THE DISTANCE OF THE VIRGO CLUSTER

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Abstract. Six different distance determination methods of Virgo cluster members yield a mean distance modulus of \((m-M)_\text{Virgo}^0 = 31.60 \pm 0.09\) (20.9 \pm 0.9 Mpc). This value can be carried out to \(\geq 10\,000\) km s\(^{-1}\) by means of 31 clusters whose distances are well known relative to the Virgo cluster. They yield \(H_0 = 56 \pm 4\) (random error) \(\pm 6\) (systematic error), independent of local streaming motions.

1. Introduction

The Virgo cluster is a fundamental milestone for the determination of \(H_0\) because it is the nearest reasonably rich cluster which is tightly tied into the large-scale expansion field through excellent relative distances to more distant clusters, circumventing thus effects of local streaming velocities.

The distance of the Virgo cluster has long been controversial mainly for three reasons. (1) The cluster which spans \(\geq 15^\circ\) in the sky has a considerable depth effect making even good distance determinations of few member galaxies vulnerable to small-number effects. This becomes particularly precarious if the selection criteria of the few members are themselves distance-dependent. (2) Distance indicators with non-negligible intrinsic scatter lead always to too small distances if they are applied to only the brightest cluster members (Malmquist bias). This has made Virgo cluster distances useless especially from the 21cm-line width (Tully-Fisher) method until a very deep Virgo cluster catalogue became available (Binggeli, Sandage, & Tammann 1985). The catalogue is complete as to normal E and spiral galaxies because it goes below the cutoff magnitude of these objects. (3) Undue weight has been given to distance indicators in the past which had never been tested in the relevant distance range. In the case of the bright tail of the luminosity function of planetary nebulae the ineffectiveness as distance indicator is now explained by the dependence on the sample (i.e. galaxy) size (Bottinelli et al. 1991; Tammann 1993; Méndez et al. 1993; Soffner et al. 1996). The reasons why surface brightness fluctuations of E galaxies fail to provide useful absolute distances beyond 10 Mpc are less clear. The applicability of the method to dwarf ellipticals is presently investigated (Jerjen, Freeman, & Binggeli 1998).

With these difficulties in mind six different distance determinations of the Virgo cluster are discussed in the following.
Cepheids are presently, through their period-luminosity (PL) relation, the most reliable and least controversial distance indicators. The slope and the zeropoint of the PL relation is taken from the very well-observed Cepheids in the Large Magellanic Cloud (LMC), whose distance modulus is adopted to be \((m - M) = 18.50\) (Madore & Freedman 1991).

An old PL relation calibrated by Galactic Cepheids in open clusters, and now vindicated by Hipparcos data (Sandage & Tammann 1998), gave \((m - M)_{\text{LMC}} = 18.59\) (Sandage & Tammann 1968, 1971). Hipparcos data combined with more modern Cepheid data give an even somewhat higher modulus (Feast & Catchpole 1997). Reviews of Cepheid distances (Federspiel, Tammann, & Sandage 1998; Gratton 1999) cluster around \(18.56 \pm 0.05\), – a value in perfect agreement with the purely geometrical distance determination of SN 1987A (18.58 \pm 0.05; Gilmozzi & Panagia 1999). In his excellent review Gratton (1999) concludes from the rich literature on RR Lyr stars that \((m - M)_{\text{LMC}} = 18.54 \pm 0.12\). He also discusses five distance determination methods which give lower moduli by 0.1 – 0.2 mag, but they are still at a more experimental stage. – There is therefore emerging evidence that the adopted LMC modulus of 18.50 is too small by \(\sim 0.06\) or even 0.12 mag (Feast 1999) and that all Cepheid distances in the following should be increased by this amount.

There has been much debate about the possibility that the PL relation of Cepheids depends on metallicity. Direct observational evidence for a (very) weak metallicity dependence comes from the fact that the metal-rich Galactic Cepheids give perfectly reasonable distances for the moderately metal-poor LMC Cepheids and the really metal-poor SMC Cepheids and, still more importantly, that their relative distances are wavelength-independent (Di Benedetto 1997; cf. Tammann 1997). – Much progress has been made on the theoretical front. Saio & Gautschy (1998) and Baraffe et al. (1998) have evolved Cepheids through the different crossings of the instability strip and have investigated the pulsational behavior at any point. The resulting (highly metal-insensitive) PL relations in bolometric light have been transformed into PL relations at different wavelengths by means of detailed atmospheric models; the conclusion is that any metallicity dependence of the PL relations is negligible (Sandage, Bell, & Tripicco 1998; Alibert et al. 1999; cf. however Bono, Marconi, & Stellingwerf 1998, who strongly depend on the treatment of stellar convection).

Most extragalactic Cepheid distances are now due to HST observations. The reduction of these observations is by no means simple. The photometric zeropoint, the linearity over the field, crowding, and cosmic rays raise technical problems. The quality of the derived distances depends further on (variable) internal absorption and the number of available Cepheids in view of the finite width of the instability strip. (An attempt to beat the latter problem by using a PL-color relation is invalid because the underlying assumption of constant slope of the constant-period lines is unrealistic; cf. Saio & Gautschy 1998). Typical errors of individual Cepheid distances from HST are therefore \(\pm 0.2\) mag (10% in distance).

There are now three bona fide cluster members and two outlying members (cf. Binggeli, Popescu, & Tammann 1993) with Cepheid distances from HST (Table 1; cf. Freedman et al. 1998). The wide range of their distance moduli, corresponding to 14.9 to 25.5\,Mpc, reveals the important depth effect of the cluster. The first four galaxies in Table 1 have been chosen from the atlas of Sandage & Bedke (1988) because they are highly resolved and seemed easy as to their Cepheids. They are therefore expected to
Table 1. The Virgo cluster members with Cepheid distances

| Galaxy     | $(m - M)_{\text{Cepheids}}$ | Remarks               | $(m - M)_{\text{TF}}$ |
|------------|------------------------------|-----------------------|------------------------|
| NGC 4321*  | 31.04 ± 0.21                 | highly resolved        | 31.21 ± 0.40           |
| NGC 4496A* | 31.13 ± 0.10                 | highly resolved        | 30.67 ± 0.40           |
| NGC 4536*  | 31.10 ± 0.13                 | highly resolved        | 30.72 ± 0.40           |
| NGC 4571   | 30.87 ± 0.15                 | extremely resolved     | 31.75 ± 0.40           |
| NGC 4639   | 32.03 ± 0.23                 | poorly resolved        | 32.53 ± 0.40           |

* From a re-analysis of the HST observations Narasimha & Mazumdar (1998) obtained $(m - M) = 31.55 ± 0.28$.

** In the W-cloud outside the confidence boundaries of the Virgo cluster (cf. Federspiel et al. 1998).

lie on the near side of the cluster. In contrast NGC 4639 has been chosen as parent to SN 1990N and hence independently of its distance (Saha et al. 1997); correspondingly this distance is expected to be statistically more representative. A straight mean of the distances in Table 1 is therefore likely to be an underestimate. Indeed the mean Tully-Fisher (TF) distance modulus of the five galaxies is $0.02$ (corresponding to 10% in distance) smaller than the mean distance of a complete and fair sample of TF distances (Federspiel et al. 1998). It should be noted that NGC 4639 with the largest distance in Table 1 has a recession velocity of only $v_0 = 820$ km s$^{-1}$, i.e. less than the mean cluster velocity of $v_0 = 920$ km s$^{-1}$, and that it can therefore not be assigned to the background. In fact the redshift distribution in the Virgo cluster area shows a pronounced gap behind the cluster minimizing the danger of background contamination (Binggeli et al. 1993).

Böhringer et al. (1997) have proposed that the Cepheid distances of the spiral galaxies NGC 4501 and NGC 4548 would be significant because these galaxies are spatially close to the Virgo cluster center on the basis of their being stripped by the X-ray intracluster gas. In the case of NGC 4548 there are some doubts because it is, like NGC 4571, exceptionally well resolved (Sandage & Bedke 1988). The resolution of NGC 4501 is about intermediate between the two last-mentioned galaxies and the poorly resolved NGC 4639. A first rough distance of NGC 4501 is provided by the TF method (Section 4) which gives $(m - M) = 31.5 ± 0.4$ in good agreement with the preferred mean Virgo cluster distance. However, the inherent errors of the TF method if applied to individual galaxies prevent a stringent test. NGC 4501 is therefore an interesting candidate for Cepheid observations.

A preliminary Cepheid distance of the Virgo cluster is obtained by taking the Cepheid distance of the Leo group of $(m - M) = 30.20 ± 0.12$, based now on three galaxies with Cepheids from HST (Saha et al. 1999), and to step up this value by the modulus difference of $\Delta (m - M) = 1.25 ± 0.13$ (Tammann & Federspiel 1997) between the Leo group and the Virgo cluster. The result is $(m - M)_{\text{Virgo}} = 31.45 ± 0.21$, a value which is well embraced by the individual Cepheid distances in Table 1.
Table 2. Blue SNe Ia with good photometry in the Virgo cluster

| SN   | Galaxy     | $m_B$ | $m_V$ | $\Delta m_{15}$ | $m_{B\text{corr}}$ |
|------|------------|------|------|----------------|------------------|
| 1981B | NGC 4536   | 12.04| 11.96| 1.10           | 11.89            |
| 1984A | NGC 4419   | 12.45| 12.26| 1.20           | 12.06            |
| 1990N | NGC 4639   | 12.76| 12.70| 1.03           | 12.68            |
| 1994D | NGC 4526   | 11.86| 11.87| 1.27           | 11.81            |
| 1960F | NGC 4496A  | 11.60| 11.54| —             | —                |

The spectroscopically unusual SN 1991T is omitted.

3. The Virgo cluster distance from Supernovae type Ia

Blue SNe Ia (i.e. $B_{\text{max}} - V_{\text{max}} \leq 0.20$) at maximum light are nearly perfect standard candles. After small corrections for second parameters (decline rate and color) their scatter about the mean Hubble line amounts to only $0^m 12$ for $v > 10,000 \text{ km s}^{-1}$ (Parodi et al. 1999). The equally corrected absolute peak magnitude of $M_B^{\text{corr}} = -19.44 \pm 0.04$, based on seven (!) SNe Ia with known Cepheid distances (Parodi et al. 1999), is secure. The value is also in perfect agreement with present theoretical models (Branch 1998).

Four blue SNe Ia with complete photometry are known in the Virgo cluster (Table 2). The photometric data from the Tololo/Calan survey are compiled by Parodi et al. (1999). The magnitudes, corrected for second parameters ($\Delta m_{15}$ and color), are calculated from equation (30) in Parodi et al. (1999).

With the above calibration for $M_B^{\text{corr}}$ and the mean value of $m_B^{\text{corr}}$ in Table 2, the cluster modulus becomes $(m - M)_{\text{Virgo}} = 31.55 \pm 0.20$.

The error of the result is dominated by the depth effect of the cluster. Additional SNe Ia in the cluster will improve the result considerably. Its present advantage over the Cepheid distance of the cluster is that the four SNe Ia have been discovered independently of their position within the cluster.

To increase the sample one additional blue SNe Ia in the Virgo cluster may be added which, however, has no known decline rate $\Delta m_{15}$ (cf. Table 2). But since the Virgo SNe Ia and the calibrating SNe Ia (except one) lie in spirals the second-parameter correction cancels in first approximation. Eight SNe Ia with Cepheid distances (including SN 1960F without $\Delta m_{15}$) give a straight calibration of $M_B = M_V = -19.48 \pm 0.04$ (Saha et al. 1999), while the five Virgo SNe Ia in Table 2 have a mean (uncorrected) apparent magnitude of $m_B = 12.14 \pm 0.21$, $m_V = 12.07 \pm 0.20$. From this follows a mean Virgo cluster modulus of $(m - M)_{\text{Virgo}} = 31.59 \pm 0.15$ which is essentially indistinguishable from the result of the four corrected SNe Ia.

4. The Virgo cluster distance from 21cm-line widths

The method using 21 cm line-widths, the so-called Tully-Fisher (TF) relation, has been applied many times but with variable success. Widely divergent values are in the literature which in some cases favor the short distance scale (e.g. Pierce & Tully 1992 with $m - M = 30.9$) and in others the long scale (Kraan-Korteweg et al. 1988...
with $m - M = 31.6$; Fouqué et al. 1990 with the same value if corrected to the modern local calibrators; Federspiel et al. 1998).

It has been shown (Federspiel et al. 1994; Sandage, Tammann, & Federspiel 1995) that the reasons for small values of $(m - M)$ for Virgo (the short scale) using TF are two; (1) use of incorrectly small distances to the local calibrators in earlier papers by proponents of the short scale, and (2) neglect of the disastrous effect of the Teerikorpi (1987, 1990) cluster incompleteness bias. It can be shown that this bias produces errors in the modulus up to 1 mag depending on how far one has sampled into the cluster luminosity function regardless how the sample is chosen, if only the sample is cut by apparent magnitude. The modulus error is a strong function of the fraction of the luminosity function that remains unsampled (Kraan-Korteweg et al. 1988; Sandage et al. 1995).

The calibration of the TF relation has been much improved by the advent of Cepheid distances with HST. There are now 18 Cepheid distances available for spirals suitable for the calibration. Detailed data with complete references to the extensive literature are given elsewhere (Tammann & Federspiel 1997; Federspiel et al. 1998) and are not repeated here.

The most recent applications of the TF relation on the Virgo cluster (Schröder 1996; Tammann & Federspiel 1997; Federspiel et al. 1998) use a complete sample of Virgo cluster spirals. Rigid criteria have been invoked in the selection of members within the cluster boundaries defined by counts, redshifts, and X-ray contours. Several subtleties, not seen in earlier studies, have been found. These include a variation of the derived modulus on the wavelength of the observations (covering UBVRI), and a correlation of the derived modulus on the degree of hydrogen depletion for the spirals. With this in mind Federspiel et al. (1998) have derived from a complete sample of 49 sufficiently inclined spirals

$$(m - M)_{\text{Virgo}} = 31.58 \pm 0.24.$$  

5. The Virgo Cluster distance from Globular Clusters

Extragalactic GCs, discovered in M 31 by Hubble (1932), took a role in distance determinations when Racine (1968) proposed the bright end of the globular cluster luminosity function (GCLF) to be used as a “standard candle”. First applications of this tool provided reasonable distances to M 87 (Sandage 1968, de Vaucouleurs 1970), yet it was soon realized that the results were sensitive to the GC population size, and that the luminosity $M^*$ of the turnover point of the bell-shaped GCLF is a much more stable standard candle. This required, however, that one had to sample at least four magnitudes into the GCLF which became feasible only with the advent of CCDs. The first application of the new method to a giant E galaxy (M 87; van den Bergh et al. 1985) was followed by many papers such that $m^*$ magnitudes are now available for about two dozen full-size galaxies (for reviews e.g. Harris 1991; Whitmore 1997; Tammann & Sandage 1999).

The absolute magnitude $M^*$ of the peak of the globular cluster luminosity function (GCLF), approximated by a Gaussian, can be calibrated independently in the Galaxy and M 31 through RR Lyr stars and Cepheids, respectively. They yield, in perfect agreement, $M^*_B = -6.93 \pm 0.08$ and $M^*_V = -7.62 \pm 0.08$ (Sandage & Tammann 1995; Tammann & Sandage 1999). Remaining differences between different authors of the luminosity calibration of RR Lyr stars are vanishingly small for the mean metallicity of
Table 3. Virgo cluster members with known turnover magnitude \( m^* \) of the GCLF

| Galaxy     | \( m_B \)       | \( m_V \)       | \( m_B - m_V \) | Source |
|------------|----------------|----------------|----------------|--------|
| NGC 4365   | 25.18 ± 0.16(2)| 24.47 ± 0.21(1)| 0.71 ± 0.26    | (1)    |
| NGC 4374   | 24.12 ± 0.30(1)| 0             | 0.21 ± 0.24(2) | (2)    |
| NGC 4406   | 24.25 ± 0.30(1)|              | 0.85 ± 0.24    | (3)    |
| NGC 4472   | 24.70 ± 0.11(1)| 23.85 ± 0.21(2)| 1.08 ± 0.13    | (4)    |
| NGC 4486   | 24.82 ± 0.11(2)| 23.74 ± 0.06(5)| 1.08 ± 0.13    | (4)    |
| NGC 4552   | 23.70 ± 0.30(1)| 0             | 0.85 ± 0.107(2)| (1)    |
| NGC 4636   | 24.18 ± 0.20(1)|              | 0.85 ± 0.107(2)| (1)    |
| NGC 4649   | 24.65 ± 0.14(1)|              | 0.85 ± 0.107(2)| (1)    |

straight mean: \( (m - M) = 24.84 ± 0.12 \) \( V \) magnitudes following Whitmore (1997). No (precarious) attempt was made to transfer \( m_B \) into \( m_V \).

As seen in Table 3 the GCLF leads to \( (m - M)_{Virgo} = 31.70 ± 0.10 \), which is adopted in the following. For the adopted error see below.

The question arises whether it is justified to apply \( M^* \), calibrated in two spiral galaxies, to the GCs of the early-type galaxies in Table 3. A positive answer within the errors is provided by the Leo group. Two early-type galaxies in this group give a GCLF modulus of \( (m - M) = 30.08 ± 0.29 \) whereas the Cepheids in three spirals of the same group give \( (m - M) = 30.20 ± 0.12 \) (Tammann & Sandage 1999).

The formation of GCs not being understood, there is no theoretical reason why the value of \( M^* \) should be universal. It is worrisome that the width of the GCLF varies significantly for different galaxies and that the two brightest galaxies in Table 3, NGC 4486 (M 87) and NGC 4472 (M 49), as well as NGC 4552 (M 89) have \( m_V^* \) 0.55 \( m^* \) brighter than the remaining four galaxies. Moreover, the color \( m_B^* - m_V^* = 1.08 \) of NGC 4486 is exceptionally red, and its GCLF seems to be bimodal. Finally it is alarming that the mean GCLF modulus of seven early-type Fornax cluster members is \( 0.54 ± 0.15 \) smaller than the secure cluster distance from three blue SNe Ia, the latter value being also supported by the relative distance from secondary distance indicators.

Sources: (1) Harris et al. 1991; Secker & Harris 1993; Forbes 1996 (2) Ajhar et al. 1994 (3) Harris et al. 1991; Ajhar et al. 1994; Cohen 1988 (4) van den Bergh et al. 1985; Harris et al. 1991; Cohen 1988; McLaughlin et al. 1994; Whitmore et al. 1995; Elson & Santiago 1996(a,b) (5) Kissler et al. 1994 (6) Harris et al. 1991. – The values in parentheses in columns 2 and 3 give the number of independent determinations.

The Galactic GCs of \([\mathrm{Fe/H}] = -1.35\), because different adopted luminosity-metallicity relations meet for this value very closely at \( M_V(\text{RR}) = 0.54. \) The calibration of \( M^* \), independently confirmed by the M 31 Cepheids, is therefore uncontroversial.

Different values of \( m_B^* \) and \( m_V^* \) of bona fide members of the Virgo cluster (cf. Binggeli et al. 1985) are compiled in Table 3. The values have been corrected for the small and variable Galactic absorption according to Burstein & Heiles (1984). The \( g \) magnitudes of Cohen (1988) and the \( R \) magnitudes of Ajhar et al. (1994) were transformed into \( V \) magnitudes following Whitmore (1997). No (precarious) attempt was made to transfer \( m_B^* \) into \( m_V^* \).

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between the early-type members of the Virgo and Fornax clusters (Tammann & Sandage 1999; cf. Fig. 2 below). In addition the GCLF distances of some individual field galaxies are highly questionable.

Account of these problems is taken by assigning a relatively large error to the GCLF distance of the Virgo cluster.

6. The Virgo cluster distance from the D_n − σ relation

It has been shown that the well known D_n − σ relation of early-type galaxies (Dressler et al. 1987) applies also to the bulges of early-type spiral and S0 galaxies with surprisingly small scatter (Dressler 1987). Here D_n is an isophotally defined galaxy diameter (in arcsec), i.e. the diameter of a circle which encompasses a mean surface brightness of 19.75 B mag arcsec^−2, and σ is the aperture-dependent, normalized velocity dispersion σ (in km s^−1) in the bulge. The isophotal values of D_n are, of course, affected by front absorption A_B. The corresponding correction amounts to ∆ log D = 0.32A_B (Lynden-Bell et al. 1988), which translates into a distance effect of ∆(m − M) = 1.6A_B. The absorption has paradoxically thus a stronger effect on this diameter distance than on a luminosity distance.

From a sample of 26 S0–Sb Virgo cluster members Dressler (1987) has determined

log D_n = 1.333 log σ − (1.572 ± 0.014)  

with a scatter of σ(log D_n) = 0.06, corresponding to σ(m − M) = 0^m.34. The two deviating galaxies NGC 4382 and NGC 4417 were excluded.

It is somewhat worrisome that equation (1) is based on only 24 galaxies, i.e. one third of the total Virgo population of S0–Sb galaxies. This may invite selection bias. However, the brighter half of the sample yields the same distance modulus as the fainter one to within 0^m.07 ± 0^m.14. Moreover, the missing Virgo members are on average fainter (smaller) at any given value of σ than the sample of 24, and they can make the constant term in equation (1) only more negative, which would in any case increase the cluster distance.

Yet for another reason the Virgo distance derived from equation (1) may be somewhat low. As discussed below (Section 8) the Virgo cluster consists of two main concentrations A and B, B being, if anything, slightly more distant. The Virgo distance quoted throughout refers to the mean of all cluster members and therefore depends on a fair representation of A and B. In the case of equation (1) 21 galaxies lie in A and only 3 in B, which is an overrepresentation of A even if one allows for the smaller size of B.

The Virgo cluster distance can be derived from equation (1) if the linear diameters D_n at given σ are known. As calibrators have been used M 31 and M 81 (Dressler 1987; Sandage & Tammann 1988) as well as the bulge of our Galaxy (Terndrup 1988); all three galaxies have been combined by Tammann (1988). The Galaxy, as a calibrator, may be of somewhat later type than the S0–Sb sample, but also the Sbc galaxy NGC 4501 fits well equation (1) (Dressler 1987). In principle the Virgo cluster distance has to be known to match the velocity dispersion σ of the calibrators to the aperture size (5″ × 5″) that was applied for Virgo. However, the remaining mismatch should introduce only negligible systematic errors (cf. Dressler 1987). The derivation of the cluster distance is repeated in Table 4 with updated Cepheid distances and absorption values for M 31 and M 81. The Table is self-explanatory.
Table 4. The local calibration of the $D_n - \sigma$ relation of the bulges of early-type spirals and S0 galaxies

| Calibrator | $(m - M)^0$ | log $D_n$ | $\sigma$ (km s$^{-1}$) | log $D_n$ (eq. 1) | $\Delta(m - M)$ | $(m - M)^0$ |
|------------|-------------|-----------|------------------------|--------------------|-----------------|-------------|
| Gal. Bulge | $14.46 \pm 0.20$ | $4.74 \pm 0.04$ | $124 \pm 9$ | $1.22 \pm 0.06$ | $17.60 \pm 0.30$ | $32.06 \pm 0.36$ |
| M31        | $24.44 \pm 0.20$ | $2.83 \pm 0.04$ | $150 \pm 5$ | $1.33 \pm 0.04$ | $7.50 \pm 0.20$ | $31.94 \pm 0.28$ |
| M81        | $27.80 \pm 0.20$ | $1.15 \pm 0.03$ | $166 \pm 6$ | $1.39 \pm 0.04$ | $3.80 \pm 0.19$ | $31.60 \pm 0.28$ |

weighted mean:  $31.85 \pm 0.17$

(1) Terndrup 1988 (2) Madore & Freedman 1991 (3) Freedman & Madore 1994 (4) Dressler 1987. $D_n$ corrected for bulge absorption of $A_B = 0.33$; cf. text (5) Dressler 1987. $D_n$ corrected for front absorption of $A_B = 0.16$ (Freedman & Madore 1994); cf. text (6) Dressler 1987.

The method is so promising that one would hope for additional bulge data of local calibrators as well as remaining Virgo cluster members of the appropriate Hubble types. At present we adopt $(m - M)_{\text{Virgo}} = 31.85 \pm 0.17$ as the best $D_n - \sigma$ distance from intermediate-type galaxies.

The classical $D_n - \sigma$ relation of early-type (E/S0) galaxies encounters the difficulty of lacking local calibrators. The only way is to use the two early-type members of the Leo group and to adopt the mean Cepheid distance of $(m - M) = 30.20 \pm 0.12$ of the three spirals in the same group. Faber et al. (1987) find the modulus difference between the Virgo cluster and the Leo group to be $\Delta(m - M) = 0.97 \pm 0.29$ from the $D_n - \sigma$ relation. This value is somewhat suspicious because it is significantly smaller than from four other relative distance indicators (cf. Tammann & Federspiel 1997). But taken the modulus difference at face value, one obtains $(m - M)_{\text{Virgo}} = 31.17 \pm 0.31$ from E/S0 galaxies.

The weighted mean distance modulus of the intermediate-type and early-type Virgo cluster members becomes then

$$(m - M)_{\text{Virgo}} = 31.70 \pm 0.15.$$  

7. The Virgo cluster distance from Novae

Pritchet & van den Bergh (1987) found from six novae in Virgo cluster ellipticals that they are $7.0 \pm 0.34$ more distant than the apparent distance modulus of M31 of $(m - M)_{\text{AB}} = 24.58 \pm 0.10$ from Cepheids (Madore & Freedman 1991) and Galactic novae (Capaccioli et al 1989). Livio (1997) found from a semi-theoretical analysis of the six Virgo novae $(m - M)_{\text{Virgo}} = 31.35 \pm 0.35$.

A low-weight mean of $(m - M)_{\text{Virgo}} = 31.46 \pm 0.40$ is adopted.

8. Conclusions

The results of Sections 2 - 7 are compiled in Table 5. The individual values lead to a weighted mean distance modulus of $(m - M)_{\text{Virgo}} = 31.60 \pm 0.09$, corresponding to a distance of $r = 20.9 \pm 0.9$ Mpc.

It is remarkable that the individual distance determinations agree to within their mean internal errors. The result gains additional weight by the fact that it is based on spiral as well as early-type cluster members. The zeropoint of the distance
Table 5. Compilation of the different Virgo cluster moduli

| Method          | \((m - M)_{\text{Virgo}}\) | Type   | Calibration Source               |
|-----------------|-----------------------------|--------|----------------------------------|
| Cepheids        | 31.45 ± 0.21                | S      | \((m - M)_{\text{LMC}} = 18.50\) Tammann & Sandage 1999 |
| Supernovae Ia   | 31.55 ± 0.20                | S      | Cepheids                        | Tammann & Reindl 1999 |
| Tully-Fisher    | 31.58 ± 0.24                | S      | Cepheids                        | Federspiel et al. 1998 |
| Globular Clusters | 31.70 ± 0.30           | E      | RR Lyr, Cepheids                | Tammann & Sandage 1999 |
| Dn - σ          | 31.70 ± 0.15                | E, S0, S | Galaxy, Cepheids              | Dressler 1987 |
| Novae           | 31.46 ± 0.40                | E      | M31 (Cepheids)                 | Pritchet & van den Bergh 1987 |

Mean: 31.60 ± 0.09 \(\Rightarrow 20.9 \pm 0.9\) Mpc

determination, as seen in Table 5, rests mainly, but not exclusively on Cepheids, and hence on the adopted LMC distance.

The Virgo cluster shows clear subclustering. There are two major clumpings A (with M 87) and B (with M 49) (Binggeli et al. 1985, 1993) as well as a concentration around M 86 (Schindler, Binggeli, & Böhringer 1999). There is rather strong evidence from the TF method that cluster B is more distant than A by \(\sim 0^\circ46 \pm 0.18\) (Federspiel et al. 1998). However, at present it is save to include all cluster members as defined by Binggeli et al. (1993) and to quote a single mean distance of the common gravitational well.

Future determinations of the Virgo cluster distance may include the brightness of the tip of the red-giant branch (TRGB). A first experiment is available (Harris et al. 1998), and if a sufficient number of cluster members will become available to beat the cluster depth effect the method may become competitive.

It has been argued many times that the recession velocity of the Virgo cluster is too small to yield the cosmic value of the Hubble constant \(H_0\). Indeed the observed mean cluster velocity of \(v_0 = 920 \pm 35\) km s\(^{-1}\), corrected to the centroid of the Local Group (Binggeli et al. 1993) and combined with the above cluster distance would provide too low a value of \(H_0 = 44\) [km s\(^{-1}\) Mpc\(^{-1}\)] mainly due to the gravitational deceleration by the Virgo complex. The Virgocentric pull has decelerated the Local Group’s recession velocity by 200 – 250 km s\(^{-1}\) (Kraan-Korteweg 1986; Tammann & Sandage 1985; Jerjen & Tammann 1993). \(H_0\) becomes then rather 54 with some leeway as to remaining peculiar velocity effects.

However the problem of the Virgo cluster velocity can be entirely circumvented by using the distances of clusters out to 10000 km s\(^{-1}\) relative to the Virgo cluster (Sandage & Tammann 1990; Jerjen & Tammann 1993; Giovanelli 1997). The exquisite quality of these relative distances is shown by their defining a Hubble line of slope 0.2 with very small scatter (Fig. 1).

A linear regression through the points in Fig. 1 with forced slope of 0.2, corresponding to linear expansion, gives

\[
\log v = 0.2 \left( (m - M) - (m - M)_{\text{Virgo}} \right) + (3.070 \pm 0.011).
\]

From this follows directly

\[
\log H_0 = -0.2 \left( (m - M)_{\text{Virgo}} \right) + (8.070 \pm 0.011).
\]

Inserting the mean Virgo cluster modulus from Table 5 yields

\[H_0 = 56 \pm 4,\]
Figure 1. Hubble diagram of 31 clusters with known relative distances. Asterisks are data from Jerjen & Tammann (1993). Open circles are from Giovanelli (1997). Filled circles are the average of data from both sources. Velocities of $\geq 3000 \text{ km s}^{-1}$ are corrected for a local CMB anisotropy of $620 \text{ km s}^{-1}$.

where the additional external error is generously estimated to be $\pm 6$.

The route to the Virgo cluster distance and to $H_0$ is schematically summarized in Fig. 2.

The figure also shows the distance modulus of the Fornax cluster. The modulus holds strictly only for the early-type cluster members. The Cepheid distance of the large spiral NGC 1365 of $(m - M) = 31.35$ (Madore et al. 1998) proves it to lie on the near side of the cluster. Also other cluster spirals may be at relatively small distances because a compilation of about 30 determinations by various methods and authors of the relative distance between the Fornax and Virgo clusters suggests that the Fornax spirals are nearer on average than the Fornax E/S0 members by $0.35 \pm 0.10$ (Tammann & Federspiel 1997). In any case the Fornax cluster distance is not helpful for the determination of $H_0$ because the observed mean cluster redshift of $\sim 1300 \text{ km s}^{-1}$ carries an uncertainty of $\sim 20\%$ due to its totally unknown peculiar motion.

The Coma cluster distance in Figure 2 is not either very helpful for the determination of $H_0$. Its main weight hinges on distances relative to the Virgo cluster and the cluster contributes therefore only a limited amount of independent evidence. Moreover, its observed mean velocity of $6900 \text{ km s}^{-1}$ may be affected by local streaming velocities at the level of about $10\%$. The cluster lies probably outside the large local bubble which moves with $630 \text{ km s}^{-1}$ toward the warm pole of the MWB (Smooth et al. 1991), but it seems plausible that it has a similarly large peculiar motion by its own.

The value of $H_0 \approx 58$, also shown in Fig. 2, is based on purely physical distance determinations, i.e. gravitationally lensed quasars, the Sunyaev-Zeldovich effect, and
$H_0 = 56 \pm 4$

Clusters out to 10,000 km s$^{-1}$

$H_0 \approx 58$

$(H_0 = 60 \pm 6)$

Coma Cluster
(m-M) = 35.29 \pm 0.11
114 \pm 6 Mpc

Virgo Cluster
(m-M) = 31.60 \pm 0.09
20.9 \pm 0.9 Mpc

$(H_0 = 58 \pm 10)$

Fornax Cluster
(m-M) = 31.80 \pm 0.09
22.9 \pm 1.0 Mpc

Fig. 1

Figure 2. Schematical presentation of the distance determination of the Virgo cluster

CMB fluctuations. The reader is referred to the abstract by G. Theureau & G.A. Tammann in these Conference Proceedings where the original authors are quoted.

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