# THE HUBBLE CONSTANT: PRESENT STATUS

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**Abstract.** The current status on the value of the Hubble constant is reviewed with the emphasis given to the origin of the discrepancy among authors. I argue that the situation is not too controversial and straightforward reading of observations indicates a high value ($H_0 \simeq 75$ km s$^{-1}$ Mpc$^{-1}$).

## 1. Introduction

The value of the Hubble constant has been an issue of controversy over many years, the current version being summarized as whether $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ or 80 km s$^{-1}$ Mpc$^{-1}$ (see Jacoby et al. 1992; van den Bergh 1992, Fukugita, Hogan & Peebles 1993 for general reviews). The great advances that have been made over the last five years, however, lead us to the conclusion, in my opinion, that we have no serious controversy on $H_0$.

In this talk I shall discuss the key points that gave rise to the longstanding controversy and summarize the recent advances concerning these points. In particular, I will address the reasons why I believe that the controversy is basically resolved, although I do not mean that all problems in the distance scale were resolved.

There are two paths to estimating the Hubble constant: one is to measure the distance to the Virgo cluster and derive $H_0$ either by estimating the Hubble recession velocity of the Virgo cluster, after correcting for large peculiar motions, or by using the relative distances of the Virgo and Coma clusters plus the recession velocity of the Coma cluster. The other path is to circumvent the Virgo cluster and to tie distant clusters directly to nearby galaxies with securely determined distances. In the first approach the controversy is ascribed to the distance to the Virgo cluster, and whether

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it is 16 or 22 Mpc. In the second approach, the controversy is whether the Tully-Fisher (TF) relation, which has been believed to be the most reliable distance indicator that reaches the distances beyond the Virgo cluster, gives a correct distance or suffers from a strong selection bias: a straightforward reading of the TF relation, when calibrated with nearby galaxies, leads to a high value of $H_0$. There are a few other distance indicators that reach beyond the Virgo cluster. They occasionally lead to a low value of $H_0$. The credibility of these results is also a subject for this talk.

## 2. Where People Agree

### 2.1. THE DISTANCES TO NEARBY GALAXIES

There are no debates over the distances to galaxies determined with the Cepheid period-luminosity relation. The most fundamental of these is the distance to the Large Magellanic Cloud (LMC). The Cepheid distance (Feast 1991), obtained both in the optical and the near infrared, is confirmed by the expanding photosphere method using SN1987A (Schmidt et al. 1992) and the time delay of the ring echo associated with this supernova (Panagia et al. 1991), both of which are physical methods that do not need local calibrations. We conclude that the distance to LMC is 50±3 kpc, although RR Lyraes give a value a little smaller than this.

About 20 galaxies have distances measured with Cepheid observations, an area where great advances have been made with the *Hubble Space Telescope*. Among these galaxies M31, M33, NGC300, N2403 and M81 (and NGC3109) have been used as local calibrators for a variety of secondary distance indicators. No doubt has been cast on these distances up to the error of the measurement, which is 5-10% relative to the LMC distance. The most recent advances are the determination of the distances to two galaxies in the Virgo cluster (Pierce et al. 1994, Freedman et al. 1994) and M96 in the Leo group (Tanvir et al. 1995)

### 2.2. THE RELATIVE DISTANCES AMONG CLUSTERS

In contrast to the case of the distance to the Virgo cluster, there is little dispute over the relative distances of the Virgo and Coma clusters. De Vaucouleurs (1993) compiled the estimates in the literature and concluded that the ratio is 5.60±0.30 (5%), and few authors disagree with this value. After correcting for the proper motion of our Galaxy, one obtains $v_H = 7200 \pm 80\text{km s}^{-1}$ (1.1% error). Taking these values, we obtain $H_0 = 80$ if $d(\text{Virgo}) = 16$ Mpc, and 58 if $d(\text{Virgo}) = 22$ Mpc.

We note that little controversy is seen for the distance ratios between other clusters. A classical example is given by the Hubble diagram of first rank elliptical galaxies (Kristian, Sandage & Westphal 1978), which extends linearly at least to $z = 0.4$. The scatter is small, and if $H_0 = 80$ is obtained from nearby clusters, it should represent a global value up to at least 1000 Mpc. We stress that the present controversy about $H_0$ comes from the calibration of the absolute distance to galaxies near the Virgo distance.

## 3. Local Calibrations and Checks Between Distance Indicators

Distance ladders require calibrations to determine the zero point, and local calibrations are made primarily using galaxies with Cepheid distances. The TF relation can be calibrated using M31, M33, NGC300, NGC2403 and M81 (and NGC3109). The scatter is 0.3 mag for these galaxies even for the $B$ band TF relation. There are two novel secondary distance indicators developed over the last five years: one technique using surface brightness fluctuations (SBF) (Tonry & Schneider 1988) and one using planetary nebula luminosity functions (PLNF) (Jacoby et al. 1990). These two indicators are applied to old objects, elliptical galaxies or spiral galaxy bulges, where the composition of the stellar population is reasonably uniform. Calibrations are made using M31, and M81 gives an additional check.

The expanding photosphere method for type II supernovae (EPM) is a physical method that does not need local calibrations (Schmidt et al. 1992). A check against the Cepheid distances to the LMC, M101 and M100, however, is valuable, since it verifies the elaborate procedures involved in the EPM.

Most of secondary distance indicators do not have a solid physical basis, but are based on empirical grounds; this has been taken to be a weak point in the distance ladder argument. For this reason it is of crucial importance to check the distances obtained by various indicators with each other, which would justify the validity of indicators and allows us to document the error.

It was shown that the rms scatter between the Tully-Fisher distance and that estimated with SBF is 10-15% for clusters, where ellipticals and spirals are supposed to be well mixed. A remarkable agreement is seen for a number of galaxies between the distance obtained with SBF and that with PNLF: the rms scatter is 5-7% for 16 galaxies up to 17 Mpc (Ciardullo, Jacoby & Tonry 1993). Such excellent agreement is unlikely to be fortuitous. Another interesting test is between EPM and Tully-Fisher distances (Pierce 1994; Schmidt et al. 1994). Good agreement is found between the two for 11 galaxies after allowing for a 10% offset (the EPM distance is longer). The rms scatter is on the order of 15%. This test not only gives us an additional verification of EPM, but also justifies many steps needed to obtain the TF distance. It is unlikely that the TF relation gives a wrong distance beyond 20% error for majority of spiral galaxies.

TABLE 1. Distances to Leo I galaxies

| | Type | SBF | PNLF | TF | Cepheid |
|---|---|---|---|---|---|
| NGC3377 | E | 9.72 | 10.61 | | |
| NGC3379 (M105) | E | 9.42 | 10.05 | | |
| NGC3384 | S0 | 9.46 | 10.42 | | |
| NGC3368 (M96) | Sab | | | 11.96 | 11.59 |
| NGC3351 (M95) | Sb | | | 10.94 | |

The new observation of Cepheids in M96 in the Leo I group (Tanvir et al. 1995) gives an interesting testing ground for a number of indicators. In Table 1 we present distances (in Mpc) to five galaxies of the Leo I group. All distances agree to 20%. However, we see that the distance to M96 (both Cepheids and TF) is systematically 10-20% larger than the distance to E and S0 galaxies estimated with SBF and PNLF. Two possible explanations are: (i) that calibrations of SBF (and also PNLF) for early type galaxies with the bulges of spirals (M31 and M81) have 20% (10%) errors, and (ii) that M96 is actually located behind the elliptical-S0 system, although Leo I is usually supposed to be a small system from its dimension on the sky. Allowing for possibility (i), we conclude that the error of these four indicators is at most 20% for Leo I located at 10 Mpc from the Milky Way.

## 4. The Distance to the Virgo Cluster

Application of the PNLF to five ellipticals in the Virgo cluster (M87, M86, M84, M49 and NGC4649) gives 15.2±0.2 Mpc, and SBF yields 15.6±0.6 Mpc for the same five galaxies (Ciardullo et al. 1993). These values agree with the 15.8±1.3 Mpc obtained from the TF relation applied to 26 spiral galaxies (Pierce & Tully 1988; see also Mould et al. 1983). Cepheid measurements for two spiral galaxies also give consistent results: 14.9±1.2 Mpc for NGC4571 (Pierce et al. 1994) and 17.1±1.8 Mpc for M100 (Freedman et al. 1994). These distances (summarized in Table 2) support the high value of $H_0$.

On the other hand, Sandage & Tammann (Sandage 1995; Sandage & Tammann 1994; 1990) have been claiming differently, as summarized in Table 3. The six methods listed in Table 3 consistently give 20–23.5 Mpc. I believe only two methods, the distances from the TF relation and from supernovae, deserve serious attention, since the other indicators are not well qualified. The distance from globular cluster luminosity functions (GCLF) depends on how it is derived. Secker & Harris (1993) discussed how the

TABLE 2. Distances to the Virgo cluster (the short scale)

| method | distance (Mpc) | ref. |
|---|---|---|
| TF(bright spirals) | 15.8 ± 1.3 | Pierce & Tully 1988 |
| PNLF | 15.2 ± 0.2 | Ciardullo et al. 1993 |
| SBF | 15.6 ± 0.6 | Ciardullo et al. 1993 |
| Cepheid (M100) | 17.8 ± 1.2 | Freedman et al. 1994 |
| Cepheid (NGC4571) | 15.6 ± 1.3 | Pierce et al. 1994 |

GCLF distances to NGC4365, M49, and M60 are consistent with those inferred from the PNLF and SBF methods, while Sandage & Tammann, using the same data, but a different manipulation of the data, find the longer distance. The problems are that the position of the peak of the GCLF does not quite agree between Milky Way and M31, and that the positions of the peak for Virgo galaxies are not well determined due to a flat feature and poor statistics. This allows a distance that depends on how the data are manipulated. The method also lacks a cross-check with other distance indicators. The data for novae (Pritchet & van den Bergh 1987) are too poor to infer any accurate result: the result is basically derived from one nova in NGC4472, which is given the smallest error bar. Also, the data are too poor to constrain the form of the maximum luminosity-decline rate relation, so the result depends largely on how to parametrize the relation. I would ignore the result of $D_n - \sigma$ relation, since it lacks a good local calibration. When a distance indicator relation with a large scatter is calibrated with a single galaxy, the resulting distance is largely uncertain. If the PNLF/SBF distance to E and S0 galaxies of Leo I is used for a calibration, the Virgo distance becomes 16Mpc instead of 23Mpc obtained with a calibration using the M31 or M81 bulge. Cross checks that allow us to know the error are not made for $D_n - \sigma$.

*The Origin of the controversy in the TF distance to the Virgo cluster.* This is a serious issue, since it could discredit the use of the TF relation to estimate extragalactic distance scales. An important point, however, is that there is no serious disagreement on the distance to each galaxy; the difference between the two schools arises from the different choice of the sample. Kraan-Korteweg, Cameron & Tammann (1987) (as quoted in Table 3) and Fouqué et al. (1990) have used complete spiral samples in the Virgo cluster region of the sky. On the other hand, Pierce & Tully (1988) have chosen only bright spiral galaxies and discarded some galaxies which give larger distances. Mould et al. (1983)'s sample shares the same characteristics as Pierce & Tully's. This selection procedure has naturally aroused

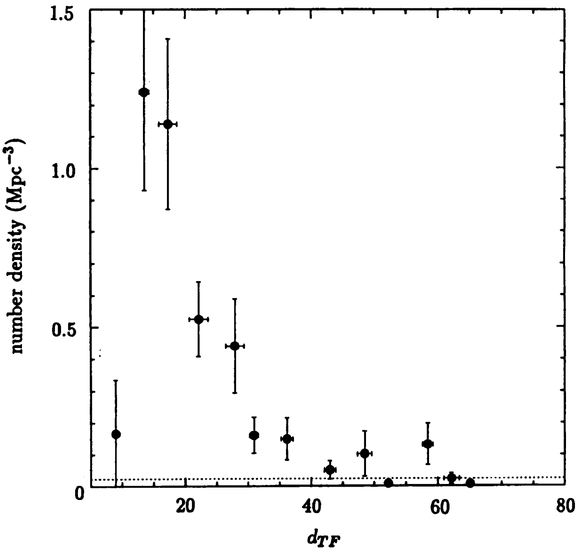

*Figure 1.* The distribution of spiral galaxy number density as a function of the TF distance. The dotted line is the base line for the field.

the suspicion that their samples suffer from a very strong selection bias. On the other hand, it is suspected that the Virgo cluster has a substantial depth, and that fainter spirals in the "complete sample" are those actually located in the background of the core.

A further study explicitly demonstrated that the Virgo cluster is elongated from 10 to 30 Mpc almost along the line of sight, and that the peak of the galaxy number density is located at about 15 Mpc (Fukugita et al. 1993; Yasuda et al. 1995). This means that an unusually large scatter of the TF relation for the complete sample of the Virgo spirals is caused by the actual depth, and not by the intrinsic scatter of the TF relation. The best evidence for the depth effect comes from the fact that HI deficient galaxies are located only in the range 14-20 Mpc, and this coincides with the region where the density is very high. We show in Fig. 1 the distribution of spiral-galaxy number density as a function of the distance. The position of the density peak also agrees with the positions of elliptical galaxies given by PNLF and SBF. If the density peak is identified as the Virgo core, the distance is about 15 Mpc. On the other hand, a simple average of all spiral galaxies gives 20 Mpc in agreement with the long distance listed in Table 3. (This also explains 20Mpc from the size of spiral galaxies in Table 3.)

We remark here that the present Cepheid observation does not give a compelling distance to the Virgo core, since we do not know the relative position of these spiral galaxies to the core. It is unfortunate that these

TABLE 3. The Distance to the Virgo cluster by Sandage & Tammann (the long scale)

| method | distance (Mpc) |
|---|---|
| TF | $20.9 \pm 1.5$ |
| SNe Ia and II | $20.9 \pm 2.6$ |
| GCLF | $21.3 \pm 2.6$ |
| Novae | $20.6 \pm 4.5$ |
| $D_n - \sigma$ | $23.4 \pm 2.1$ |
| size of Galaxy | $20.0 \pm 1.9$ |

galaxies cannot be used to calibrate the TF distance, since they are too face-on to obtain a reliable distance with the TF relation.

## 5. The Use of Supernovae as Distance Indicators

### 5.1. TYPE IA SUPERNOVAE

The conventional use of type Ia SNe is to take the maximum brightness as a universal standard candle. Now, it is well recognized that there are some type Ia SNe with absolute brightnesses that are clearly dimmer. The scatter in the Hubble diagram varies from 0.2 mag (Branch & Miller 1993; Vaughan et al. 1995) to 0.6 mag (Leibundgut & Pinto 1992), depending on the selection of the sample. The zero point of the Hubble diagram is then determined with SN1937C in IC4182 (4.8 Mpc) or SN1972E in NGC5253 (4.1 Mpc). In this way Sandage & Tammann (1993) obtained $H_0 = 47 \pm 5$ or $H_0 < 55$ (Sandage & Tammann 1994) and Branch & Khokhlov (1995) obtained $H_0 = 55 \pm 5$.

Riess, Press & Kirshner (1995) have recently reconsidered the issue of the standard candle. They have shown that the maximum luminosity is correlated with the luminosity decline rate, as indicated earlier by Phillips (1993). Using the light curve shape (LCS) as a control parameter, they found that the scatter of the Hubble diagram is reduced to as small as 0.21 mag without any selection of the sample. This correction affects significantly both Hubble diagram and calibrator SN1972E, and brings $H_0 = 53 \pm 11$ with the conventional method up to $H_0 = 67 \pm 9$.

I admit, however, that the value of $H_0$ from type Ia SNe is still controversial. Branch and collaborators (Nugent et al. 1995) claim that it is difficult to reconcile the high $H_0$ with current models of SNeIa for the amount of radioactive $^{56}$Ni.

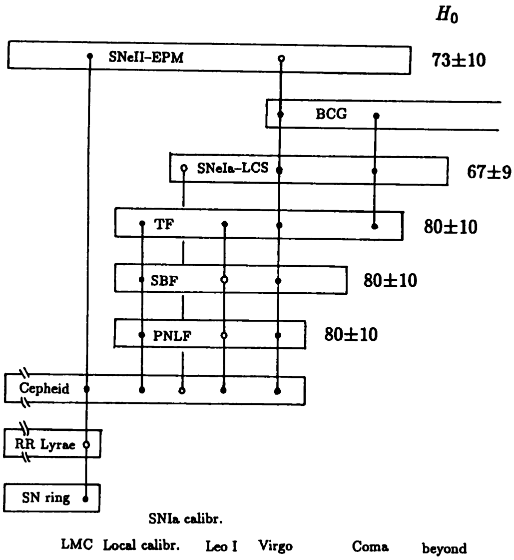

*Figure 2.* The distance ladder that leads to $H_0 = 70 - 80\text{km s}^{-1}\text{ Mpc}^{-1}$. The vertical lines connected with solid dotts mean that the relevant ladders are tightly constrained with each other, and those with open dotts are those constrained allowing for ≈ 10% offset. Typical $H_0$ resulting from each ladder is also indicated.

## 5.2. TYPE II SUPERNOVAE

Type II SNe do not give a standard candle. A variant of the Baade-Wesselink method, named EPM, has been developed to estimate the distance to type II SNe (Schmidt et al. 1992). SNeII do not emit photons like a black body, because the flux is substantially diluted by a scattering dominated atmosphere (Wagoner 1981). The distance obtained with this method agrees well with that from the TF relation, allowing for a 10% offset. The Hubble constant derived by Schmidt et al. (1994) is 73±6, which is about 10% smaller than the value obtained with TF, PNLF and SBF.

Sandage & Tammann have given long distances to the Virgo cluster with both type Ia and type II SNe. The distance with type II SNe is derived from two methods, radiation flux calculated assuming a black body (which overestimates the flux) and the radio sphere parallax measurement for SN1979C in M100 with VLBI. The latter assumes that the radio sphere and optical sphere are identical, which yields 22Mpc to M100, compared to 17Mpc from Cepheids.

## 6. The Global value of the Hubble constant

The linearity of the distance-recession velocity relation for type II SNe extends to 180 Mpc (Schmidt et al. 1994), and the Hubble diagram of type Ia SNe shows excellent linearity up to 300 Mpc (Riess et al. 1995). A classical example of the Hubble diagram for first rank ellipticals in clusters indicates linearity between the apparent $V$ (or $R$) magnitude and the recession velocity to $z \simeq 0.4$, where evolution may affect the results (Kristian et al. 1978). The scatter in the diagram is small enough to exclude a change of the intercept (=Hubble constant) by a factor of 1.5. A modern version is provided by Lauer & Postman (1992) up to $cz \simeq 15000$ km s$^{-1}$, and their diagram does not allow a change of $H_0$ by more than 15%. The results make the suspicion that a high $H_0$ is a local effect unlikely: once $H_0$ is determined with nearby galaxies, the same value describes the expansion of the Universe up to at least $z \sim 0.4$.

Another interesting physical method, which has recently attracted our attention, is the use of the Zeldovich-Sunyaev (ZS) effect (Birkinshaw et al. 1991). All earlier attempts gave small values of $H_0$. A general caution to be made, however, is that clusters are selected on the basis of surface brightness and such a selection method induces a bias towards clusters elongated along the line of sight. Since the argument using the ZS effect assumes spherical symmetry for clusters, this readily causes a bias towards a low $H_0$. This bias should be stronger for distant clusters, such as those used for the ZS test. Recent observations (Herbig et al. 1995; Meyers et al. 1995) of nearby clusters allow this point to be examined. Meyers et al. (1995) derived $H_0 = 74^{+29}_{-24}$ for the Coma cluster, consistent with the value obtained from other methods albeit with a large error. The lesson is that it is too premature to take $H_0$ measurements using the ZS effect in distant clusters seriously.

## 7. Conclusions

The most important advance in recent years is that the errors of a number of distance indicators are now well documented using cross-checks among distances from a variety of methods, and we are able to discriminate between reliable and unreliable indicators. We summarize that TF, SBF and PNLF give $H_0 = 80 \pm 10$, and SNeII (EPM) and SNeIa (LCS) give $H_0 = 70 \pm 10$. We conclude that the current best value is

$$H_0 = 75 \pm 10 \text{ km s}^{-1}\text{Mpc}^{-1}.$$

We note that many different distance indicators are so tightly correlated (allowing for occasional 10% error), as shown in Fig. 2, that it seems difficult to break the chain to obtain $H_0 \approx 50$. We are now tempted to take the difference between $H_0 = 80$ from the conventional distance ladders and $H_0 = 70$ from supernovae more seriously. I believe that there is not much controversy as to the value of the Hubble constant as far as its observational status is concerned. The reason why many people quote "Hubble constant is highly uncertain" comes from its notorious history during its infancy, and more importantly that "theorists want the controversy".

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