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Evidence for the extragalactic Cepheid distance bias from the kinematical distance scale

P. Teerikorpi[1] and G. Paturel[2]

[1] Tuorla Observatory, University of Turku, 21500 Piikkiö, Finland
[2] CRAL–Observatoire de Lyon, 69561 Saint-Genis Laval Cedex, France

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Abstract. We present new evidence for the extragalactic Cepheid distance bias. A dependence between the Hubble parameter and the absolute Cepheid magnitude limit for a galaxy may be interpreted as a significant bias in the derived photometric distances: those from Cepheid samples with a bright absolute magnitude limit apparently are underestimated. This may be caused not only by the dispersion of $\bar{M}$ at a fixed Cepheid period, but also by the whole amplitude of variation, together with an upper limit in the period of the observed Cepheids, and other factors. If so, then the value of H_0 based on methods using Cepheid distances is expected to be often overestimated (i.e. the distances underestimated). We discuss whether the effect could be not real, but rather caused by uncertainties in kinematical distances.

Key words. galaxies: general – cosmology

1. Introduction

In the present letter we investigate the importance of the Cepheid population incompleteness bias, tending to produce too small distances: of the Cepheids in a galaxy only those with long periods P may be fully sampled, because of the limiting magnitude. This was first discussed by Sandage (1988). Lanoix et al. (1999) suggested a rule to avoid the bias by excluding short period Cepheids. Paturel et al. (2001) have used an analytical correction to the bias, and they have found evidence for a small differential bias in the HST Cepheid distances beyond $\mu \approx 30$ by comparing the HST values to the distances obtained via the differential ("sosies") method.

Here we use still another route. In analogy with the succesful use of a kinematic distance scale for revealing the Malmquist bias in TF distance moduli (see e.g. Teerikorpi 1997), we now study the bias in Cepheid distances by comparing them with the kinematical distances (corrected velocities) V_c derived from Peebles's infall model with $v_{IF} = 220$ km s^{-1}, $V_{Virgo} = 980$ km s^{-1}. This same model was used e.g. in Theureau et al. (1997). The local Hubble velocity field, when corrected for the infall flow towards the Virgo cluster, appears to be remarkably smooth, with the velocity dispersion $\leq$50 km s^{-1} (e.g. Sandage 1999; Ekholm et al. 2001; Karachentsev & Makarov 2000), and deserves to be utilized as an independent distance measure. In using this velocity field model, the six galaxies in the direction of the Virgo cluster have been put at $V_c = 980 + 220 = 1200$ km s^{-1}. We have excluded NGC 4414 from the data, as it is in the sky close to, but not in the Virgo cluster[1]. For other non-Virgo galaxies at an angular distance <30 deg we have used the Tolman–Bondi solution from Ekholm et al. (1999), also based on $V_{IF} = 220$ km s^{-1} and $V_{Virgo} = 980$ km s^{-1}.

We also check the result for different infall velocities and for the more complex velocity field model preferred by Freedman et al. (2001).

We use distances r_{ceph}, mostly from the HST projects, as given by Freedman et al. (2001). Table 1 gives the data.

2. *H* vs. the Cepheid sample deepness

We consider the deepness of the Cepheid sample in a galaxy as an important parameter related to the possible bias. This is based on the absolute magnitude limit $M_{lim} = m_{lim} - 5\log V_c - 16.5 + 5\log H/50$ for the Cepheids. The limiting magnitude m_{lim} comes from Paturel et al. (2001). Then following the old idea that the behaviour of the Hubble parameter $H = V_c/r_{ceph}$ may reveal a bias in the inferred distances, we show in Fig. 1a $\log H$ versus the absolute magnitude limit M_{lim}. The pattern in the distribution of the points is familiar from our other selection bias studies made in the past. On the right one sees the

Send offprint requests to: P. Teerikorpi,
e-mail: pekkatee@oj287.astro.utu.fi

[1] The Tolman–Bondi calculation by Ekholm et al. (1999) puts NGC 4414 at a distance of about 0.8 in Virgo units.

Table 1. Data for the Cepheid galaxy sample.

name	μ	V_0	V_c	$m_{\rm lim}$	$\log P_{\rm lim}$	$\log H$
224	24.48	-14	-14	21.0	1.65	-
300	26.50	124	112	21.5	1.55	1.75
598	24.62	68	68	20.0	1.55	1.91
925	29.81	782	775	26.0	1.60	1.93
1326	31.00	1716	1655	27.0	1.60	2.02
1365	31.27	1565	1515	27.0	1.65	1.93
1425	31.70	1440	1394	27.0	1.65	1.80
2090	30.35	755	807	26.0	1.65	1.84
2403	27.51	299	366	22.0	1.90	2.06
2541	30.25	647	802	26.0	1.65	1.85
3031	27.80	123	141	24.0	1.60	1.59
3109	25.22	130	140	22.0	1.30	2.10
3198	30.70	703	857	26.0	1.70	1.79
3319	30.62	763	929	26.0	1.65	1.84
3351	30.00	641	552	26.0	1.65	1.74
3368	30.11	760	624	26.0	1.60	1.77
3621	29.11	436	493	25.0	1.65	1.87
3627	30.01	596	504	26.0	1.65	1.70
4258	29.51	510	512	26.0	1.50	1.81
4321	30.91	1481	1200	26.0	1.70	1.90
4496A	30.86	894	1200	26.0	1.70	1.91
4535	30.99	1822	1200	26.0	1.65	1.88
4536	30.87	1640	1200	26.0	1.65	1.91
4548	31.05	379	1200	27.0	1.55	1.87
4639	31.71	894	1200	27.0	1.70	1.74
4725	30.46	1160	696	26.0	1.60	1.75
5253	27.49	155	161	24.5	1.50	1.71
5457	29.13	361	388	25.0	1.65	1.76
6822	23.27	8	8	19.5	1.50	-
7331	30.84	1115	1099	26.5	1.60	1.87
SEXA	25.81	118	115	22.0	1.40	1.90
SEXB	25.72	139	134	22.0	1.40	1.98
IC4182	28.37	337	303	25.0	1.60	1.81

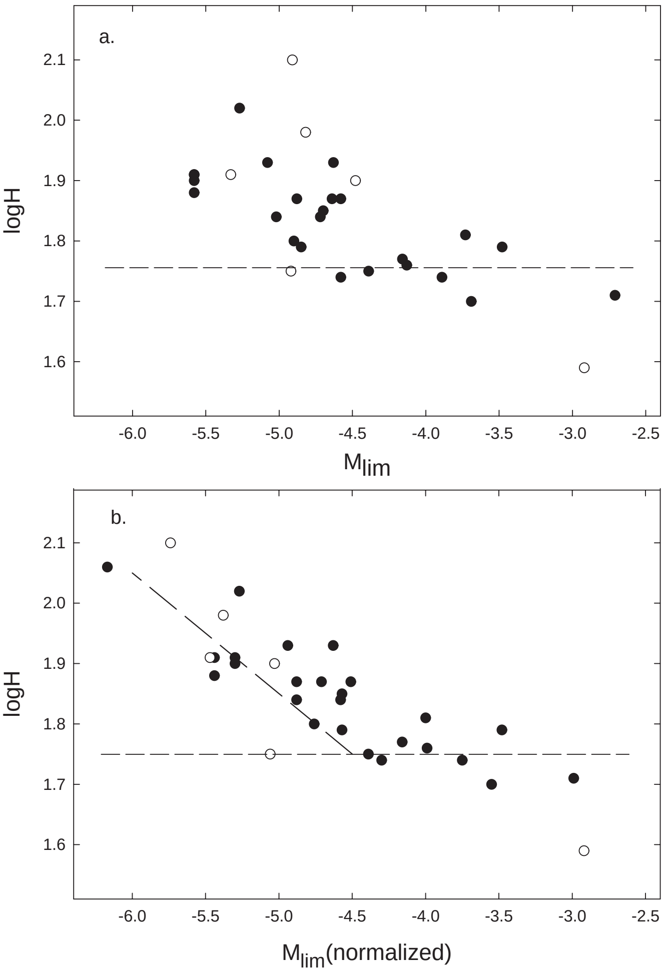

Fig. 1. (Log) Hubble parameter H versus increasingly normalized parameters: **a)** the absolute limiting magnitude $M_{\rm lim}$, **b)** $M_{\rm lim}$ normalized to account for different limiting Cepheid periods. NGC2403 with $\log H = 2.06$, outside the $M_{\rm lim}$ range in **a)**, now follows the trend of the other galaxies. Open circles are nearby galaxies having $V_{\rm cor} < 150$ km s^{-1}. The horizontal line is for $H = 58$. Note the "unbiased plateau", an expected feature in such a diagram and the slope -0.2 of the biased part, also expected in the simple scenario described in the text.

expected "unbiased plateau", and when $M_{\rm lim}$ gets brighter or the Cepheid sample less deep, $\log H$ starts to increase. The horizontal line is at $H = 58$.

It has been stated (Freedman et al. 2001) that the bias in the Cepheid method is very small for the present galaxies, because of the small intrinsic scatter σ_M in the PL-relation, and this small bias may be removed by cutting from the data short-period Cepheids. The differential bias in the HST values relative to the "sosies" distances (Paturel et al. 2001) was at most 0.1–0.2 mag.

3. A tentative model

But the bias indicated by Fig. 1a, if thus interpreted, appears to reach 0.5–1.0 mag for galaxies where the absolute limit is bright. Before presenting more evidence for the reality of the bias, we briefly consider how this can be possible, in spite of the precautions taken by the analyzers? We suspect that one should take into account not only the small dispersion σ_M, but also the amplitude of variation at the detection wavelength (Sandage 1988), and the maximal observed period. We also note the importance of the (unknown) true average extinction for the whole Cepheid population in a host galaxy.

Suppose that the Cepheid magnitude limit is $m_{\rm lim}$, the true distance modulus is μ, at the period P the average magnitude is $M(P)$, and the (half-) amplitude of variation is ΔM. The determination of $\bar{m}(P)$ presupposes that the whole range $m(P) \pm \Delta M$ is observed. But as the average $M(P)$ has also a dispersion σ_M, an unbiased determination of $\bar{m}(P)$ requires a still wider range, up to the faint magnitude of $m(P) + \Delta M + \alpha\sigma_M$, where $\alpha \approx$1–2. This range can be covered only for periods longer than $P_{\rm lim}$ where $M_P = a \log P_{\rm lim} + b = m_{\rm lim} - \mu - \Delta M - \alpha\sigma_M$. For periods shorter than $P_{\rm lim}$ this requirement forces into the sample only such Cepheids for which the true average M is brighter than the unbiased average, causing an underestimate of the distance.

The bias increases sharply, if there is a maximum observable period which is equal to or shorter than the above limit $P_{\rm lim}$. Then the brightening of the absolute magnitude limit $M_{\rm lim} = m_{\rm lim} - \mu$ directly enters the derived average distance modulus. In this interval of $M_{\rm lim}$ one expects that $\log H$ changes with the slope of -0.2 (coming from $\Delta \log r = 0.2\Delta\mu$).

Figure 1a shows that the slope of the increasing part of $\log H$ indeed is close to -0.2. But does the increase start at an expected value of $M_{\rm lim}$?

We take the period–luminosity law as follows: $M_V = -2.76 \log P - 1.46$, the amplitude $\Delta M = 0.5$ mag, $\sigma_M = 0.3$, $\alpha = 1$ (1 sigma), and calculate $M_{\rm lim} = V_{\rm lim} - 5 \log V_{\rm c} - 16.2$ for $H = 58$. Furthermore, one must brighten the absolute limit by the average amount of extinction in the Milky Way and in the host galaxy. Note that this does not refer to the extinction for the *observed* Cepheids, but to the *true* average extinction which must be higher. We conservatively take the (unknown) total extinction to be 0.5 mag. It should be emphasized that just correcting for the individual extinctions (reddenings) does not remove the fact that it is the total extinction that changes the effective magnitude limit.

Then the limiting $\log P$ corresponding to $M_{\rm lim} = -4.5$ (Fig. 1) is =1.57. This agrees rather well with the general period limit achieved in HST observations (Freedman et al. 2001; Paturel et al. 2001).

In principle, one could treat this bias using the model discussed by Teerikorpi (1987) in connection with the TF distance moduli of galaxy clusters (cf. Paturel et al. 2001), with the modification that now at a fixed period there are Cepheids with different average M and the function of the absolute magnitude limit is to throw away a Cepheid when its average magnitude is brighter than but sufficiently close to the limit. Furthermore, in the calculation of the mean bias one must take into account the upper limit in the relevant parameter, here the period P. However, at this stage we prefer this simple demonstration. A full treatment of the bias may need deeper understanding of the difficult art of detecting Cepheids against the galaxy background, obscured by extinction.

4. Checking the correlation

One might argue that the correlation between $\log H$ and $M_{\rm lim}$ is due to errors in the Hubble flow model, as $V_{\rm c}$ enters both quantities. If so, the peculiar velocities would be large, contrary to other evidence, and this would not explain the bias pattern in Fig. 1a. Here we give more evidence that the culprit is the distance and not the velocity.

We first show in Fig. 1 how different steps of normalization sharpen the bias pattern. In Fig. 1a the purely photometric quantity $m_{\rm lim}$ has been added to the ($-5\log$) kinematical distance, which normalization leads to the absolute magnitude limit $M_{\rm lim}$ and to the bias pattern.

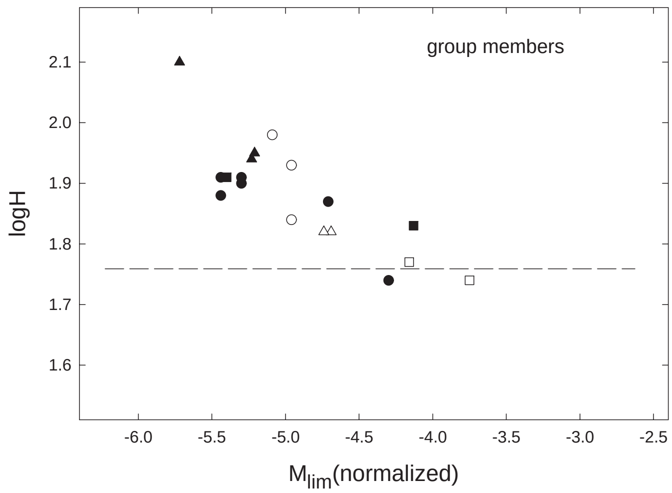

Fig. 2. (Log)H versus the normalized absolute limiting magnitude $M_{\rm lim}$ for galaxies in systems, using for each system an average radial velocity. The symbols: Dot (Virgo), open circle (Fornax), filled square (M81-gr.), open square (Leo), filled triangle (Ant-Sex), open triangle (de Vaucouleurs's G12).

4.1. *Normalizing M_{lim} to the same limiting period*

Because the limiting Cepheid period is different for different galaxies, one may, as a further step, attempt to normalize the limiting magnitude by adding the quantity $2.76(\log P_{\rm lim} - 1.6)$: a small limiting period enhances the effect discussed in Sect. 3. The approximate $P_{\rm lim}$ comes from Paturel et al. (2001), but for NGC2403 it is from Tammann & Sandage (1968). This has been done in Fig. 1b, where now NGC2403 is also found close to the "0.2-line". The normalization still decreases the scatter, as expected if the correlation is due to the bias.

4.2. *The correlation within galaxy groups*

There are a few cases where two or more Cepheid sample galaxies have been ascribed to a group or a cluster: Virgo, M81-group, Leo, Fornax, Ant-Sex, de Vaucouleurs's G12. We give such galaxies the common velocity and plot them in the normalized $\log H$ vs. $M_{\rm lim}$ diagram. Figure 2 shows that the correlation remains to exist within individual groups, as it should if distance errors are involved.

4.3. *Varying the velocity field model*

We have used the rather standard correction for the Virgo infall velocity field. In addition to its simplicity, it has the advantage of preserving the Hubble law for the local galaxies with good distance estimates. There are in the literature other, more complex solutions for the velocity field, based on large samples of galaxies and attempting to make the corrections down to the rest frame of the CMBR. However, the discrepancies with different solutions remain large, as was emphasized by

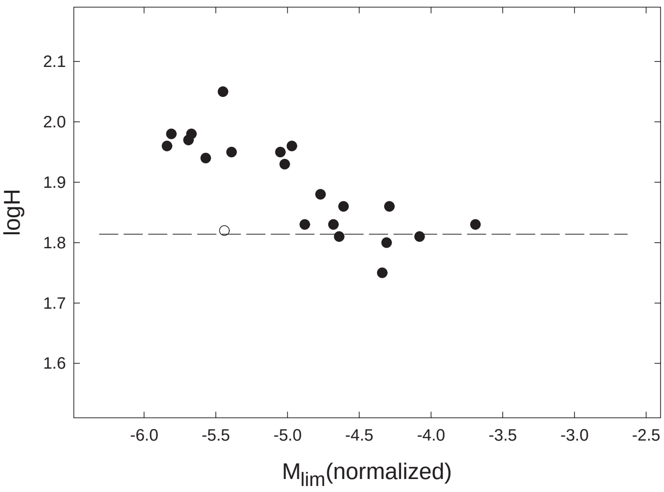

Fig. 3. (Log)H versus the normalized absolute limiting magnitude $M_{\rm lim}$ for the galaxies in Table 5 of Freedman et al. (2001), with the corrected velocity $V_{\rm Shapley}$. Open circle: the velocity <150 km s^{-1}. The horizontal line is now for $H = 65$.

Freedman et al. (2001). One may suspect that systematic errors are still present in these solutions, influencing different samples and distance indicators in different manners.

In order to see how a different velocity field model influences our result, we calculated the $\log H$ vs. $M_{\rm lim}$ diagram also for the linear infall model with three mass concentrators, used by the HST Key Project (velocities "$V_{\rm Shapley}$" in Table 5 of Freedman et al. 2001). The strong correlation remains (Fig. 3), though the average $\log H$ is increased.

We also made experiments with different values of the Virgo infall velocity around the 220 km s^{-1} which was derived in Theureau et al. (1997). The strong correlation remains, even for the large value of 440 km s^{-1} as preferred by Marinoni et al. (1998). One may conclude that the effect is rather robust for generally used velocity field models.

5. Concluding remarks

The Cepheid method thus may suffer from a significant selection bias, which we suspect leads to underestimated distances even when the usual precautions are taken. That a bias exists (Sandage 1988; Lanoix et al. 1999; Paturel et al. 2001), is not surprising in view of the selection generally affecting photometric distance indicators (e.g. Teerikorpi 1997), but its strength, according to our interpretation of Figs. 1–3, was unexpected.

If such a bias exists, its reason must be more complicated than merely the dispersion in the average luminosity and requires careful study. However, it seems that the amplitude of variation at the detection wavelength and, as we suspect, the total extinction between us and the total Cepheid population in a galaxy are involved, together with the observational upper limit to the Cepheid period. We note that the exclusion of light-curves, where the faint bottoms of the curves are poorly sampled, as generally done, directly works towards the enhanced bias (Sect. 3).

Examination of the calibrator galaxy TF diagram suggests that the result of the KLUN project (Theureau et al. 1997; Ekholm et al. 1999), $H_0 \approx 55$ km s^{-1}/Mpc, does not need significant revision even in the presence of the suspected bias (this will be discussed elsewhere). However, generally the approaches to H_0 relying on the Cepheid distances may be affected (depending on which host galaxies are used), with a trend towards too high values for H_0. Note also that five out of the six galaxies assumed to be in the Virgo cluster, seem to be outside of the unbiased plateau, suggesting that Virgo's Cepheid distance is too short.

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