DISTANCES FOR 17 NEARBY GALAXIES BASED ON THE HIPPARCOS CALIBRATION OF THE PERIOD-LUMINOSITY RELATION

G. Paturel[1], P. Lanoix[1], R. Garnier[1], J. Rousseau[2], L. Bottinelli[2,3], L. Gouguenheim[2,3], G. Theureau[2], C. Turon[2]

[1]Observatoire de Lyon, F69561 Saint-Genis Laval, France
[2]Observatoire de Paris-Meudon, F92195 Meudon Principal Cedex, France
[3]Université Paris-Sud, F91405 Orsay, France

ABSTRACT

From new geometrical parallaxes of galactic Cepheids obtained with the Hipparcos satellite a new calibration of BVRI period-luminosity relations is defined independently of previous determinations. Using a compilation of extragalactic Cepheids new distances are derived for a sample of 17 nearby galaxies. It is shown that the PL relation is affected by a statistical bias. Distances should be increased by about 10 per cent and sometimes more when the statistical bias is taken into account. A comparison with independent results from Feast & Catchpole shows a good agreement and confirms the existence of the statistical bias. From the method of sosies galaxies applied to the Tully-Fisher relation and from Type Ia Supernovae the new calibration leads to a Hubble constant of: $H_0 = 53 \pm 6$ km s^{-1}Mpc^{-1}.

Key words: cosmic distance; Cepheids; bias.

1. INTRODUCTION

The Period-Luminosity (hereafter, PL) relation of Cepheids is one of the most powerful means of obtaining distances to nearby galaxies because Cepheids are very luminous and easy to recognize in an external galaxy. However, the direct, geometrical calibration of this PL relation was unpossible before the launch of the Hipparcos satellite due to the location of Cepheids in the Galaxy.

Thanks to the Hipparcos satellite and to the scientific consortium who worked several years for this program, some galactic Cepheids have now their distances known from geometrical parallaxes. In this paper we are presenting distances we obtained for 17 galaxies on the basis of the multicolour PL relation calibrated from Hipparcos observations.

2. BASIC CONCEPTS OF THE MULTICOLOUR PERIOD-LUMINOSITY RELATION

In addition to the 36 galactic Cepheids observed by Hipparcos for our proposal, we made a compilation of 2236 multicolour (between 440–880 nm) extragalactic Cepheid measurements for 17 nearby galaxies. This material will be used with quite conventional equations which are summarized below. The PL relation at the equivalent wavelength λ is:

$$M_\lambda = a_\lambda \log P + b_\lambda \quad (1)$$

The distance modulus ($\mu = 5 \log r_{\rm Mpc} + 25$) is:

$$\mu = m^c_\lambda - M_\lambda \quad (2)$$

where m^c_λ is the mean apparent magnitude corrected for extinction and metallicity effects:

$$m^c_\lambda = m_\lambda - R_\lambda . E \quad (3)$$

where m_λ is the mean raw apparent magnitude, E is the colour excess defined as $C - C_0$, where C is the observed colour and C_0 the intrinsic colour. This colour excess is produced by the extinction and partly, by metallicity effect. R_λ is the ratio of the magnitude correction to the colour excess. It is assumed that it is constant for a given photometric band. The wavelength dependence of a_λ and R_λ is accurately represented by the following equations:

$$a_\lambda = a_0 + a_1/\lambda \quad (4)$$

$$R_\lambda = r_0 + r_1/\lambda \quad (5)$$

where a_0, a_1, r_0 and r_1 are constants.

The colour C is defined from any couple (i, j) of apparent magnitudes from the equation:

$$C = \frac{m_i - m_j}{1/\lambda_i - 1/\lambda_j} \quad (6)$$

This remarkable propriety is justified by the fact that the relation m_λ versus $(1/\lambda)$ is perfectly linear at least over the wavelength range 440–880 nm (see Figure 1).

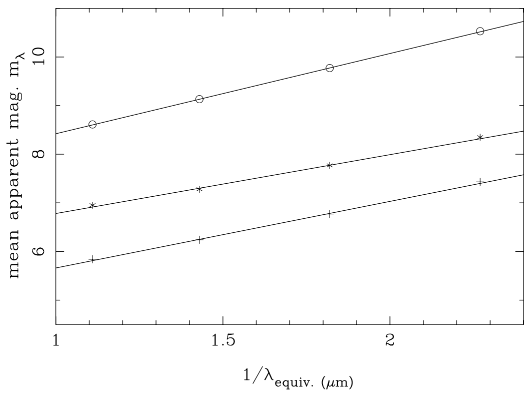

Figure 1. The relation m_λ versus $(1/\lambda)$ for three calibrating Cepheids. The relation is perfectly linear over the range 440–880 nm). For all calibrating Cepheids there is no exception and no departure from linearity.

The intrinsic colour C_0 is a function of $\log P$:

$$C_0 = c_0 \log P + d \tag{7}$$

where c_0 and d are two constants. Combining all these equations, the distance modulus of any Cepheid can be written as:

$$\mu = m_\lambda - a_\lambda log\ P - R_\lambda(C - c_0 \log P + d) - b_\lambda \tag{8}$$

The same equation can be written for galactic Cepheids observed by Hipparcos. Further, because this equation is linear it can be applied to a 'mean calibrating Cepheid' built by averaging all quantities of the Hipparcos calibrating sample. The corresponding expression is thus:

$$\mu = \overline{m_\lambda} - a_\lambda \overline{\log P} - R_\lambda(\overline{C} - c_0 \overline{\log P} + d) - b_\lambda \tag{9}$$

where overlined parameters refer to mean parameters of our Hipparcos sample. Finally, the difference between the two previous equations leads to the expression of the distance modulus of any Cepheid.

$$\mu = \Delta m_\lambda - a_\lambda \Delta \log P - R_\lambda(\Delta C - c_0 \Delta \log P + d) + \overline{\mu} \tag{10}$$

where $\Delta X = X - \overline{X}$ is set for any parameter X. This equation depends only on 5 parameters: a_0, a_1, r_0, r_1 and c_0, which will be calculated by minimizing the dispersion of individual distance moduli of a same galaxy. The adopted parameters will be the mean of the 17 determinations obtained for the 17 galaxies of our compilation.

3. RESULTS

From ten galactic Cepheids observed with Hipparcos (overtone pulsators and binaries were rejected from the sample of 36 observed Cepheids) we got: $\overline{\mu} = 7.859$, $\overline{\langle B \rangle} = 5.393$, $\overline{\langle V \rangle} = 4.648$, $\overline{\langle R \rangle} = 4.024$, $\overline{\langle I \rangle} = 3.556$, $\overline{C} = 1.613$, $\overline{\log P} = 0.772$. Then, we applied Equation 10 to derive the 5 parameters from all BVRI measurements of our compilation. The first result shows that the coefficient a_0 which defines the slope of the PL relation through Equation 4, seems to change from one galaxy to another. We plotted a_0 versus the assumed distance modulus (Figure 2).

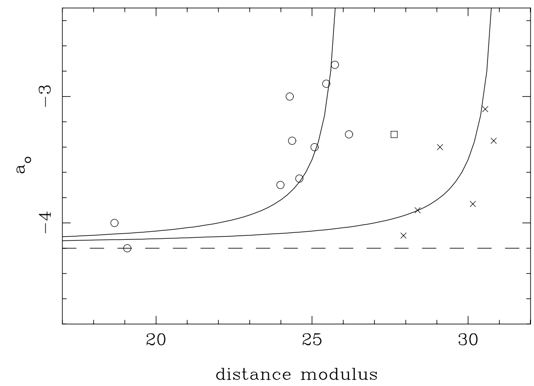

Figure 2. Variation of the coefficient a_0 as a function of the distance. Open circles correspond to ground-base observations and crosses to Hubble Space Telescope observations. The square represents M81 observed with both techniques. Interpretation of this change by a statistical bias model gives the solid curves.

Open circles represent ground-based observations while crosses represent observations by the Hubble Space Telescope (HST). These two modes differ by their apparent limiting magnitude. This suggests the presence of a statistical bias. The way the bias works is explained in Figure 3. Forcing a linear solution onto the distorted distribution, the slope will be flatter than the true one. A simple model describing this relative change of a_0 leads to the relation:

$$\Delta a_0 / a_0 = -\sigma / (m_l - \mu - M_M) \tag{11}$$

where σ is the intrinsic dispersion of the PL relation and m_l the limiting apparent magnitude. M_M is the mean absolute magnitude of the brightest Cepheids. Using realistic values for these parameters we obtain the curves in Figure 2. The agreement is satisfactory and shows that our interpretation may be correct.

From this interpretation two additional consequences can be predicted: (i) for a biased galaxy the calculated distance modulus should depend on $\log P$; (ii) distant galaxies should have shorter period Cepheids than nearby galaxies. Both predictions are actually satisfied (Figures 4 and 5).

Presently, we will adopt the slope found with unbiased galaxies. This gives: $a_0 = -4.20$. The four remaining coefficients are less sensitive to the bias because they appear only as secondary terms. We thus obtain: $a_1 = 0.67 \pm 0.05$, $r_0 = -1.40 \pm 0.13$, $r_1 = 1.04 \pm 0.05$ and $c_0 = 0.58 \pm 0.02$.

The distance moduli for the 17 galaxies of our compilation are given in Table 1. These distances may still be subject to revision for two reasons: (i) biased galaxies may have larger distances (but the correction for the bias is not obvious); (ii) The Lutz-Kelker (1973) bias may change the value of $\overline{\mu}$ (preliminary tests suggest that distance moduli could be slightly affected).

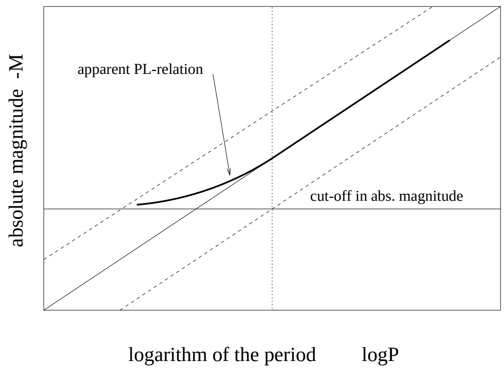

Figure 3. Description of the bias on the PL relation. Due to the limiting apparent magnitude and to the intrinsic dispersion of the PL relation there is a cut-off in absolute magnitude which distorts the linear distribution of points for short period Cepheids.

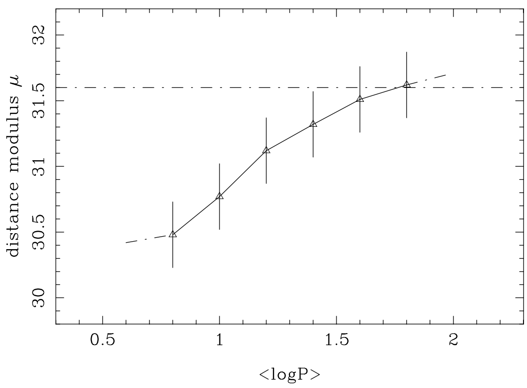

Figure 4. Sliding mean distance modulus of NGC4536 calculated using Cepheids with increasing log P. There is a clear dependence as expected if a statistical bias exists. Unbiased galaxies do not show this effect.

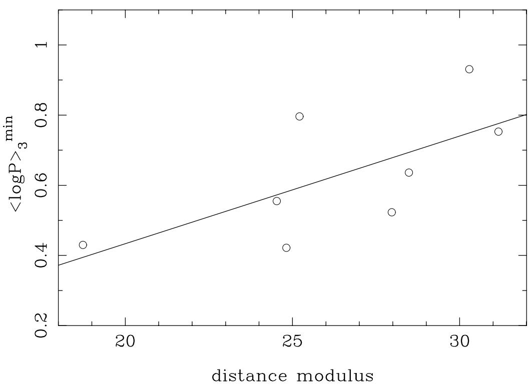

Figure 5. Mean log P of the three shortest-period Cepheids as a function of distance modulus. On the mean, distant galaxies have shorter period Cepheids than expected if there is a statistical bias.

4. COMPARISON WITH OTHER DETERMINATIONS

4.1. Comparison of the Zero-Point of the Distance Scale

Feast & Catchpole (1997) independently derived from Hipparcos Cepheids that $\mu(LMC) = 18.70$ and they deduced $\mu(M31) = 24.77$. These results are in fair agreement with ours: $\mu(LMC) = 18.72$ and $\mu(M31) = 24.84$. In order to compare more precisely we applied Feast & Catchpole method to our sample. The basic equations are almost the same except that R_λ is a function of colour and colour excess (Feast & Catchpole use the PL relation in V and $(B-V)$ colour and colour excess). In practice, the results are the same, within a few per cent, than those found using R_V = constant = 3.26. We thus extend the application to Cepheids for which only the $(V-I)$ colour is available, assuming that the ratio $E(V-I)/E(B-V)$ is constant (Savage & Mathis 1979). The comparison with Feast & Catchpole method applied to our sample is given in Figure 6. There is no departure from linearity and no systematic shift. On the other hand, the comparison with distance moduli from the literature (see Figure 6) shows that previous extragalactic distances must be stretched by about 10 to 12 per cent.

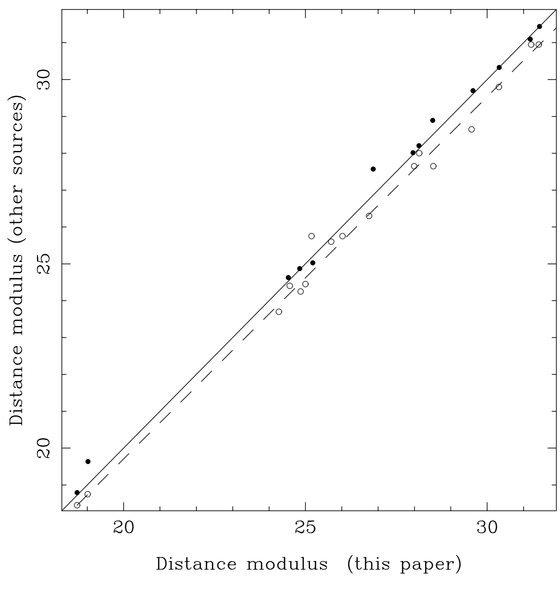

Figure 6. Comparison of distance moduli from this paper and those from other sources. Our distance moduli are in good agreement with those derived from Feast & Catchpole method (filled circles). They are about 10 per cent larger than those generally adopted from the literature (open circles).

4.2. Independent Confirmation of the Existence of a Statistical Bias

Using our compilation of extragalactic Cepheids, we calculated distances from the Feast & Catchpole method as explained in the previous section. The slope of the PL relation adopted by Feast & Catchpole is not biased (or very slightly) because it is deduced from the LMC which is not biased.

In order to show that the bias discussed in Section 3 does not result from our own method we tested it again by plotting, for each galaxy, the distance modulus calculated with different ranges of $\log P$. We did that separately for ground-based observations and HST observations (Figures 7 and 8, respectively), because the bias does not appear at the same distance for both methods (see Figure 2).

The result clearly confirms our previous results. For ground-based observations (Figure 7), nearby galaxies do not shown any variation of the calculated distance modulus with $\log P$ (they are not biased). Distant galaxies show an increase of the calculated distance modulus (they are biased). Intermediate galaxies show an intermediate variation (they are slightly biased). For HST observations the same effect is visible (Figure 8).

Another signature of the bias is also visible on both Figures 7 and 8. The minimum and maximum values of $\log P$ change with distance modulus. Distant galaxies seems to contain more long-period (luminous) Cepheids.

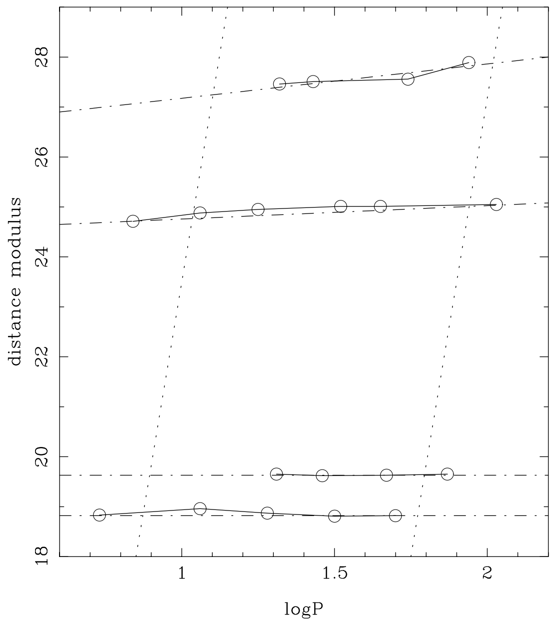

Figure 7. Distances obtained from different ranges of $\log P$ *for ground-based observations. From the bottom to the top we encounter LMC, SMC, M31 and NGC300. Nearby galaxies do not shown variation of the calculated distance modulus with log P (they are not biased). Distant galaxies show an increase of the calculated distance modulus (they are biased). Intermediate galaxies show an intermediate variation (they are slightly biased). This demonstrates, from an independent method (distances are calculated using the method by Feast & Catchpole), that a bias exists. Further, the change of maximum and minimum log P with distance is clearly visible (dotted lines).*

In order to take into account the effect of the bias, we tentatively estimated the correction to be applied on the mean distance moduli given in Table 1. For

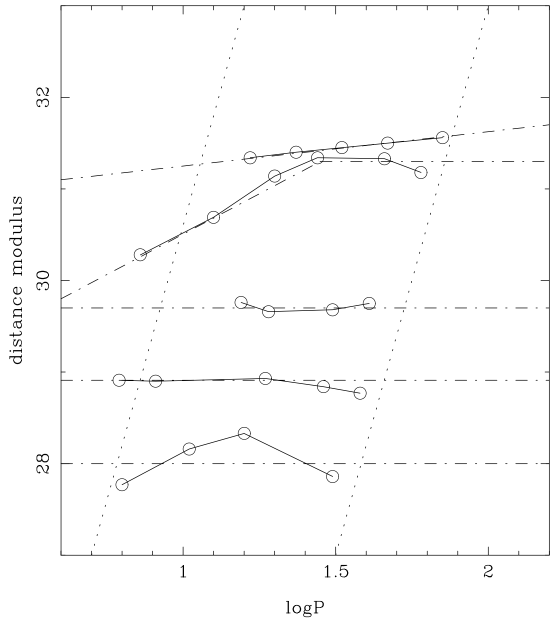

Figure 8. The same as the previous figure for HST observations. From the bottom to the top we encounter NGC5253, IC4182, M101, NGC4536 and M100.

each galaxy we noted as above the level of the bias (NB, SB, B) and applied a correction deduced from the plot μ versus $\log P$.

5. APPLICATION TO THE CALCULATION OF THE HUBBLE CONSTANT

5.1. Tully-Fisher Relation and 'Sosies' Galaxies

The Tully-Fisher relation, a relation between the absolute magnitude and the 21-cm line width W, is one of the most powerful method to extend the determination of extragalactic distances to distant galaxies. This relation can be written as:

$$M = \alpha \log(W/2\sin i) + \beta \qquad (12)$$

Galaxies having the same W, the same inclination i and even the same morphological type, as M31, must have the same absolute magnitude, without any assumption about the exact expression of the Tully-Fisher relation. These galaxies are called 'sosies' (in English, 'look-alike') galaxies. In fact, due the Malmquist bias, the mean absolute magnitude will change with the actual distance of the considered galaxy. This bias is now well understood. Figure 9 shows the result obtained for M31. The solid curve represents the model of the Malmquist bias (Teerikorpi 1975). From unbiased *sosies* galaxies of M31 and M81 we found a very secure Hubble constant:

$$H_0 = 53 \pm 8(\text{external})\ \text{km s}^{-1}\ \text{Mpc}^{-1} \qquad (13)$$

M31 and M81 are slightly biased. Thus, the Hubble constant could still be overestimated.

Table 1. Distance moduli calculated from BVRI PL relations calibrated with Hipparcos parallaxes of galactic Cepheids. The level of the bias is noted as: **NB**, *for not biased;* **SB**, *for slightly biased; and* **B**, *for biased. In the last column, we give the distance moduli tentatively corrected for the bias.*

Galaxy	μ_B	μ_V	μ_R	μ_I	$\langle\mu\rangle \pm m.e.$ (n)	bias	$\mu_{probable}$
LMC	18.69	18.71	19.12	18.78	18.72±0.02 (96)	NB	18.7
SMC	19.00	19.04			19.02±0.03 (54)	NB	19.0
NGC6822	24.26	24.21	24.26	24.31	24.25±0.04 (44)	NB:	24.3
IC1613	24.55	24.44	24.58	24.53	24.53±0.06 (62)	SB:	24.6
M31	24.90	24.72	24.90	24.84	24.84±0.03 (176)	SB	24.9
M33	24.97	25.03	25.05	25.01	25.01±0.03 (133)	B:	25.1
NGC3109	25.20	25.22			25.20±0.04 (64)	B:	25.3
SEXB	26.06	25.83	25.96	25.94	25.94±0.12 (58)	?	25.9?
SEXA	26.06	25.96	26.06	26.03	26.03±0.05 (15)	?	26.0?
NGC300	26.86	26.84	26.86	26.86	26.86±0.04 (33)	B	27.2
NGC5253		27.96		27.96	27.96±0.05 (24)	NB	28.0
M81		28.12		28.12	28.12±0.05 (50)	SB:	28.2
IC4182		28.50		28.50	28.50±0.03 (54)	NB	28.5
M101		29.60		29.61	29.61±0.04 (58)	NB	29.6
NGC925		30.32		30.33	30.33±0.02 (154)	NB:	30.3
NGC4536		31.17		31.18	31.18±0.03 (142)	B	31.4
M100		31.42		31.44	31.44±0.03 (96)	B	31.6

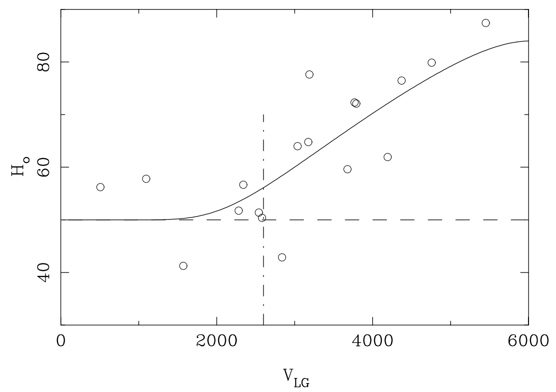

Figure 9. Calculation of the apparent Hubble constant from the method of sosies galaxies applied to the Tully-Fisher relation. The solid curve shows the model of Malmquist bias according to Teerikorpi (1975).

5.2. Type Ia Supernovae

Among our 17 calibrating galaxies we checked those which have produced type Ia Supernovae. We found four events located in three galaxies: SNe 1895B and 1972E in NGC 5253, SN 1937C in IC4182 and SN 1981B in NGC4536. Using the best B-band photometry of their maximum light curves our calibrating distance moduli allowed us to determine the maximum peak brightness of SNe Ia (let us recall that SNe Ia at maximum are supposed to have a small dispersion): $\langle M_B(MAX)\rangle = -19.64 \pm 0.07$.

We then built a sample of SNe Ia as large as possible, assuming that their type is certain, that they are not peculiar events and that their photometry in the B-band at maximum is reliable. We obtained a sample of 50 SNe Ia whose parent-galaxy radial velocities v_{Vir} are corrected for Virgo infall. Then, we plotted a Hubble diagramme with these data ($\log v_{\rm Vir}$ versus $m_B^{\rm cor}$) in order to determine its zero-point (ZP). Forcing the slope to be exactly the theoretical one, we obtained from the 33 (among 50) more reliable SNe Ia: $ZP = 0.660 \pm 0.023$. Finally, both the maximum peak brightness and the zero-point led us to the value of the Hubble constant: $H_0 = 54 \pm 9$ km s^{-1} Mpc^{-1}. NGC4536 is biased, thus the Hubble constant could still be overestimated.

6. CONCLUSION

The new geometrical calibration of the PL relation provided by the Hipparcos satellite leads us to distances larger than those previously accepted. Although the geometrical method is less subject to systematic errors the accuracy is comparable with older ones (0.1 mag). Hence, it seems important to combine other methods based on Hipparcos parallaxes to make the zero-point of the distance scale more secure and to work with a larger sample in order to test the effects of Lutz-Kelker type bias.

Another conclusion of our study, is that a statistical bias affects the use of the PL-luminosity relation. This bias has the same origin as the one encountered in study of galaxies in clusters. This bias also tends to make apparent distances larger than the true ones. The Hubble constant we have found here is still an upper-limit. Anyway, the present result agrees with the long distance scale proposed by Sandage & Tammann for many years.

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