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Calibration of the distance scale from galactic Cepheids

I. Calibration based on the GFG sample*

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Abstract. New estimates of the distances of 36 nearby galaxies are presented based on accurate distances of galactic Cepheids obtained by Gieren et al. (1998) from the geometrical Barnes-Evans method. The concept of "sosie" is applied to extend the distance determination to extragalactic Cepheids without assuming the linearity of the PL relation. Doing so, the distance moduli are obtained in a straightforward way. The correction for extinction is made using two photometric bands (V and I) according to the principles introduced by Freedman & Madore (1990). Finally, the statistical bias due to the incompleteness of the sample is corrected according to the precepts introduced by Teerikorpi (1987) without introducing any free parameters (except the distance modulus itself in an iterative scheme). The final distance moduli depend on the adopted extinction ratio R_V/R_I and on the limiting apparent magnitude of the sample. A comparison with the distance moduli recently published by the Hubble Space Telescope Key Project (HSTKP) team reveals a fair agreement when the same ratio R_V/R_I is used but shows a small discrepancy at large distance. In order to bypass the uncertainty due to the metallicity effect it is suggested to consider only galaxies having nearly the same metallicity as the calibrating Cepheids (i.e. Solar metallicity). The internal uncertainty of the distances is about 0.1 mag but the total uncertainty may reach 0.3 mag.

Key words. galaxies: distances and redshift – galaxies: stellar content – cosmology: distance scale

1. Introduction: Discussion of the problems related to Cepheids

As an extension of our study of the kinematics of the local universe (KLUN+) we need an accurate value for the global Hubble constant and accurate distances of individual galaxies. The calibration of the distance scale is thus a fundamental step in this process. The aim of this work was to calibrate the distance scale from nearby galactic Cepheids for which the HIPPARCOS satellite measured geometrical parallaxes. This should avoid the step of calibrating the distance scale by assuming a given distance to the Large Magellanic Cloud (LMC). Unfortunatelly, it turns out that these measurements are very difficult to use due to a statistical bias (Lutz & Kelker 1973). The difficulties can be solved by proper treatment, like the one proposed by Feast & Catchpole (1997). It has been shown that this leads to unbiased results (Pont et al. 1997; Lanoix et al. 1999).

On the other hand, individual measurements of Cepheids from HIPPARCOS are relatively inaccurate because of the distance of galactic Cepheids. Excluding α UMi which does not pulsate in the fundamental mode, the best geometrical parallax of an individual Cepheid obtained from HIPPARCOS is 3.32 ± 0.58 marcsec for δ Cephee. This leads to an uncertainty in the distance modulus of 0.38 mag. In comparison, the *quasi-geometrical* method of Barnes-Evans applied to Cepheids (Gieren et al. 1998; hereafter GFG), gives distance moduli with a typical uncertainty less than 0.1 mag (the external error can be estimated to about 0.2 mag according to Table 7 in GFG). We call this method *quasi-geometrical* because it requires only a few assumptions. The method is independent of any determination of the LMC distance and has a relatively small systematic error (about 0.2 mag). *Thus, we decided to calibrate the distance scale using the work done by Gieren et al. (1998).*

Nevertheless, other difficulties appear. The slope of the Period-Luminosity relation (hereafter, PL relation)

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* The table of the Appendix and Table 3 are available in electronic form at CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/383/398`, and on our anonymous `ftp-server www-obs.univ-lyon1.fr (pub/base/CEPHEIDES.tar.gz)`.

Table 1. Slopes of the PL relation.

source	a_V	a_I
GFG(MW)	-3.037 ± 0.138	-3.329 ± 0.132
GFG(LMC)	-2.769 ± 0.073	-3.041 ± 0.054
OGLE(LMC)	-2.765	-2.963

determined from the adopted calibrating galactic Cepheids differs from the slope obtained for the LMC by the same authors (GFG) (Table 1). For the LMC, the slopes in V and I bands are now confirmed by the OGLE survey (Udalski et al. 1999). What slope should we adopt?

The true physical relation is actually a Period-Luminosity-Color (hereafter, PLC) relation written as $M = \alpha \log P + \beta C_o + \gamma$, where M is the absolute magnitude and C_o the intrinsic color. The PL relation is simply the projection of the PLC onto the P–L plane. In the PLC relation the slope $\partial M / \partial \log P$ is constant. However, the observed slope of the PL relation depends on the distribution of observed Cepheids in the PLC plane (i.e., on the color distribution of the sample). Hence, the slope in a given photometric band may partially depend on the metallicity, because it affects the intrinsic color. Linear non-adiabatic models do predict that the slope is constant when one uses bolometric magnitudes (Baraffe et al., private communication), whereas non-linear models predict that the slope depends on the metallicity also for the bolometric magnitudes (Bono et al. 2000 and references therein) and predict that the slope in a given band depends on the metallicity. Because the metallicity of the LMC differs from the metallicity in the Solar neighbourhood, the choice of slopes in different bands is difficult. *In order to avoid this dilemma we decided to apply the method of "sosie" (Paturel 1984) because it does not require knowledge of the slope and zero point of the PL relation*[1].

The correction for extinction produced by interstellar matter is another difficulty. It can be solved by assuming that the extinction law is universal. We will thus assume that the extinction on an apparent magnitude is proportional to the color excess ($A_\lambda = R_\lambda (C - C_o)$, where C is the reddened color). The factor of proportionality R_λ is taken from tabulations (e.g., Cardelli et al. 1989; Caldwell & Coulson 1987; Laney & Stobie 1993). It depends on both the considered band and color. With such an assumption it is possible to use the Freedman & Madore (1990) precepts of de-reddening. Two bands are needed in order to calculate a color. Because most extragalactic Cepheids are measured in V- and I-band from The *Hubble Space Telescope* (hereafter, HST), we will use these two bands. *Thus, the Freedman & Madore (1990) de-reddening method will be adapted to the sosie method, used in V and I photometric bands.*

Finally, an ultimate difficulty comes from the incompleteness bias. This bias was first studied by Teerikorpi (1987) for application to galaxy clusters (Bottinelli et al. 1987). It was first denounced by Sandage (1988) in application to the PL relation and re-discussed later by Lanoix et al. (1999a). The sample to which we are applying the PL relation must be statistically representative of the calibrators themselves. Indeed, due to the intrinsic scatter of the PL relation, there is a given distribution of absolute magnitudes at a given period. At increasing distances the fainter end of this distribution is progressively missed and the distribution of the actual sample changes. Restricting the sample to Cepheids with a period larger than a given limiting period reduces this bias. The limiting period depends on a first estimate of the distance, on the apparent limiting magnitude and on the characteristics of the PL relation (dispersion, slope and zero-point). In fact, the full theory of Teerikorpi is applicable. The method is much more complete than the rough rule of thumb used as a quick approach in an application in which a detailed treatment was not needed. However, we want to derive final distance moduli and the precise bias correction must be used. Note that the slope and zero point of the PL relation are needed but only as second order terms and thus, the uncertainties mentioned about their choice do not present any significant difficulty (this will be confirmed in Sect. 4.3). *The incompleteness bias will be corrected using the precepts given by Teerikorpi (1987).*

In Sect. 2 we will describe the material used for this study: the calibrating sample by GFG and our extragalactic Cepheid database (Lanoix et al. 1999b).

In Sect. 3 we describe the "sosie" method and give the basic equation for the calculation of the distance modulus of an extragalactic Cepheid.

In Sect. 4 we give the results obtained for 1840 Cepheids belonging to 36 nearby galaxies described in the previous section. We also discuss these results and compare them with those recently published by Freedman et al. (2001).

2. Observational material

The guideline in the constitution of the observational material is the selection of the most secure observations. This leads us to reject some data, as explained below, both galactic and extragalactic.

2.1. The list of galactic Cepheids

The starting point of our study is the choice of the galactic Cepheids used for the calibration. We adopt the list given in Gieren et al. (Table 3 in GFG) but we rejected three Cepheids (EV Sct, SZ Tau and QZ Nor) because they do not pulsate in the fundamental mode (they are overtone Cepheids). They correspond to the three lowest periods of the list. Because we use only the V and I photometric bands, three Cepheids are also rejected (CS Vel, GY Sge and S Vul) because they do not have I-band magnitude. Thus, 28 Cepheids remain. Their distance moduli

[1] This method was first introduced to solve the same kind of problems for the Tully-Fisher relation (1977).

Table 2. Adopted calibrating sample of galactic Cepheids. Column 1: Name of the galactic Cepheid; Col. 2: log of the period (P in days); Col. 3: adopted distance modulus and its mean error according to Gieren et al. (1998); Col. 4: Mean V-band apparent magnitude; Col. 5: Mean I-band apparent magnitude.

Cepheid	log$P$	$\mu \pm m.e.$	$\langle V \rangle$	$\langle I \rangle$
BF Oph	0.609	9.50 ± 0.11	7.33	6.41
T Vel	0.666	10.09 ± 0.02	8.03	7.01
CV Mon	0.731	10.90 ± 0.05	10.31	8.68
V Cen	0.740	9.30 ± 0.02	6.82	5.81
BB Sgr	0.822	9.24 ± 0.02	6.93	5.84
U Sgr	0.829	8.87 ± 0.01	6.68	5.45
S Nor	0.989	9.92 ± 0.03	6.43	5.41
XX Cen	1.039	10.85 ± 0.06	7.82	6.75
V340 Nor	1.053	11.50 ± 0.13	8.38	7.15
UU Mus	1.066	12.26 ± 0.09	9.78	8.49
U Nor	1.102	10.77 ± 0.07	9.23	7.36
BN Pup	1.136	12.92 ± 0.05	9.89	8.55
LS Pup	1.151	13.73 ± 0.04	10.45	9.06
VW Cen	1.177	13.01 ± 0.04	10.24	8.77
VY Car	1.277	11.42 ± 0.04	7.46	6.28
RY Sco	1.308	10.47 ± 0.04	8.02	6.30
RZ Vel	1.310	11.17 ± 0.03	7.09	5.85
WZ Sgr	1.339	11.26 ± 0.02	8.02	6.53
WZ Car	1.362	12.98 ± 0.14	9.26	7.95
VZ Pup	1.365	13.55 ± 0.04	9.63	8.28
SW Vel	1.370	11.99 ± 0.06	8.12	6.83
T Mon	1.432	10.58 ± 0.07	6.12	4.98
RY Vel	1.449	12.10 ± 0.05	8.37	6.84
AQ Pup	1.479	12.75 ± 0.04	8.67	7.12
KN Cen	1.532	12.91 ± 0.06	9.85	7.99
ι Car	1.551	8.94 ± 0.05	3.73	2.59
U Car	1.589	11.07 ± 0.04	6.28	5.05
SV Vul	1.654	12.32 ± 0.07	7.24	5.75

are adopted directly from Table 5 given by GFG. Only three Cepheids have a mean error in their distance modulus larger than 0.1 mag. We give in Table 2 the adopted calibrating sample of galactic Cepheids.

2.2. The list of extragalactic Cepheids

In 1999 we have constructed an Extragalactic Cepheid database (Lanoix et al. 1999b) by collecting 3031 photometric measurements of 1061 Cepheids located in 33 galaxies. This list has been updated. Especially, the V and I band measurements by Udalski et al. (OGLE survey, 1999) were added for the LMC from the data available through [`astroph/9908317`]. The new database contains 6685 measurements for 2449 Cepheids in 46 galaxies. In order to make this compilation available, the full contents of the extragalactic part will be published in electronic form for the A&A archives at CDS. A description is given in the Annex.

In this database, each light curve has been inspected in order to describe the main features. In the present study only light curves considered as "Normal" are used[2]. We reject all peculiar light curves including light curves classified as "low amplitude" because they are often associated with overtone Cepheids.

Only the mean V and I band magnitudes are kept. When several magnitudes are averaged from different sources we keep the mean only if the mean error is less than 0.05 mag. It is to be noted that HST measurements of seven galaxies[3] have been analyzed by two independent groups. This leads to two different sets of magnitudes. Independent treatment of both sets shows that the distance modulus differs by less than 0.1 mag, except for IC4182 for which the difference is 0.28 mag (Lanoix, private communication). Because we have no means to decide which set is the best we decided to keep them both.

The final catalogue (Table 3) results in 1840 extragalactic Cepheids. They belong to 36 galaxies, 27 of which come from HST observations and 9 from ground-based observations. The full Table is available in electronic form in the A&A archives at CDS.

3. Method of sosie

The method of "sosie" was introduced (Paturel 1984) to avoid the problem encountered in the practical use of the Tully-Fisher relation (Tully & Fisher 1977), a linear relation between the absolute magnitude of a galaxy and its 21-cm line width. Here we are in similar conditions with a linear relationship between the absolute magnitude and an observable parameter, the logarithm of the period. In French, the word "sosie" refers to someone who looks very similar to someone else without being necessarily genetically related. Here two Cepheids will be considered as "sosie" if their light curves have the same shape and if they have the same period (within a given error). Because of the selection based on the shape of the light curve we will consider that all Cepheids of our sample pulsate in the fundamental mode. They all obey the same P–L relation.

We write the distance modulus of a calibrating Cepheid and of an extragalactic Cepheid through a universal PL relation. The calibrating Cepheid is identified with subscripts "c" and no subscript for the extragalactic one. Presently, we assume thatboth stars have the same

[2] Lanoix et al. give eight classes of light curves: "Normal", "Symetrical", "Bumpy", "Scattered", "Overtone", "Low amplitude", "Peculiar", "No curve". A "Normal" light curve is characterized by a non-symetrical variation: a fast increase and a slower decrease.

[3] IC 4182, NGC 3368, NGC 3627, NGC 4496A, NGC 4536, NGC 4639 and NGC 5253.

Table 3. Sample of extragalactic Cepheids. Column 1: Name of the host galaxy; Col. 2: Name of the Cepheid according to the following reference; Col. 3: Reference (coded) from which the Cepheid name is taken; Col. 4: log of the period (P in days); Col. 5: Mean V-band apparent magnitude; Col. 6: Mean I-band apparent magnitude. Only a part of the table is given. The rest is available in electronic form.

galaxy	Cepheid	Ref.	log P	$\langle V\rangle$	$\langle I\rangle$
IC 4182	C11	Gib99	1.423	23.10	22.21
LMC	109838	Uda99	0.732	16.14	15.11
NGC 1365	V32	Sil98	1.460	26.77	25.94
NGC 1425	C15	Mou99	1.295	26.63	25.90
NGC 2090	C13	Phe98	1.461	25.44	24.55
NGC 224	FI13	Fre90	1.497	19.24	18.33
NGC 2541	C25	Fer98	1.270	25.68	24.90
NGC 3031	C13	Fre94	1.270	23.56	22.75
NGC 3109	P2	Mus98	0.722	22.18	21.87
NGC 3198	C19	Kel99	1.220	26.23	25.12
NGC 3319	C13	Sak99	1.398	25.61	24.89
NGC 3351	C25	Gra97	1.207	25.77	24.49
NGC 3368	C09	Gib99	1.483	25.13	24.11
NGC 3621	C14	Raw97	1.498	23.28	22.76
NGC 3627	C14	Gib99	1.366	24.66	23.46
NGC 4258	MAO14	Mao99	1.330	24.65	23.88
NGC 4321	C9	Fer96	1.700	25.93	24.88
NGC 4414	C1	Tur98	1.658	25.89	24.85
NGC 4496	C24	Gib99	1.717	25.27	24.26
NGC 4535	C35	Mac99	1.390	26.14	25.22
NGC 4536	C12	Gib99	1.484	25.81	24.89
NGC 4548	C09	Gra99	1.270	25.96	25.38
NGC 4603	2984	New99	1.570	27.19	26.37
NGC 4639	C14	Gib99	1.717	26.33	25.28
NGC 4725	C09	Gib98	1.590	24.85	23.87
NGC 5253	C07	Gib99	1.025	23.71	22.86
NGC 5457	V4	Kel96	1.471	23.51	22.78
NGC 598	V31	Chr87	1.572	19.17	18.14
NGC 7331	V4	Hug98	1.354	26.13	24.93
NGC 925	V18	Sil96	1.439	24.99	23.97
SEXB	V2	Sa85b	1.444	20.60	20.00
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metallicity and the same intrinsic color. We will see how to bypass this problem, later.

$$\mu_c = m_c^o - a \log P_c - b, \quad (1)$$
$$\mu = m^o - a \log P - b \quad (2)$$

m^o is the apparent mean magnitude in a given band. The superscript "o" means "corrected for extinction". If one selects an extragalactic Cepheid having the same period as the calibrating one, i.e., $\log P = \log P_c$, the distance modulus of the extragalactic Cepheid is then

$$\mu = \mu_c + m^o - m_c^o. \quad (3)$$

The distance modulus of the extragalactic Cepheid is deduced without having to know the slope and zero-point of the PL relation.

In order to correct for extinction we apply the previous equation to two different bands and express the extinction term as a function of the color excess $E = E(B-V)$. In order to make the notations clearer we note the apparent magnitudes V and I for the two considered bands. From Eq. (3) one has:

$$\mu = \mu_c + V - R_V E - V_c + R_V E_c \quad (4)$$
$$\mu = \mu_c + I - R_I E - I_c + R_I E_c \quad (5)$$

which can be written as

$$\mu = \mu_c + V - V_c - R_V(E - E_c) \quad (6)$$
$$\mu = \mu_c + I - I_c - R_I(E - E_c). \quad (7)$$

Then, eliminating $E - E_c$ between the two previous equations we obtain:

$$\mu = \mu_c + \frac{(V - V_c) - \frac{R_V}{R_I}(I - I_c)}{1 - \frac{R_V}{R_I}}. \quad (8)$$

This is the desired equation. It can be written in a more elegant manner by using the reddening-free Wesenheit function (Van den Bergh 1968):

$$W = \frac{V - (R_V/R_I).I}{1 - (R_V/R_I)} \quad (9)$$

$$\mu = \mu_c + W - W_c. \quad (10)$$

In practice, the intrinsic color is not known and this equation is valid only for Cepheids of the same intrinsic color and metallicity. Thus, for a true sample, we will write it as (see the discussion below):

$$\langle\mu\rangle = \mu_c + \langle W - W_c\rangle\cdot \quad (11)$$

W is an observable quantity. Then, the mean distance modulus of a sample of Cepheids which have the same period of pulsation as a calibrating Cepheid can be obtained directly from Eq. (11).

The physical relationship in this result is a Period-Luminosity-Color relation. This means that we should search for sosie of calibrators by considering both their similarity in $\log P$ and intrinsic color C_o. But the intrinsic color is not observable. Thus, Eq. (11) must be considered as a statistical relation exactly as the PL relation. Because of the statistical relation between C_o and $\log P$, the selection in $\log P$ will guarantee that a calibrator Cepheid and its sosies have, *on average*, the same intrinsic color. So, the problem of the intrinsic color is partially bypassed. For the metallicity problem, the solution is to consider that the method is valid only for galaxies having nearly the same metallicity as the calibrating Cepheids. In the

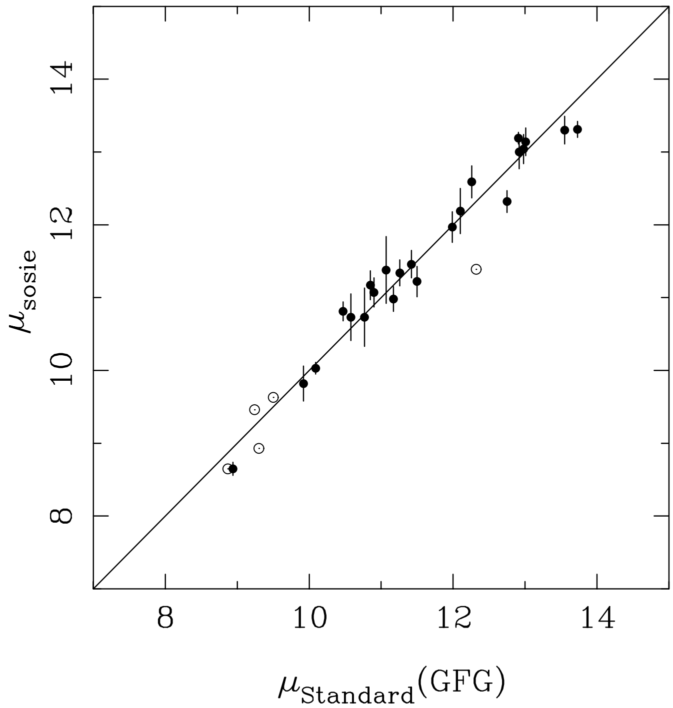

Fig. 1. Comparison of standard distance moduli with those calculated from the method of sosie. The solid line corresponds to a slope of one and a zero-point of zero. Open circles represent the points for which there is only one determination and then no standard deviation.

present paper this means that, *stricto sensu*, only galaxies with a nearly Solar metallicity can be considered as valid. In practice, we applied the method to different kinds of galaxies without noting strong metallicity dependence.

As a test, we apply the method to the calibrating sample itself. Indeed, some galaxies of the sample can be considered as sosie of another. Note that each calibrating Cepheid has at least itself as a sosie. Obviously, we will not consider this special case. We will accept two Cepheids as sosie when the difference of their $\log P$ is smaller than 0.07. With a PL slope of ≈ -3, this will give an uncertainty $\approx$0.2 mag. in the distance modulus. We adopt the ratio $R_V/R_I = 1.69$ because it corresponds to the most widely accepted one (it corresponds to a ratio of total-to-selective absorption $A_V/(A_V - A_I) = R_V/(R_V - R_I) = 2.45$).

In Table 4 we give the distance moduli obtained with Eq. (11) for 23 Cepheids which are sosie of another calibrator. In Fig. 1 the comparison of the calculated distance moduli with the calibrating ones is given.

From a direct regression we find that the slope is not different from one (1.00 ± 0.03). The observed mean difference between the calculated distance modulus and its standard value is obtained together with its standard deviation:

$$\langle \mu_{\text{sosie}} - \mu_{\text{standard}} \rangle = -0.00 \pm 0.24. \quad (12)$$

The method does not introduce any systematic shift in the zero point. *This means that the calibrating Cepheids constitute a coherent system* (at least for the 28 Cepheids used in the test). The observed standard deviation (0.24) is in agrement with the expected standard deviation 0.2.

Table 4. Distance moduli we obtain with Eq. (11) for 28 Cepheids which are sosie of another calibrator. Column 1: Name of the galactic Cepheid; Col. 3: Distance modulus calculated from Eq. (11); Col. 3: Standard deviation on the calculated distance modulus; Col. 4: Number of sosies (excluding its own case).

Cepheid	μ	std.dev.	No.
T Vel	10.03	0.08	2
BF Oph	9.63	-	1
CV Mon	11.07	0.20	2
V Cen	8.93	-	1
U Sgr	8.65	-	1
BB Sgr	9.46	-	1
XX Cen	11.17	0.20	4
V340 Nor	11.22	0.21	4
S Nor	9.82	0.24	2
UU Mus	12.59	0.22	3
U Nor	10.73	0.40	5
BN Pup	13.00	0.23	3
LS Pup	13.31	0.11	3
VW Cen	13.14	0.19	2
RY Sco	10.81	0.13	6
RZ Vel	10.98	0.17	6
WZ Sgr	11.34	0.18	6
VY Car	11.46	0.19	3
WZ Car	13.04	0.20	5
VZ Pup	13.30	0.19	6
SW Vel	11.97	0.21	6
T Mon	10.73	0.32	4
RY Vel	12.19	0.31	2
AQ Pup	12.32	0.15	3
KN Cen	13.19	0.08	3
ι Car	8.65	0.09	2
U Car	11.38	0.46	3
SV Vul	11.39	-	1

4. Application to extragalactic Cepheids

4.1. Preliminary determination of extragalactic distance moduli

The method is applied to the 1840 Cepheids of Table 3. To accept two Cepheids as sosie, we still adopt the criterion $|\log P - \log P_{\text{c}}| < 0.07$ which guarantees that the standard deviation is about 0.2 mag, assuming a PL slope of -3. We adopt the ratio $R_V/R_I = 1.69$ which corresponds to the first order terms proposed by Caldwell & Coulson (1987) and Laney & Stobie (1993). This is also the value adopted by Freedman et al. (2001), following Cardelli et al. (1987), for their HST key project about

Cepheids[4]. For each of the 36 host galaxies we plot the different distance moduli given by Eq. (11) as a function of $\log P$. This result appears in Fig. 3.

The most important feature to point out is a significant trend leading to higher distance moduli for long period Cepheids. This trend is visible for almost all the host galaxies. This is visible even for nearby galaxies if short periods are observed. For distant galaxies the trend is visible also at long periods. This was expected from the incompleteness bias we discussed elsewhere (e.g., Lanoix et al. 1999a). Another signature of the bias comes from the fact that only nearby galaxies (IC 1613, IC 4182, LMC, NGC 224, NGC 3109; NGC 5253) have Cepheids with short periods. This clearly depends on the limiting magnitude of the considered host galaxy. This important question is discussed in the following subsection.

4.2. Correction for the incompleteness bias

In order to get the proper distance moduli we have to correct for the incompleteness bias. In a previous paper (Lanoix et al. 1999a) we suggested using a rule of thumb to avoid this bias. The rule consists of using only $\log P$ values larger than a given limit $\log P_l$. This limit is expressed as:

$$\log P_l = \frac{V_{\rm lim} - \mu - b - 2\sigma}{a}. \qquad (13)$$

Unfortunatelly, this method does not take into account the pieces of information contained in smaller periods. The detailed theory of this incompleteness bias was given by Teerikorpi (1987) in the study of galaxy clusters. The bias for extragalactic Cepheids is of the same nature because the Cepheids of a given galaxy are all at the same distance from us, like the galaxies of a cluster. Assuming that the dispersion σ at a given $\log P$ is constant, the basic equations adapted to the problem of extragalactic Cepheids are the following (for the sake of simplicity we will consider only the V band):

The observed distance modulus μ will appear smaller than the true one. The bias $\Delta\mu$ at a given $\log P$ is:

$$\Delta\mu = -\sigma\sqrt{\frac{2}{\pi}}\frac{{\rm e}^{-A^2}}{1+erf(A)} \qquad (14)$$

where

$$A = \frac{V_{\rm lim} - \mu - a_{\rm v}\log P - b_{\rm v}}{\sigma\sqrt{2}} \qquad (15)$$

and

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x {\rm e}^{-t^2}{\rm d}t. \qquad (16)$$

In these equations $a_{\rm v}$ and $b_{\rm v}$ are the slope and zero point of the PL relation. We adopt the values found by GFG from their galactic sample, i.e., $a_{\rm v} = -3.037$ and $b_{\rm v} = -1.021$[5]. Note that this requirement seems to reduce the interest of the sosie method because the slope and zero-point are needed anyway. In fact, the slope and zero-point appear only as parameters in a second order correction.

Two additional quantities are required to apply these equations:

- the limiting magnitude $V_{\rm lim}$;
- the standard deviation σ of the PL relation at a constant $\log P$.

The first quantity is derived from the histograms of $\langle V\rangle$ presented in Fig. 2 for each galaxy. We adopt for $V_{\rm lim}$ the fainter edge of the most populated class. In a few cases where the histogram has no dominant class, we move the value by ± 0.5 mag. $V_{\rm lim}$ values do not change significantly when one changes the binning size. Only one galaxy (NGC 5457) changed by more than the binning size, but its histogram shows two classes with almost the same population. Nevertheless, the global influence of a change in $V_{\rm lim}$ is discussed in Sect. 4.3 (Table 5) and we show its influence on each individual galaxy in Table 6. The second quantity (σ) is derived by a direct linear regression on each plot of Fig. 3. The adopted quantities $V_{\rm lim}$ and σ are listed in Cols. 2 and 3 of Table 6.

These parameters being fixed, there is no free parameter to adjust the bias curve to the plot of Fig. 3 except the distance modulus μ itself which is then determined through an iterative process. The final bias curves are plotted in Fig. 3 for each host galaxy. In Col. 9 of Table 6 we give the number of remaining sosies after the cut-off at $V_{\rm lim}$. In Fig. 3 the points which are rejected by the cut-off are represented by crosses.

4.3. Analysis of the results

Freedman et al. (2001) recently published their final study of their HST keyproject (HSTKP). They publish distance moduli calculated differently to those used here. They calibrate the PL relation with the LMC distance modulus, assumed to be μ(LMC) = 18.5. They, adopt the V- and I-band PL relations and an extinction law giving $R_V/R_I = 1.69$. In order to avoid bias, they cut their sample at a given limiting period $\log P_l$ as explained above and they apply a small (but still uncertain) correction for metallicity effect.

The comparisons between the HSTKP results and our solution is shown in Fig. 4 for 31 galaxies in common. There is a fair agreement. A direct regression between HSTKP distance moduli and ours leads to a slope which is not significantly different from one (1.017 ± 0.010) and a zero point difference which is not significantly different from zero (-0.11 ± 0.16). Assuming both determinations carry the same uncertainty, this means that our distances are good within $0.16/\sqrt{2} = 0.1$ mag. This is the internal uncertainty.

From a detailed check of Fig. 4 one sees a slight departure from a slope of one at large distances. The effect

[4] This value corresponds to a ratio of total-to-selective absorption $A_V/(A_V - A_I) = R_V/(R_V - R_I) = 2.45$.

[5] GFG give $b_{\rm v} = -4.058$ because they consider the zero-point at $\log P = 1$.

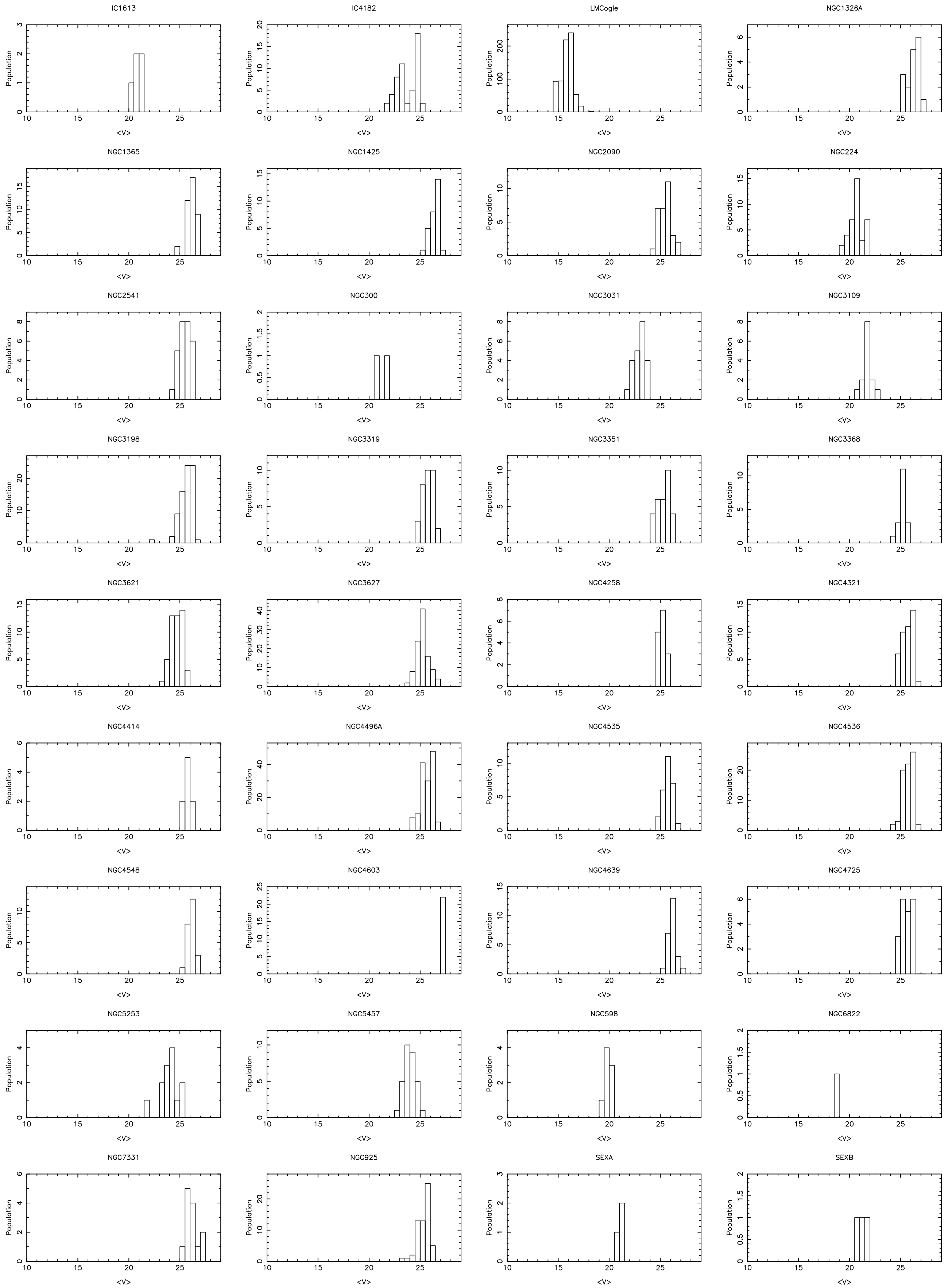

Fig. 2. Histograms of apparent $\langle V \rangle$ magnitudes for each host galaxy. On the x-axis we give $\langle V \rangle$. On the y-axis we give the population. The completeness limit in magnitude is generally (see text) taken from the upper limit of the most populated class.

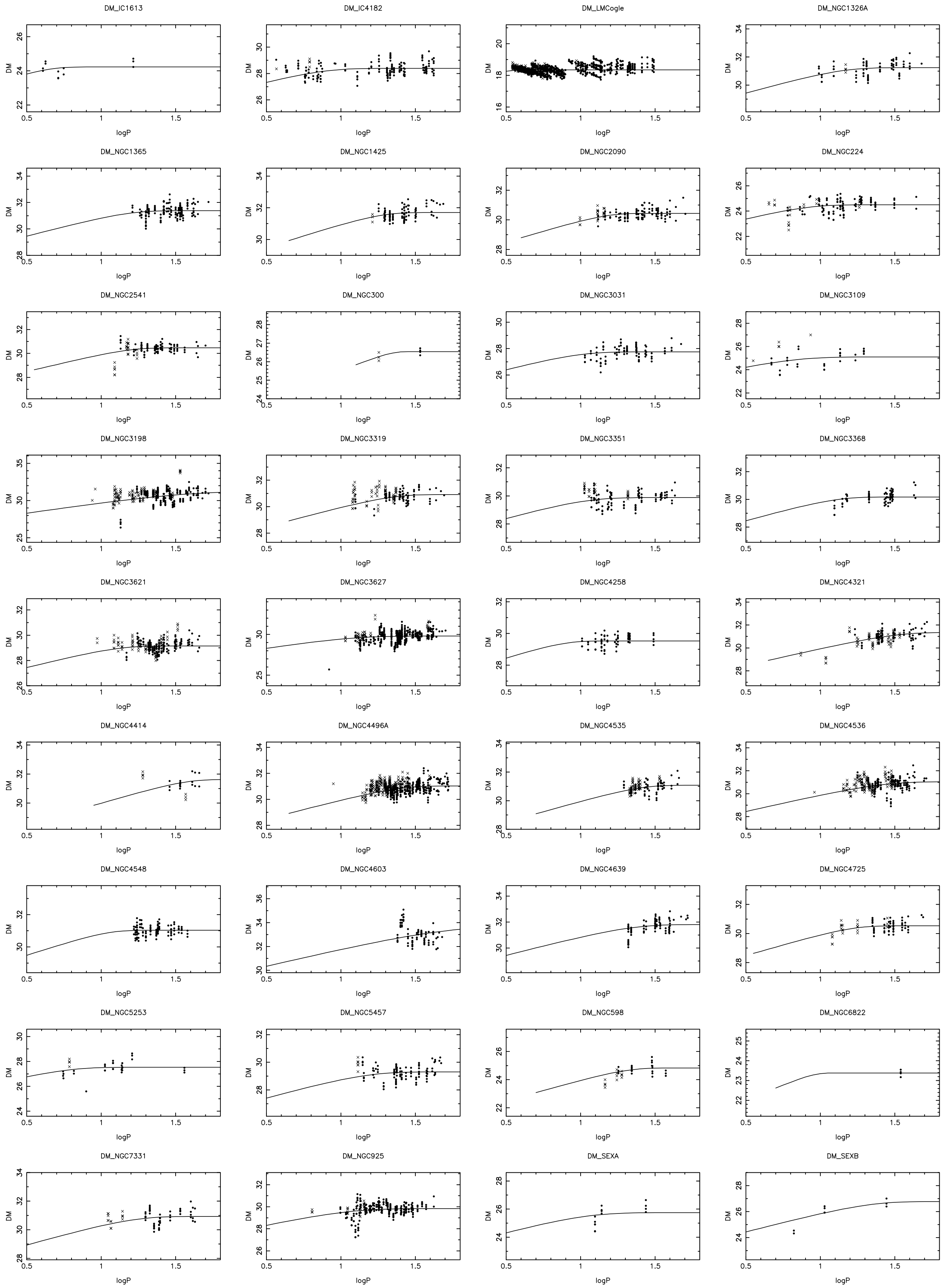

Fig. 3. Distance moduli (y-axis) from the method of sosie vs. $\log P$ (x-axis) for each host galaxy. Each point corresponds to an extragalactic Cepheid which is sosie of a calibrating Cepheid. The solid curves correspond to the adopted bias curves (Sect. 4). The points rejected by the cut-off at $V_{\rm lim}$ are represented with crosses.

is, on average, 0.17 mag for μ larger than 30 mag. Two possibilities can explain this discrepancy:

- The PL relation of the GFG sample shows a departure from linearity for large $\log P$. This effect is visible (see for instance Fig. 4 in GFG) even when one excludes the three overtone Cepheids ($\log P < 0.6$). Judging by the error bars of individual points, this non-linearity seems real.
- The distance moduli of Freedman et al. may suffer from a small residual incompleteness bias. Using a simulation we have shown that it is difficult to remove the bias just by cutting the sample at a given $\log P_l$. If we refer to our Fig. 7 in Lanoix et al. (1999a), one can see that at large distances ($\mu > 32$) the bias may reach 0.17 mag after the $\log P$ cutoff. At intermediate distances ($29 < \mu < 32$) the bias may still reach 0.08 mag.

Three external sources of uncertainty come from: (i) the adopted ratio R_V/R_I, (ii) the adopted limiting magnitude $V_{\rm lim}$ and (iii) from the adopted PL relation used for second order bias correction. In order to check the stability of the solution, we repeated the previous calculations with another PL relation (the one found by GFG for LMC), with a variation of R_V/R_I by ± 0.2 and a variation of $V_{\rm lim}$ by ± 0.5 mag. The results are summarized in Table 5, where we give the mean shift between distance moduli from different solutions and the adopted mean distance moduli (reference solution). One can see that the choice of the PL relation has no actual influence on the result. However, a change of R_V/R_I by ± 0.1 may change the mean distance modulus by nearly 0.2 mag and a change of $V_{\rm lim}$ by 0.5 mag may produce similar change. The influence of $V_{\rm lim}$ depends clearly on the actual distribution of magnitudes. For some galaxies the effect is negligible while it is large for some others. In order to give a better judgement of the stability of the distance modulus with respect to the adopted $V_{\rm lim}$, we give the changes $\Delta\mu^-$ when $V_{\rm lim}$ is reduced by 0.5 mag (respectively, $\Delta\mu^+$ when $V_{\rm lim}$ is augmented by 0.5 mag).

The actual uncertainty (internal plus external) can thus reach 0.3 mag and may be more if our actual sources of uncertainty act in the same sense.

Table 5. Test of the stability of the results. We give the departure from our reference solution for: 1) a different PL relation (note that this PL relation is used only for the second order bias correction 2) several R_V/R_I ratios.

$\Delta V_{\rm lim}$	R_V/R_I	$a_{\rm v}$	$b_{\rm v}$	$\mu - \mu_{\rm ref}$
0.0	1.69	−2.769	−4.063	$+0.03 \pm 0.05$
0.0	1.89	−3.037	−4.058	-0.22 ± 0.10
0.0	1.79	−3.037	−4.058	-0.12 ± 0.06
0.0	1.69	−3.037	−4.058	0
0.0	1.59	−3.037	−4.058	$+0.17 \pm 0.09$
0.0	1.49	−3.037	−4.058	$+0.45 \pm 0.21$
−0.50	1.69	−3.037	−4.058	$+0.20 \pm 0.27$
−0.25	1.69	−3.037	−4.058	$+0.09 \pm 0.12$
+0.25	1.69	−3.037	−4.058	-0.05 ± 0.08
+0.50	1.69	−3.037	−4.058	-0.08 ± 0.10

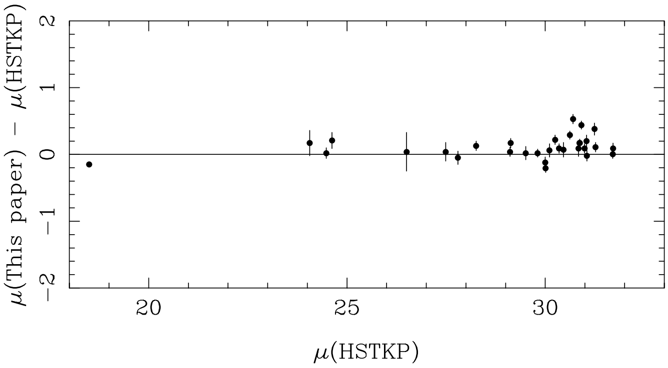

Fig. 4. Comparison of the distance moduli from Freedman et al. (2001) and those from this paper. The general agreement is satisfactory but at large distances our distances become larger.

5. Conclusion

The distance scale can be calibrated using galactic Cepheids. LMC provides us with numerous Cepheids located at the same distance. This gives a way to derive an accurate slope for the Cepheid PL relation. But its low metallicity (with respect to most of the galaxies of the sample) is a cause of suspicion; we are not sure that this slope can be applied to all kinds of metallicity.

So, we preferred, in a first step, to calibrate the distance scale by using accurate distances of galactic Cepheids published by Gieren et al. (1998). These distances are based on the geometrical Barnes-Evans method.

Further, we applied the concept of "sosie" (Paturel 1984) to extend distance determinations to extragalactic Cepheids without having to know either the slope or the zero-point of the PL relation. The distance moduli are obtained in a straightforward way. For the calibrating galactic Cepheids we checked the internal coherence from the same method.

The correction for the extinction is made by using two bands (V and I) according to the principles introduced by Freedman & Madore (1990). There is no need for color excess estimation.

Finally, the incompleteness bias is corrected according to the precepts introduced by Teerikorpi (1987). Without any free parameters (except the distance modulus itself), the bias curve calculated for each individual host galaxy fits very well the observed distance moduli. This gives us confidence in our final distance moduli. Nevertheless, the small departure from the measurements published recently by Freedman et al. (2001) at distances larger than 10 Mpc ($\mu = 30$) must be clarified.

Table 6. Distance moduli calculated from this paper using the ratio $R_V/R_I = 1.69$. Column 1: Name of the host galaxy. Column 2: The adopted limiting magnitude $V_{\rm lim}$. Column 3: Standard deviation σ. Column 4: The adopted distance modulus and its mean error. An asterisk marks the distance moduli of galaxies having nearly a Solar metallicity. Column 5: The change $\Delta\mu^-$ of the distance modulus when $V_{\rm lim}$ is reduced by 0.5 mag (i.e., a brighter limit). Column 6: The change $\Delta\mu^+$ of the distance modulus when $V_{\rm lim}$ is augmented by 0.5 mag (i.e., a fainter limit). Column 7: The number of sosie Cepheids after the $V_{\rm lim}$ cut-off.

galaxy	$V_{\rm lim}$	σ	$\mu \pm m.e.$	$\Delta\mu^-$	$\Delta\mu^+$	n
IC 1613	21.5	0.36	24.23 ± 0.19	0.16	-0.09	12
IC 4182	25.0	0.50	28.39 ± 0.07	0.00	-0.05	169
LMCogle	16.5	0.24	18.36 ± 0.03	0.03	0.01	947
NGC 1326A	27.0	0.46	31.24 ± 0.09	0.07	-0.07	70
NGC 1365	27.0	0.43	* 31.38 ± 0.07	0.04	-0.03	152
NGC 1425	27.0	0.35	* 31.70 ± 0.06	0.31	-0.08	99
NGC 2090	26.0	0.31	* 30.44 ± 0.07	0.09	-0.03	103
NGC 224	21.0	0.47	* 24.50 ± 0.08	0.19	-0.08	106
NGC 2541	26.0	0.35	* 30.47 ± 0.07	0.03	-0.07	88
NGC 300	21.5	0.14	26.54 ± 0.29	0.08	-0.11	4
NGC 3031	24.0	0.47	* 27.75 ± 0.10	0.09	-0.05	92
NGC 3109	22.0	0.61	25.10 ± 0.16	0.30	0.11	31
NGC 3198	26.0	0.86	31.23 ± 0.07	0.70	-0.17	187
NGC 3319	26.0	0.38	30.91 ± 0.06	0.89	-0.03	88
NGC 3351	26.0	0.50	* 29.88 ± 0.08	0.07	0.01	110
NGC 3368	26.0	0.39	* 30.17 ± 0.10	0.09	-0.05	74
NGC 3621	25.0	0.43	* 29.15 ± 0.07	0.06	0.04	152
NGC 3627	26.0	0.66	* 29.80 ± 0.06	0.06	-0.03	369
NGC 4258	26.0	0.34	* 29.53 ± 0.10	0.09	-0.01	65
NGC 4321	26.0	0.47	31.35 ± 0.06	0.85	-0.28	78
NGC 4414	26.0	0.33	31.62 ± 0.09	0.78	-0.15	18
NGC 4496A	26.0	0.41	31.03 ± 0.04	0.42	-0.06	280
NGC 4535	26.0	0.38	* 31.08 ± 0.07	0.15	-0.08	64
NGC 4536	26.0	0.52	* 31.04 ± 0.06	0.18	-0.12	153
NGC 4548	27.0	0.31	* 31.03 ± 0.08	0.05	-0.01	100
NGC 4603	28.0	0.84	33.70 ± 0.09	0.00	-0.52	79
NGC 4639	27.0	0.52	31.80 ± 0.08	0.41	-0.12	77
NGC 4725	26.0	0.36	* 30.53 ± 0.11	-0.01	-0.04	53
NGC 5253	24.5	0.52	* 27.53 ± 0.14	0.13	-0.01	30
NGC 5457	25.0	0.51	* 29.30 ± 0.07	0.10	-0.01	102
NGC 598	20.0	0.34	24.83 ± 0.12	-0.38	-0.23	22
NGC 6822	19.5	0.14	23.38 ± 0.52	0.00	0.00	4
NGC 7331	26.5	0.50	30.93 ± 0.12	0.39	-0.05	48
NGC 925	26.0	0.62	* 29.83 ± 0.06	0.02	-0.08	238
SEXA	22.0	0.62	25.75 ± 0.23	0.31	-0.15	14
SEXB	22.0	0.51	26.77 ± 0.18	0.53	-0.27	9

In order to bypass the uncertainty due to metallicity effects it is suggested to consider only galaxies having nearly the same metallicity as the calibrating Cepheids (i.e. Solar metallicity). In Table 6 the distance moduli that can be considered as more secure are noted with an asterisk ($*$). Galaxies with $\Delta\mu$ larger than $\approx$0.3 mag. or with small n do not receive this flag. For a given ratio R_V/R_I, the uncertainty of the distances is about 0.1 mag but the total uncertainty may be about 0.3 mag. The choice of a given R_V/R_I ratio is a first source of uncertainty. The actual ratio depends on the extinction law in our Galaxy, on the extinction law in the host galaxy and on the color of the considered Cepheid. For the future it would be interesting to search for a clue allowing us to decide which value is the best in a given direction for a Cepheid in a given host galaxy. The proper determination of the limiting magnitude of the sample is a second source of uncertainty. It can be accurately determined only when a large number of Cepheids is available to provide us with good statistics.

Presently, the calibration of the distance scale can barely be better than $\sigma_\mu = 0.3$ mag. Thus, the uncertainty on the Hubble constant, $\sigma(H) \approx \sigma_\mu H/5 \log e$, cannot be better than about 10 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

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Appendix A: The extragalactic Cepheid database

The description of this database was given by Lanoix et al. (1999b). Because the database is no longer available on the world-wide-web the present data are published in electronic form in the A&A archives at CDS. All the data are made available, even when they are not used in the present paper, where only Normal Cepheids in V and I-bands are considered. Additional measurements were collected including the LMC ones by Udalski et al. (1999)[6] and those by Gibson et al. (1998, 1999). Data are now available for 2449 Cepheids of 46 galaxies (instead of 1061 Cepheids of 33 galaxies).

The identification of a Cepheid is given on a first line as follows:

- the name of the host galaxy,
- the name of the Cepheid and the bibliographic code from where this name is taken,
- the adopted period (in log),
- The classification of the shape of the light curve, following Lanoix et al. (1999b).

On this first line we also give the number of measurements attached to this Cepheid. Note that the Cepheid name for LMC is simply the Cepheid number from Udalski et al., without the field number (SC), that was not needed here (only three Cepheids appear with the same number in different fields: 1, 16 and 19, but they are not in our list). We tried to keep the Cepheid name of the first discovery. This was not always done, e.g., the names given by Graham (1984) are referenced as Mad87 because of the renumbering adopted by Madore (1987).

On the following lines, individual measurements are given:

- the magnitude;
- the type of magnitude (mean, maximum, minimum, average) coded according to Lanoix et al.;
- the photometric bands (B, V, R, I ...) coded according to Lanoix et al. (1999b);
- the reference code. The full reference and the associated code appears in the references.

A sample is given below to show how the data are organized.

[6] Note that we kept 720 normal Cepheids among the 1182 available with $\log P > 0.5$.

```
IC1613  V1         Fr88a  0.7480     N    8
 21.36     mea       B   Fr88a
 20.79     mea       V   Fr88a
 20.36     mea       R   Fr88a
 20.14     mea       I   Fr88a
 20.50     max       B   Sa88a
 22.03     min       B   Sa88a
 21.27     ave       B   Sa88a
 21.39     mea       B   Sa88a
IC1613  V20        Fr88a  1.6220     B    5
 16.66               H   Ala84
 18.98     max       B   Sa88a
 20.71     min       B   Sa88a
 19.85     ave       B   Sa88a
 19.90     mea       B   Sa88a
IC1613  V22        Fr88a  2.1650     S    9
 15.47               H   Ala84
 19.10     mea       B   Fr88a
 17.75     mea       V   Fr88a
 17.14     mea       R   Fr88a
 16.62     mea       I   Fr88a
 17.74     max       B   Sa88a
 20.44     min       B   Sa88a
 19.09     ave       B   Sa88a
 19.09     mea       B   Sa88a
IC1613  V25        Fr88a  0.9600     B+   5
 18.62               H   Ala84
 20.10     max       B   Sa88a
 21.84     min       B   Sa88a
 20.97     ave       B   Sa88a
 20.87     mea       B   Sa88a
IC1613  V53        Fr88a  0.5900     O    3
 21.13     max       B   Car90
 21.70     min       B   Car90
 21.46     mea       B   Car90
...
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...
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