using the Cepheid intrinsic colors and the Fernie (1990) E(B-V) values. The GF calibrating data are reproduced in Table 2.

5. The Baade-Wesselink distance scale

The most recent and most complete BW study which seems to be representative of other BW work over the past few years using appropriate color indices and techniques (e.g. Coulson, Caldwell and Gieren 1986; Caccin et al. 1981) is that of Gieren, Barnes and Moffett (1992) (=GBM). GBM use the surface brightness version of the BW technique which employs $(V-R)_J$ as the Cepheid surface brightness indicator. Using improved values for the slope (from Thompson's (1975) method) and zero point (from the Cepheid model atmosphere calculations of Hindsley and Bell (1989), and from Cepheid effective temperatures of Pel (1978) and the bolometric correction scale of VandenBerg and Bell (1985)) in the surface brightness relation

$$F_V \equiv \ log \ T_e + 0.1BC = b + m \ (V - R)_o \qquad (2)$$

GBM find $< M_V > = -1.32 - 3.06 \log P$ ($\sigma = 0.29$ mag) from 100 galactic Cepheids, and $< M_V > = -1.37 - 3.01 \log P$ ($\sigma = 0.27$ mag) from 79 Cepheids with distance determinations more accurate than 10 percent.

Table 1. Recent Calibrations of the galactic Cepheid PL(V) relation

$$< M_V > = a + b \log P$$

Source	Method	N	a	b	Disp.	$< M_V >$(0.8)
Feast & Walker 87	ZAMS-fitting	28	-1.224	-2.927	0.205	-3.57
Walker 88	ZAMS-fitting	28	-1.222	-2.906	0.193	-3.55
Fernie 92	ZAMS-fitting	28	-1.203	-2.902	0.260	-3.52
Turner 92	ZAMS-fitting	10	-1.153	-2.939	0.070	-3.50
Gieren & Fouqué 92	ZAMS-fitting	32	-1.281	-2.911	0.280	-3.61
GBM 92	BW (surface-brightness)	100	-1.37	-3.01	0.27	-3.78
HB 92	BW (model atmosph.)	23	-1.33	-3.11	0.25	-3.82
BS 84	Hβ	2[1]				-3.59
Schmidt 91	Hβ					-3.50
Wilson et al. 91	Dynamical Parallaxes					-3.46 $\pm$ 0.34

[1] CS Vel and TW Nor

6. Comparison of PL results from different methods

The relevant information for a comparison of results is given in Table 1. In the last column the $< M_V >$ at $\log P = 0.8$ as resulting from the different methods are shown. The main conclusions are:

a) The BW method yields a PL zero point ~ 0.15 mag *brighter* than the cluster scale. However, the present cluster scale is tied to μ_o (Pleiades) = 5.57 which is likely to be underestimated, as discussed before. The GBM BW zero point would further be ~ 0.05 mag *fainter* if they had used the same reddening treatment as GF in their ZAMS-fitting study, making the BW scale only ~ 0.10 mag brighter than the cluster scale. This is clearly within the present uncertainties of both methods and *strongly suggests that neither of the two methods contains systematic errors in excess of $\sim \pm 0.10$ mag.*

Table 2. Cluster Cepheid Data used in the calibration of Gieren & Fouqué (1992)

Cepheid	Cluster or association	Q	log P	μ_o	R(OB)	E(OB)	R(cep)	E(cep)	$< M_V >$
SU Cas		C	0.2899	7.07	3.1	0.29	3.178	0.287	-2.01
EV Sct	NGC 6664	B	0.4901	10.88	ass	0.60	3.112	0.679	-2.86
SZ Tau	NGC 1647	A	0.4982	8.68	3.09	0.31	3.212	0.294	-3.09
QZ Nor	NGC 6067	A	0.5782	11.13	ass	0.35	3.232	0.276	-3.16
alpha UMi		C	0.5990	5.19			3.210	0.000	-3.22
CEb Cas	NGC 7790	A	0.6512	12.68	ass	0.54	3.220	0.597	-3.61
CF Cas	NGC 7790	A	0.6880	12.68	ass	0.54	3.241	0.566	-3.38
CEa Cas	NGC 7790	A	0.7111	12.68	ass	0.54	3.240	0.597	-3.70
UY Per	King 4 or Czerny 8	B	0.7296	11.70	3.1	0.99	3.246	0.919	-3.34
CV Mon	Anon van den Bergh	A	0.7307	11.22	3.09	0.77	3.241	0.714	-3.23
V Cen	NGC 5662	C	0.7399	9.11	3.1	0.31	3.218	0.289	-3.22
CS Vel	Ruprecht 79	B	0.7712	12.55	ass	0.794	3.22	0.847	-3.58
V367 Sct	NGC 6649	A	0.7989	11.27	ass	1.35	3.251	1.284	-3.89
BB Sgr	Collinder 394	C	0.8220	9.05	3.1	0.25	3.246	0.284	-3.05
U Sgr	M25	A	0.8290	8.95		0.48	3.260	0.403	-3.57
DL Cas	NGC 129	A	0.9031	11.12	3.20	0.51	3.242	0.533	-3.88
S Nor	NGC 6087	A	0.9892	9.79	3.1	0.19	3.259	0.189	-3.99
Zeta Gem		C	1.0065	7.75			3.256	0.018	-3.89
TW Nor	Lynga 6	A	1.0328	11.41	ass	1.34	3.292	1.338	-4.14
V340 Nor	NGC 6067	A	1.0526	11.13	ass	0.35	3.288	0.315	-3.80
VY Car	Ass Car OB2	B	1.2767	11.42	3.05	0.28	3.302	0.243	-4.76
RU Sct	Trumpler 35	B	1.2945	11.61	3.0	1.03	3.276	0.957	-5.26
RZ Vel	Ass Vel OB1	B	1.3096	11.24	2.88	0.35	3.275	0.335	-5.25
WZ Sgr	C1814-191a	A	1.3394	11.27	3.0	0.61	3.318	0.467	-4.80
SW Vel	Ass Vel OB5	B	1.3700	12.00	3.20	0.38	3.278	0.349	-5.02
T Mon	Ass Mon OB2	B	1.4317	11.02	3.2	0.20	3.310	0.209	-5.59
KQ Sco	Ass Sco OB anon	B	1.4578	12.32	3.04	1.00	3.365	0.896	-5.52
U Car	Ass Car OB2	B	1.5889	11.42	3.05	0.34	3.298	0.283	-6.07
RS Pup		C	1.6172	11.28			3.329	0.446	-5.75
SV Vul	Ass Vul OB1	B	1.6532	11.82	3.0	0.49	3.309	0.570	-6.46
GY Sge	Ass OB anon	B	1.7081	12.66	3.0	1.30	3.390	1.140	-6.29
S Vul	Ass Vul OB2	C	1.8299	13.23	3.0	0.88	3.362	0.827	-7.05

Note: Q = quality. A: cluster membership well established. B: cluster membership more uncertain. C: Cepheid not in cluster or association or membership very uncertain.

b) The results from Hβ photometry of cluster B stars agree with the ZAMS-fitting scale if the Balona and Shobbrook (1984) calibration is used and the TW Nor and CS Vel clusters are rejected because of their very low number of B stars. In this case, $< \mu_o(H_\beta) - \mu_o(ZAMS) > = $ -0.03 $\pm$ 0.09 mag from six clusters. Including TW Nor and CS Vel, the difference becomes -0.20 $\pm$ 0.13 mag.

c) The model atmosphere results of Hindsley and Bell (1989), as corrected by Hindsley (1992; private communication) agree with the BW result of GBM.

d) Cepheid absolute magnitudes obtained from statistical parallaxes and binary companions agree, within their large uncertainties, with the other results.

The Cepheid distance scale according to the galactic calibration discussed here sets the Large Magellanic Cloud at μ_o (LMC) = 18.6 $\pm$0.1 mag. This is in excellent agreement with the LMC distance modulus found from the expansion parallax of supernova 1987A of 18.50 $\pm$ 0.13 (Panagia et al. 1991) and seems to be supported by all other distance indicators except RR Lyrae stars (Walker 1992; see review in this volume).

7. A note on the color term in the PLC relation

The PLC relation can be written as

$$< M_V >= \alpha + \beta \ log \ P + \gamma \ (< B >_o - < V >_o) \qquad (3)$$

To avoid correlated errors in the solution of (3), we write

$$< V > - \mu_o = \alpha + \beta \ log \ P + \gamma \ (< B > - < V >) + \delta E(B-V) \qquad (4)$$

where $\mu_o =< V >_o - < M_V >$ and $\gamma + \delta = $ R (ratio of total to selective absorption).
We have solved for (4) using the GAUSSFIT routine of W.H. Jefferys of Austin and the 100 Cepheid sample of GBM, assuming $\sigma \ (log \ P) = 0, \sigma \ (B-V) = \sigma(V) = 0.02$ for all stars, taking individual $\sigma_i \ (E(B-V))$ from Fernie (1990) and $\sigma_i \ (\mu_o)$ from GBM, and taking R = 3.3. This yields

$$< M_V >= -1.45 - 2.96 \ log \ P + 0.04 \ (< B >_o - < V >_o) \qquad (5)$$

which is not different from the GBM PL relation $< M_V >= -1.37 - 3.01 \ log \ P$. This result shows that no significant color term can be extracted from the *galactic* Cepheid data, probably due to the relatively large errors in the individual Cepheid distances.
Walker (1988) gives for the LMC PLC relation, corrected to solar metallicity

$$< M_V >= -2.11 - 3.53 \ log \ P + 2.13 \ (< B >_o - < V >_o) \qquad (6)$$

Using a purely statistical approach and assuming that the extra scatter observed in the LMC period-color relation, as compared to the galactic PC relation ($\sim$ 0.11

mag in the LMC (e.g. Martin, Warren and Feast 1979) as compared to $\sim$0.07 mag in the Galaxy (GBM) is solely due to larger uncertainties in the determination of color excesses for LMC Cepheids than for their galactic counterparts, Fouqué and Gieren (1992) have shown that the *true* color coefficient in (6) adopts a value of $\sim$0.7. This is an interesting finding but it seems to be difficult to reconcile it with the spread in Cepheid magnitudes at a given period, as observed in LMC clusters rich in Cepheid variables (Welch 1992; see review in this volume). It shows, however, that we can still not be completely confident in the true value of the color coefficient of the PLC relation.

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Discussion

A. SANDAGE: I do not understand why there is any question about the value of the color term in the PLC relation. Its value is one of the best determined numbers in the relation because it depends only on the slope of the lines of constant period in the HR diagram. The only way the color term can be zero is if the lines of constant period are *flat* in the HR diagram which is impossible. I have always believed one must fix the color coefficient from the pulsation equation rather than attempting to determine it empirically.

W. P. GIEREN: I fully agree that the slope of the lines of constant period in the HR diagram cannot be zero, so there *must* be a color term in the PLC relation. However, there are uncertainties in the theoretical and semiempirical steps needed to calculate the color term which seem larger to me than usually assumed, and so there *is* a question if the true value is not significantly different from ∼2.5. One empirical way to better clarify the question is to look at LMC clusters which contain lots of Cepheids of very similar period.

D. TURNER: I have a comment regarding the PL relation for cluster and association Cepheids, which seems to exhibit rather large scatter at the low period end. It is my belief that at least four of these Cepheids are overtone pulsators, so it makes a difference which period they are plotted for.

W. P. GIEREN: It is certainly possible that there are overtone pulsators in the sample, but the existing evidence is not convincing to me except for SU Cas. Anyway, even if one adopts all four shortest period Cepheids as overtone pulsators this does not make a significant difference in the PL coefficients although the scatter maybe somewhat lower.

D. WELCH: I have three comments. First, it is worth pointing out that the dominant error in most extragalactic distances is still the galactic calibration. Second, if most of the errors are with reddening, work at longer wavelengths. Third, the angular diameter situation should improve dramatically with SUSI coming into existence.