THE LOCAL VELOCITY FIELD AND THE HUBBLE CONSTANT

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"When you reach a fork in the road, take it"
(American folklore, sometimes attributed to Yogie Berra).

ABSTRACT
The methods are reviewed that give a distance modulus to the core of the Virgo cluster of m - M = 31.64 ± 0.08 (D = 21.3 ± 0.8 Mpc). It is shown that the cosmic velocity of the cluster core is 1179 ± 17 km s^{-1}, which, when combined with the distance gives H_o = 55 ± 3 km $s^{-1}Mpc^{-1}$ from the Virgo cluster data alone. Nine independent methods are reviewed that confirm that H_o = 50 ± 2. Discussion is made why all methods that are said to give the short distance scale (H_o ~ 85) are incorrect.

1. Introduction

The debate continues on the value of the Hubble constant despite the multiple evidence from many experiments that its value is near H_o = 50 km $s^{-1}Mpc^{-1}$. The purpose of this lecture is to list the evidence for the long distance scale. For those at the fork in the road that wish to still take it, we show why the short distance scale (H_o ~ 85 to 100) is not supported by any unbiased data and analysis.

The plan of the report is to (1) show that the local value of H_o is close to the global value because there is no step in the Hubble diagram that separates the nearby expansion field from the Machian (global) field relative to the microwave background (CMB), (2) show that the global expansion velocity of the Virgo cluster is v(cosmic) = 1179 ± 17 km s^{-1} tied to the kinematic frame of the CMB, (3) show that six distance indicators give the distance modulus of the Virgo cluster as m - M = 31.64 ± 0.08 (D = 21.3 ± 0.8 Mpc), (4) show thereby that H_o = 55 ±

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2 km $s^{-1}Mpc^{-1}$ from the Virgo cluster alone, (5) show that the result is confirmed by nine independent methods, the most powerful of which is through distant supernovae of type Ia calibrated in absolute magnitude via Cepheids, (6) justify that the local distance scale from Cepheids is confirmed to within 5% from the independent calibrations via the old population II objects (RR Lyrae variables, globular clusters, red giant stars), and (7) show how it can be understood that all methods that are said to support the short distance scale ($H_0 \sim 85$) are incorrect.

2. The Local Velocity Field Tied to the CMB

The two best established motions of the Local Group relative to the Machian frame of the cosmic CMB are (1) the perturbation of the free (cosmic) expansion of the Local group from the Virgo region due to the mass of the Virgo complex, and (2) the larger-scale, nearly bulk motion of the "local bubble" of size ≤ 6000 km s^{-1} relative to the CMB, carrying the Local Group and the Virgo complex with it. The model for the salient features is still that set out elsewhere (Tammann & Sandage 1985), given as Figure 1 here. Refinements on this picture, tying the "local

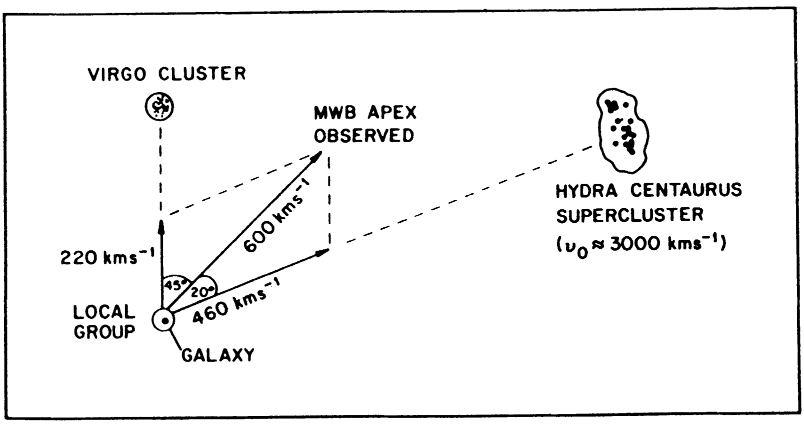

Fig. 1. Vector diagram showing the "infall" (actually retarded expansion) of the Local Group toward the Virgo cluster center plus the supposed motion in the direction of Hydra, which must be caused by the clumpy mass distribution within ≤ 6000 km s^{-1}. The two vectors together explain the observed dipole motion toward the warm pole of the CMB.

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bubble" into the Machian cosmic frame can be made using the extensive data of Mathewson, Ford, & Buchhorn (1992). Analyses by Federspiel et al. (1994, FST) show that the nearly bulk peculiar motion of the local bubble containing the Local Group, the Virgo complex, and the local region gradually peters out beyond ~ 6000 km s^{-1}, merging gradually into the unperturbed Hubble flow. Figures 15 to 19 of FST are decisive on this point.

That the effect of the peculiar dipole motion toward the CMB within the Local Supercluster and beyond is so small and can be neglected in the determination of H_0 is shown by the lack of a *step* in the Hubble diagrams at the "edge" of the Local Supercluster. The lack of an effect can be made quantitative. Figure 2 shows the Hubble diagram (*m* vs. *log cz*) for nearby clusters and groups to 10,000 km s^{-1} from both hemispheres.

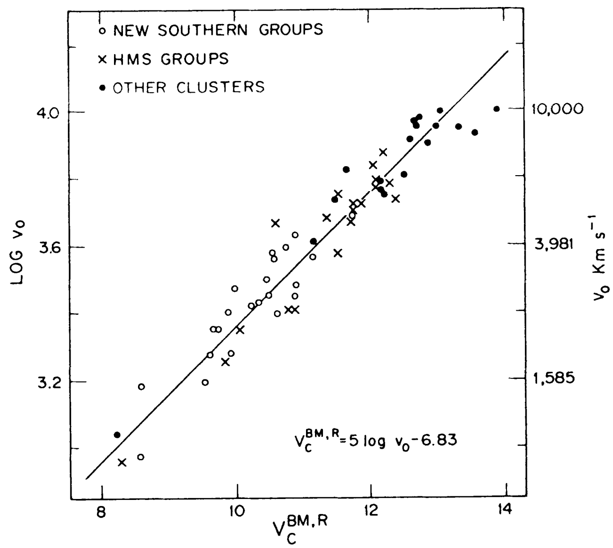

Fig. 2. Hubble diagram for nearby groups and clusters using first-ranked E galaxies corrected for richness and contrast effects. Diagram from Sandage (1975). No steps or large-scale streaming motions are visible.

The data show no step nor any other large-scale streaming motions at the level of more than ~ 500 km s^{-1}. With this limit applied at 5000 km s^{-1}, the typical effect of perturbations on the Hubble flow is <10%. The error on the Hubble constant due to streaming motions will also be equal to or less than this.

3. The Cosmic Velocity of the Virgo Cluster Core Freed From All Streaming Motions

The most direct method to sample the true expansion field devoid of all effects of local streaming motions is to tie the Virgo cluster core to remote clusters that themselves have known redshifts relative to the kinematic frame of the CMB (Sandage & Tammann 1990; Jerjen & Tammann 1993). The result, shown in Figure 3, is that the cosmic (global, Machian) redshift of the

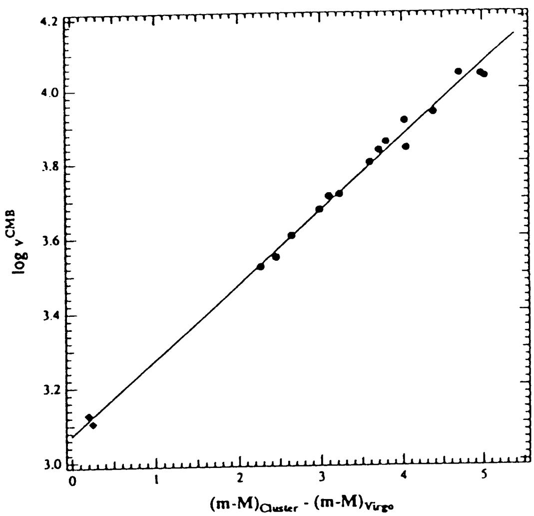

Fig. 3. The Hubble diagram using redshifts in the kinematic frame of the CMB vs. the differences in distance moduli between each of the 17 clusters and the E galaxies in the Virgo cluster core. The cosmic redshift at the distance of the Virgo cluster core, read from the Hubble line of slope 5 at zero modulus difference, is 1179 ±17 km s^{-1}.

Virgo cluster core is v(cosmic) = 1179 ±17 km s^{-1}, devoid of all streaming motions. The result can be used to determine the Hubble constant once the distance to the Virgo cluster is known.

Part of the disagreement in the Hubble constants derived by others is their use of too high a value for v(cosmic) for Virgo. The decisive result from Figure 3 with its error of only 1.4% removes this one source of the differences between our results and others.

4. Six Methods for the Distance to the Virgo Cluster Core

Before giving the synopses of six methods to find the distance of the Virgo cluster core, we give the summary of the results in Table 1. Results of the two methods (planetary nebulae and surface brightness fluctuations) that are said (Jacoby et al. 1992) to give $(m - M)_{Virgo} = 30.9$, are outside the range of the Table, and are not shown. Methods and data that apparently support the short distance scale are mentioned in section 8.

TABLE 1

Method	(m - M)	Galaxy Type	Calibrators
Globular clusters	31.64 ± 0.25	E	RR Lyraes
Novae	31.57 ± 0.43	S	M31, galactic novae
Supernovae	31.63 ± 0.25	E,S	Cepheids, model
Dn - σ	31.85 ± 0.19	E	Galaxy, M31, M81
21 cm line-widths	31.60 ± 0.15	S	13 nearby calib.
Scale length of ScIs	31.50 ± 0.20	S	MW and M31 sizes
mean	31.64 0.08		(D = 21.3 ± 0.08 Mpc)

(a) *Globular clusters*: The maximum of the globular cluster luminosity function, calibrated via RR Lyrae distances for MW globular clusters using a new calibration (Sandage 1993c) and via Cepheids for M31 clusters, is applied to the observed luminosity turnover in the cluster samples for five E galaxies associated with the Virgo cluster core (Harris et al. 1991). The modulus first obtained by Harris (1988) of m - M = 31.7 is confirmed (Sandage & Tammann 1994). The new precepts introduced by Secker & Harris (1993) that led them to a short distance scale are criticized there (cf. also McLaughlin et al. 1994).

(b) *Normal novae*: Pritchet & van den Bergh (1987) discovered nine normal novae in NGC 4472, the brightest E galxay in Virgo subcluster B, obtaining a modulus difference between M31 and NGC 4472 of 6.8 ± 0.4 mag. Using a corrected M31 modulus as argued by Sandage & Tammann (1988) gives $(m - M)_{NGC\ 4472} = 31.57 \pm 0.43$.

(c) *Supernovae*: Following Tammann (1988, 1992) and Branch & Tammann (1992), the Type Ia supernovae observed in Virgo cluster galaxies give (m - M) = 31.54 ± 0.22 using a calibration of

M_B = -19.6 based on Cepheids (Sandage et al. 1994; Saha et al. 1994b). Schmidt et al. (1992) obtained "expanding envelope" distances for two SNe II in the Virgo cluster of $(m - M)_{Virgo}$ = 31.71± 0.26 mag before they incorrectly (Branch 1994) changed (Schmidt et al. 1994a,b) their value of the dilution (Wagoner) factor. The average of the determinations using SNe Ia and SNe II is shown in the Table.

(d) $D_n - \sigma$: Combining the known variation of surface brightness (SB) of E galaxies with absolute magnitude (Oemler 1974, 1976; Kormendy 1977; Sandage & Perelmuter 1991) with the Minkowski (1962) relation (later called the Faber-Jackson relation) between absolute magnitude and central velocity dispersion gave a relation between SB, M, and velocity dispersion (Dressler et al. 1987; Dressler 1987), known now as the $D_n - \sigma$ relation. A calibration of the Dressler relation using the bulges of M31, M81 and the MW (Tammann 1988) gives a Virgo modulus of (m - M) = 31.85 ± 0.19.

(e) *21 cm line widths*: Kraan-Korteweg, Cameron, & Tammann (1988), Fouqué et al. (1990), Teerikorpi (1987), Bottinelli et al. (1987), Sandage (1988a,b, 1994a,b); Federspiel et al. (1994) and undoubtedly others demonstrate that observational selection causes all distances in flux-limited samples to be distorted toward too small values, giving Hubble constants that are too large when using the Tully-Fisher method. Theory and application of the correction for this type of bias (cf. Tammann 1988; KKCT 1988; Fouqué et al. 1990) gives $(m - M)_{Virgo}$ = 31.60 ± 0.15 for the Virgo cluster, as listed in the Table.

(f) *Size of the MW and M31 relative to Virgo spirals*: van der Kruit (1986) compares scale lengths of Virgo Sb and Sc galaxies with the known absolute scale lengths of the MW and M31 disks to derive a *lower limit* to the Virgo cluster distance of 20 Mpc, listed as a real value in the Table.

5. The Hubble Constant From the Virgo Cluster Distance Itself

Dividing the cosmic velocity of the Virgo cluster core of v = 1179 ± 17 km s^{-1} by the adopted distance from Table 1 gives

$$H_o \text{ (cosmic)} = 55 \pm 2 \text{ km s}^{-1}\text{Mpc}^{-1},$$

using the Virgo cluster data alone. Six methods that are independent of the Virgo cluster method, set out in the next section, also support this long distance scale.

6. Nine Independent Astronomical and Astrophysical Ways to H_0

The results of nine independent methods to H_0, in addition to the Virgo method, are listed in Table 2. Only the salient literature references are given here. Details of the methods are justified in these references. The principal references are:

TABLE 2: Summary of the Various Methods to H_0

Method	H_0
Virgo Distance	55 ± 2
ScI Hubble diagram	49 ± 15
M101 look-alike diameters	43 ± 11
M31 look-alike diameters	45 ± 12
Tully-Fisher field galaxies	48 ± 5
Tully-Fisher cluster data	55 ± 8
Supernovae Ia (B)	52 ± 8
Supernovae Ia (V)	55 ± 8
Supernovae Ia expansion parall. & ^{56}Ni	50-60
Sunyaev-Zeldovich effect	38 ± 17
Magn.variations of lensed double QSO	< 70
mean	~ 50

Virgo distance: last section; *ScI galaxy Hubble diagram*: The Hubble diagram itself is set out in Sandage & Tammann (1975). The calibration using the absolute magnitude of the only ScI galaxy with a Cepheid distance (as of 1993), i.e. M101 at $m - M = 29.3$, is in Sandage & Tammann (1974). The bias properties of the sample and the way to correct for them is in Sandage (1988a); *M101 look-alike diameters*, calibrated with M101 and corrected for bias is in Sandage (1993a), following the method of van der Kruit (1986); *M31 look-alike diameters* calibrated by M31 and corrected for bias is discussed in Sandage (1993b); *Tully-Fisher field galaxies* in the distance-limited sample of Kraan-Korteweg & Tammann (1979), calibrated with local galaxies by Richter & Huchtmeier (1984), give the bias-free result in Table 2 (Sandage 1994b); *Tully-Fisher cluster* data corrected for the "cluster-population-incompleteness bias" of Teerikorpi (1987, 1990), is analyzed by Sandage, Federspiel, & Tammann (1995); *The supernovae data* for the first two HST calibrations via Cepheids are discussed in Sandage et al. (1992, 1994) and Saha et al. (1994a, 1994b). - Purely physical distance determinations are: *Type Ia supernovae* from ^{56}Ni-powered light curves and expanding-photosphere models (Branch & Khokhlov 1994); from the *Sunyaev-Zeldovich effect* (Birkinshaw 1993; Jones 1994); and from *gravitational double quasars* (Dahle et al. 1994).

7. The Local Distance Scale is Stable

The value of H_0 is no better than the reliability of the local distance scale upon which the secondary calibrators rest (involving M31 and all other members of the Local group, used for example by Richter & Huchtmeier (1984) for the calibration of the TF relation, as well as M81, M101, and others in nearby groups). The reliability of the data for the Local Group is discussed by Tammann (1987, 1992), by Madore & Freedman (1991), and by Sandage (1995). The agreement on these various distance scales is within a few hundreths of a magnitude in the mean.

The agreement is particularly significant by noting that the distances to four of the local calibrators determined from RR Lyrae stars (LMC, IC 1613, M31, and M33) using the new RR Lyrae calibration given elsewhere (Sandage 1993c) agree with the distances from Cepheids to within less than 0.1 mag (Lee et al. 1993; Tammann & Sandage 1995).

8. Criticisms of the Short Distance Scale

A series of papers have appeared that show how the bias properties of flux-limited samples compared with bias-free distance-limited samples always lead to an incorrect short distance scale and to too large a Hubble constant. Entrance to the literature can be had via Teerikorpi (1987, 1990), Kraan-Korteweg et al. (1988), Sandage (1988a,b; 1994a,b), Bottinelli et al. (1988), Fouqué et al. (1990), Federspiel et al. (1994). All show that proper correction for selection bias reduces the uncorrected Hubble constants near 85 to the range centered near 50. We do not repeat the arguments here.

The two remaining methods that are said to give the short distance scale (H_o = 85) are the planetary nebulae (PNe) and the surface brightness fluctuation method (SBFM). It is useful to mention our reservations about them here.

The PN method relies on a cutoff of their luminosity function in the λ 5007Å light. PNe do not have an infinitely sharp luminosity function at the bright end. Therefore the method is susceptable to population bias. Large samples will have brighter first-ranked PNe than small samples. The nine brightest PNe in Jacoby's et al. (1990) sample are brighter than the vertical "asymptote" of the luminosity function finally adopted in Jacoby et al. (1992). The consequences of the non-sharp bright end to the LF are discussed by Bottinnelli et al. (1991), by Tammann (1993), and also by Méndez et al. (1993).

Comparison of relative distances determined by the SBFM and the $D_n - \sigma$ method show that the former are smaller by an average of 25% (Tammann & Sandage 1995). More seriously, the individual distances for 13 E and S0 galaxies in the Virgo cluster (Tonry, Ajhar, & Luppino 1990) show a large scatter in their individual distances (12 to 23 Mpc), but also that these distances are strongly correlated with metallicity (Tammann 1992), indicating uncorrected systematics in the method itself. Consequently Tonry (1991) introduced the V - I color as an additional free parameter, but some metallicity dependence yet remains (Lorenz et al. 1993), with the faint, metal poor ones being (artificially) nearer. In addition, in the one case where a direct comparison with a Cepheid distance is possible (NGC 5253), the SBFM gives 2.5 Mpc whereas the Cepheid distance is 3.9 Mpc, i.e. a distance ratio of a factor of 1.6.

Finally, it is necessary to record our disbelief concerning the announcement of the solution to H_o by Pierce et al. (1994), which also is the communication by van den Bergh in this volume. Our concerns center on (1) the technical aspects of their data, and their displayed P-L relation, and (2) their precept that the distance, even if correct, of the one spiral that is the most easily resolved in the total spiral sample of Virgo "associates" has a connection to the distance of the E galaxy Virgo core.

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