THE VALUE OF H_o

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ABSTRACT: A brief discussion of the systematic effects of selection bias on the extragalactic distance scale is given. Distance indicators with intrinsic scatter yield only upper limits to H_o, unless the true intrinsic scatter is either small or well determined. Several distance indicators (luminosity index, diameters, globular clusters, 21 cm line widths) are discussed. It is concluded that type I supernovae, calibrated through brightest M supergiants, yield presently the most reliable determination of the large-scale value of the Hubble constant, i.e. H_o(cosmic) = 50 ± 7 km s^{-1} Mpc^{-1}.

I. INTRODUCTION

Recently published values of the Hubble constant H_o range from 50 to 100 [km s^{-1} Mpc^{-1}], with a pronounced dichotomy favoring either the lower or the higher value. It is of principal importance for cosmology whether the low or the high value of H_o is nearly correct, because H_o = 50 ($1/H_o = 20 \cdot 10^9$ yrs) is compatible with a Friedman universe with an age of $\gtrsim 16 \cdot 10^9$ yrs from globular clusters (Sandage 1982; R. Cannon 1982; Carney 1983) and nucleochronometry (Schramm 1982), whereas H_o = 100 ($1/H_o = 10^{10}$ yrs) gives too short a time scale. In the latter case the age discrepancy cannot even be remedied by chosing a Lemaître model with $\Lambda \neq 0$ because the coasting period and hence a maximum of the galaxy and quasar distribution would fall at redshift $z \approx 0.3$ (Zeldovich and Sunyaev 1980), contrary to observations.

II. THE SELECTION BIAS OF APPARENT-MAGNITUDE-LIMITED SAMPLES

To derive the global value of H_o, one has to reach distances corresponding to recession velocities of $v_o > 3000$ km s^{-1}. Galaxies at this distance, drawn from an apparent-magnitude-limited sample, are systematically brighter and hence have larger diameters than nearby galaxies with firmly established distances. The size of this bias (Malmquist 1920) depends on the width and the shape of the luminosity function, -

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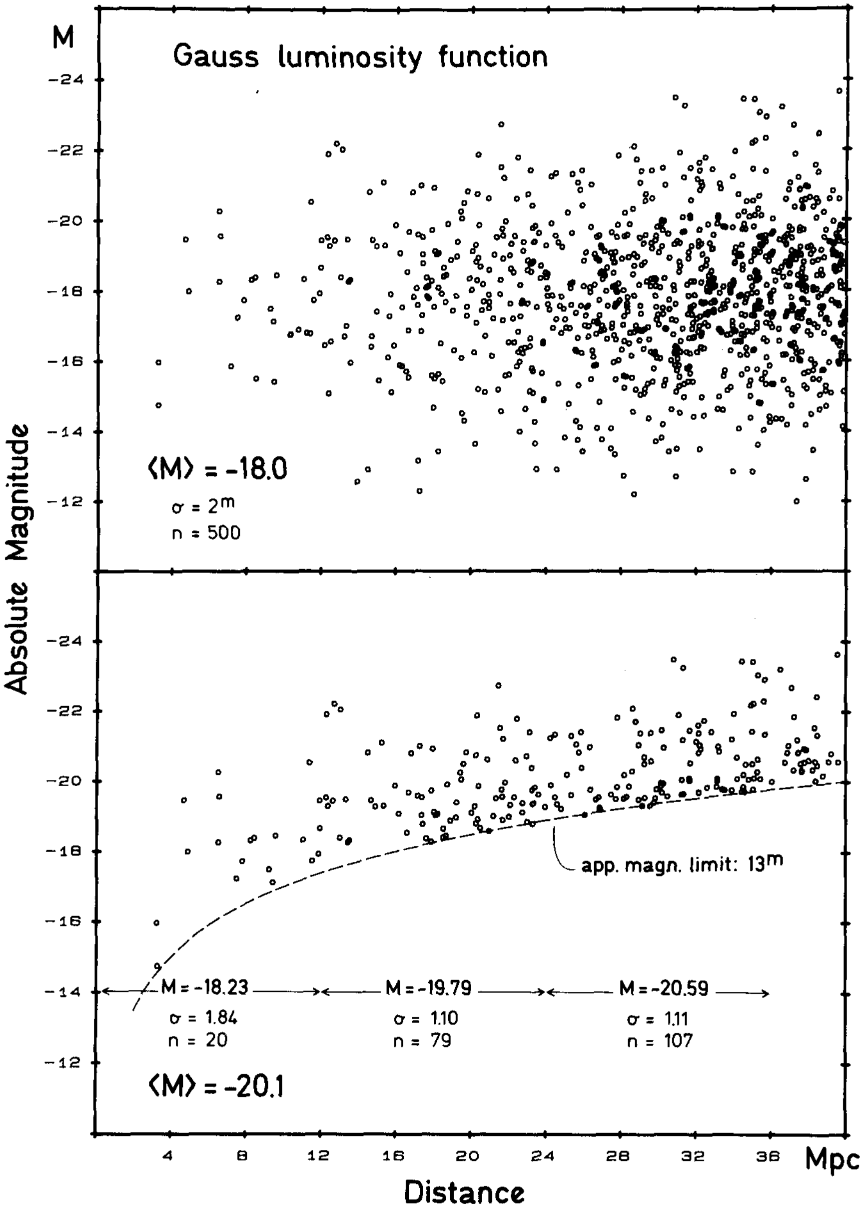

Fig. 1. Upper panel: Monte Carlo distribution in distance and absolute magnitude of 500 galaxies within 38 Mpc. Constant space density and a mean absolute magnitude of < M > = -18^m with a Gauss standard deviation of $\sigma_M = 2^m$ are assumed. Lower pannel: The same sample cut by an apparent-magnitude limit of m = $13\overset{m}{.}0$. Note the increase of the galaxian luminosities with increasing distance and the small effective (observable) scatter σ_M within individual distance intervals.

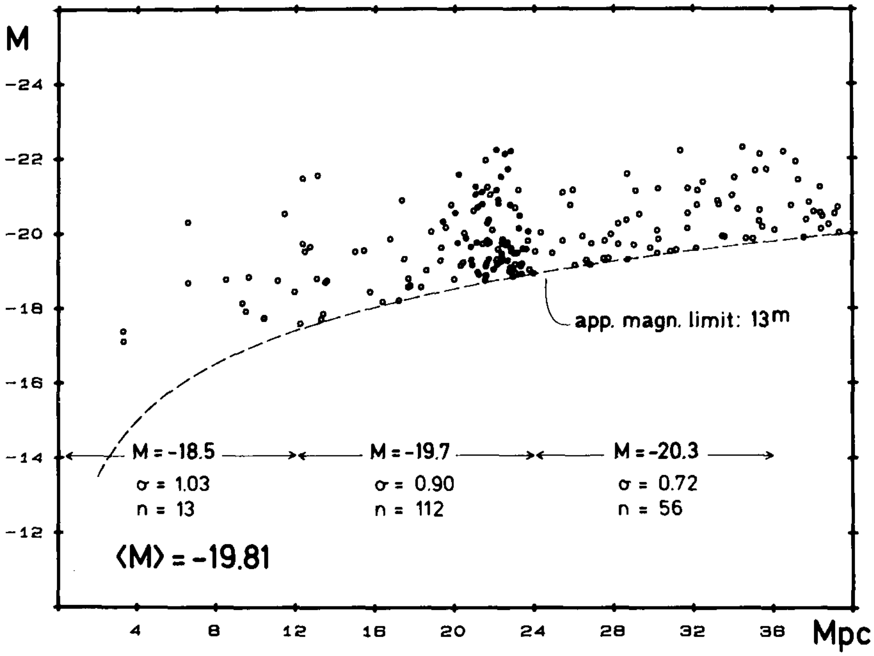

Fig. 2. Same as Fig. 1, but for 500 galaxies with $M < -17^m$ following a Schechter luminosity function typical for E to Im galaxies (Kraan-Korteweg 1981). A density fluctuation (cluster) of 150 galaxies is added at r = 22 Mpc. The true mean absolute magnitude of this sample is $< M > = -18.56$. Here only the subsample is shown which would appear in a catalog complete for $m < 13^m$. Note the increase of luminosity with distance, the small effective scatter σ_M, and the additional effect of the density fluctuation.

particularly at its bright end. Gaussian luminosity functions may be adequate for galaxies of a fixed luminosity indicator (e.g. luminosity class, color, 21 cm line width etc.); their resulting bias is illustrated in Fig. 1. Sets of galaxies of a given Hubble type have the bright end of their luminosity function better approximated by a Schechter-type function (cf. Fig. 2). In either case the mean absolute magnitude $< M >$ of a distant galaxy sample can be brighter by $\sim 2^m$ than that of the nearby calibrators, resulting in an increasing underestimate of large distances and in the unrealistic impression that H_0 increases with distance; an overestimate of H_0(cosmic) by a factor of up to 2.5 is the consequence.

To correct for the Malmquist bias the luminosity function or the true absolute magnitude scatter σ_M must be known. Unfortunately they are difficult to observe, because within any distance interval only a fraction of the luminosity function and of σ_M can be observed. This leads to a systematic underestimate of the intrinsic width of the luminosity distribution and hence of the size of the selection bias. (Note that the bias in absolute magnitude goes with $\sim \sigma_M{}^2$). The true luminosity distribution could be found from galaxies with a very wide distribution in distance, - but this requires before-hand knowledge of the distance scale. Another possibility is to consider cluster galaxies down to faint magnitudes and to assume that the luminosity distribution is the same in clusters and in the field. But an analytical correction for the bias is rendered impossible because of the additional difficulty imposed by fluctuations of the space density; the Virgo complex of the northern sky could possibly cause a spurious azimuthal change of H_o.

Empirically one can deal in first order with the selection bias by assigning brighter mean absolute magnitudes to galaxies with higher redshifts (Sandage et al. 1979), or by going to fainter apparent-magnitude catalog limits as the redshifts increase (Sandage and Tammann 1975). The best way to overcome the problem, however, is to rely on distance indicators with small intrinsic σ_M, like Cepheids, the brightest red supergiants, and type I supernovae (cf. § VII).

III. de VAUCOULEURS' LUMINOSITY INDEX Λ_c

A comparison of the "short distance scale" (with H_o = 100, de Vaucouleurs et al. 1981) and the "long distance scale" (with H_o = 50, Sandage and Tammann 1976, 1982a, b) is shown in Table 1.

Out to 4 Mpc, i.e. within the realm of primary and secondary distance indicators, the two distance scales agree within < 16%. If the galactic-absorption corrections of the short scale are updated (e.g. Burnstein and Heiles 1982) the agreement becomes even better. Furthermore,

Table 1

Object	Long Distance	Short Distance	Distance Ratio	Sources
<Local Group>	-	-	1.16	cf. Tammann et al. (1980)
M 81 Group	3.25 Mpc	3.1 Mpc	1.05	Tammann a. Sandage (1968), de Vaucouleurs (1978b)
Cen group	4.1	3.7	1.11	Sandage a. Tammann (1982b; NGC 5253), de Vaucouleurs (1979b)

(Continued)

Table 1 continued.

Object	Long Distance	Short Distance	Distance Ratio	Sources
M 101 group	7	5	1.4	Sandage a. Tammann (1974) de Vaucouleurs (1979c)
Virgo cluster	22	12.5-15	1.6	Sandage a. Tammann (1982a,b) de Vaucouleurs (1982), de Vaucouleurs a. Olson (1982)
r(at 3000 km s^{-1})	60	30	2	H_o = 50 and 100 respectively

independent work on the distances within the Local Group (Graham 1973, 1975, 1977, 1983; Martin et al. 1979; Glass and Evans 1982; Crampton 1979; Crampton and Greasley 1982; Madore 1983) confirm that the first step of the extragalactic distance scale is now secure at the 10% level.

Beyond 4 Mpc the short distance scale depends almost entirely on one tertiary distance indicator, i.e. the "luminosity index" Λ_c. The decisive question then is, how tight an indicator of the size of a spiral galaxy is Λ_c? If it has considerable intrinsic scatter the increasing shortness of the short distance scale would immediately be explained

The parameter Λ_c is essentially the sum of the numerically coded Hubble type of a spiral and its luminosity class (for details see de Vaucouleurs 1979a). A combination of Λ_c with apparent magnitude, and of Λ_c with diameter leads then to two (actually not independent) distance estimates (de Vaucouleurs 1979a, eq. 8 and 11). For 328 spirals distances from these two methods are available (de Vaucouleurs 1979c). An analysis of these best Λ_c distances reveals several undesirable features:
1) A plot of distance versus velocity has enormous scatter. If this is interpreted as the effect of random velocities, they must increase with distance and reach ∿ 2000 km s^{-1} for some spirals at ∿ 30 Mpc. It therefore seems more likely that the Λ_c distances for some spirals are in error by factors of up to 2.
2) The scatter in the distance-velocity plot is much reduced if mean distances and velocities are used for de Vaucouleurs groups. However, the mean value of H_o becomes then 80, not 100.
3) The value of H_o depends on the absolute magnitude: for $M_B = -17^m$ $\langle H_o \rangle = 116$, for $M_B = -21^m$ $\langle H_o \rangle = 76$!
4) The value of H_o depends on the Hubble type: for 44 Sab and Sb galaxies $\langle H_o \rangle = 74 \pm 4$, for the later-type spirals $\langle H_o \rangle = 94 \pm 3$!
5) The resulting luminosity function for the spirals with Λ_c distances implies a sharp cutoff at the bright end, contrary to the luminosity

function of cluster spirals (Tammann et al. 1980; a more detailed discussion will be given elsewhere).

6) The fact that the mean linear diameter of a spiral, calculated from its Λ_c distance, does not increase with distance is suspicious; with nearly luminosity-independent surface brightnesses (cf. § IV) it requires that the mean absolute magnitude does not become brighter with distance, contrary to the expectations from Fig. 1 (unless the Λ_c-luminosity relation were dispersion-free).

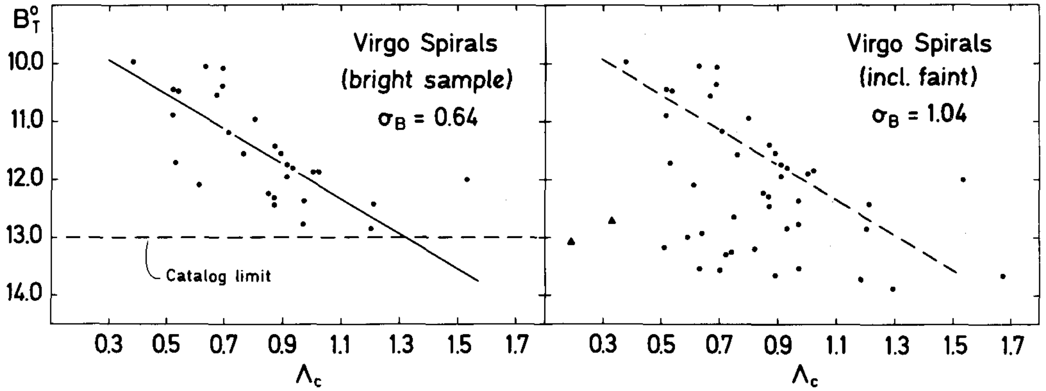

Fig. 3. Left: The Λ_c-magnitude relation of Shapley-Ames spiral galaxies within 6° of the Virgo cluster center. de Vaucouleurs' (1979) mean relation is drawn in. Right: The same diagram, but including some fainter Virgo cluster spirals. de Vaucouleurs' "mean relation" is repeated; $\sigma_M = 1.04$ relates to the best linear fit adopting the same slope. (The triangles stand for 2 Sa galaxies).

A minimum estimate of the intrinsic scatter σ_M of the Λ_c-absolute magnitude relation is provided in Fig. 3. On the left-hand side only the 28 spiral galaxies are plotted with published Λ_c values and within 6° of the Virgo cluster center. They follow reasonably well de Vaucouleurs' mean relation. They are, however, drawn from the Shapley-Ames Catalog and hence have $m < 13^m$. On the right-hand side the same galaxies are plotted together with 17 Virgo spirals down to $m = 14^m$. Their Hubble types and luminosity classes were estimated by one of us (A.S.) and the ensuing Λ_c values should correspond closely to de Vaucouleurs' system (e.g. van den Bergh 1982). Omitting two Sa galaxies and three possible background galaxies the scatter becomes now $\sigma_M = 1.04$ and may actually be still larger. This does not come as a surprise, because the luminosity distribution is not tight for a given luminosity class (Tammann et al. 1979; Sandage and Tammann 1981; Kennicutt 1982), and the correlation between Hubble type and luminosity is at best loose. Therefore the Λ_c parameter cannot depend strongly on galaxy luminosity either.

The intrinsic luminosity scatter of the Λ_c method of $\sigma_M > 1^m$ not only explains, but requires the spurious compression of the short distance scale.

IV. DIAMETERS OF GALAXIES AND OF RING STRUCTURES

For a galaxy of angular radius R" and surface brightness μ, the apparent magnitude is given by

$$m = \mu - 2.5 \log \pi R''^2 \tag{1}$$

As long as μ = const, the radii (diameters) contain no distance information beyond that contained in the apparent magnitudes.

If one assumes that μ changes with luminosity, i.e. $L \propto R^a$, one can easily show that

$$\log(\text{distance}) \propto \frac{a \log R'' + 0.4\, m}{(2-a)} . \tag{2}$$

The solution degenerates for a = 2, i.e. for μ = const! Fig. 4 shows that the effective surface brightness has considerable scatter, but is on the average nearly independent of luminosity within a given Hubble type. This situation is not significantly changed if isophotal surface brightnesses are used. Only the very brightest E galaxies have somewhat lower effective surface brightness, but the same holds for E galaxies with $M^o_{BT} > -18^m$ (Binggeli et al. 1982), such that the parameter a becomes a variable. The diameters of bright galaxies, therefore, do not contain any useful distance information.

It has been suggested to use the angular diameters of ring-like structures of galaxies as distance indicators (de Vaucouleurs and Buta 1980). However, their intrinsic size depends on absolute magnitude like $M_B = -5 \log D + \text{const}$ (Kormendy 1979), and again the solution for distance becomes degenerate.

V. GLOBULAR CLUSTERS

Globular clusters have been suggested as distance indicators on the assumption that they follow a Gaussian luminosity function with universal mean absolute magnitude and standard deviation. Surprisingly small distances to the Virgo cluster have been derived in this way (Hanes 1977, 1979).

It must be noted, however, that existing detailed photometry of globulars around Virgo galaxies (Hanes 1977; Strom et al. 1981) have not reached so far the peak of the luminosity function. In addition, the number of brightest globulars is poorly defined, because the effect of

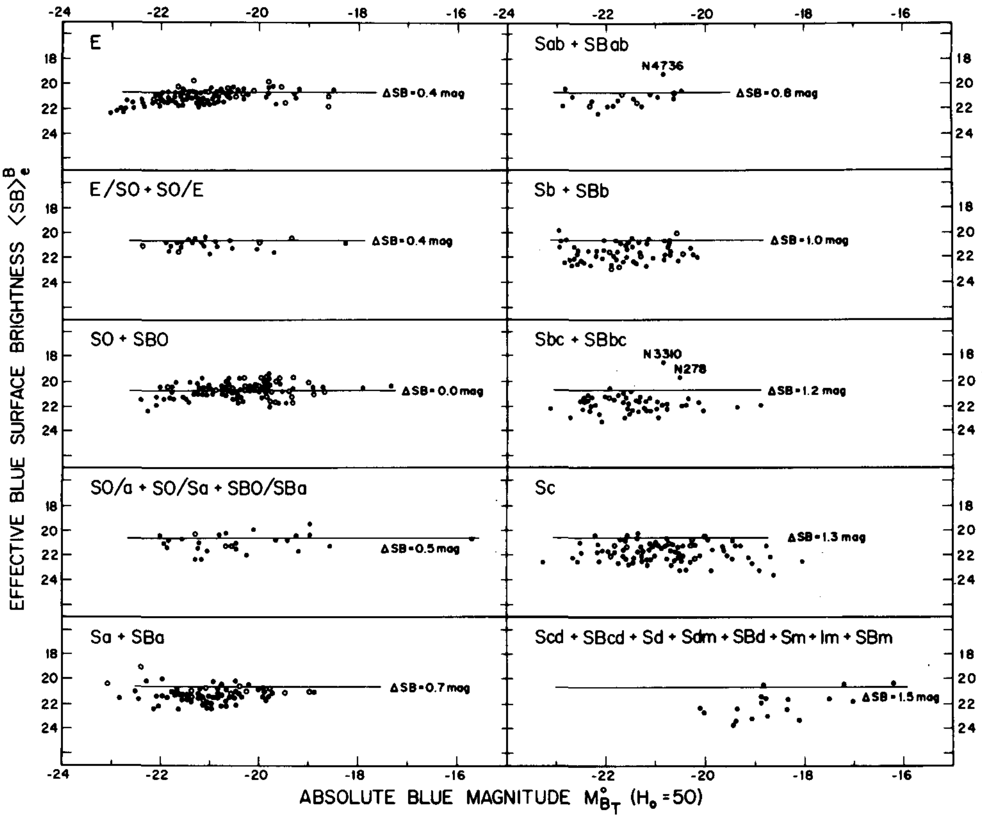

Fig. 4. The effective surface brightness of galaxies as a function of absolute magnitude for different Hubble types. The horizontal line in each panel is repeated from the SO + SBO galaxies.

foreground stars can only be statistically accounted for. At the Virgo distance one knows therefore merely a part of the rising branch of the luminosity function of globulars (cf. Fig. 5).

On the other hand it is clear that a straight-line luminosity function contains no distance information: it can be shifted left and right for the unknown distance, and it can be shifted up and down for the unknown total population. For a distance determination it is therefore necessary to fit some feature of the luminosity function. For the Virgo globulars this can only be the slight curvature of the observed distribution, which, however, is sensitive to small photometric scale errors at very faint magnitudes. Indeed, a comparison of the luminosity functions of M 87 globulars, as determined by two independent groups (Fig. 5), shows that their mutual deviations are of the same size as the deviations from a straight line. A distance determination from these data is therefore illusory.

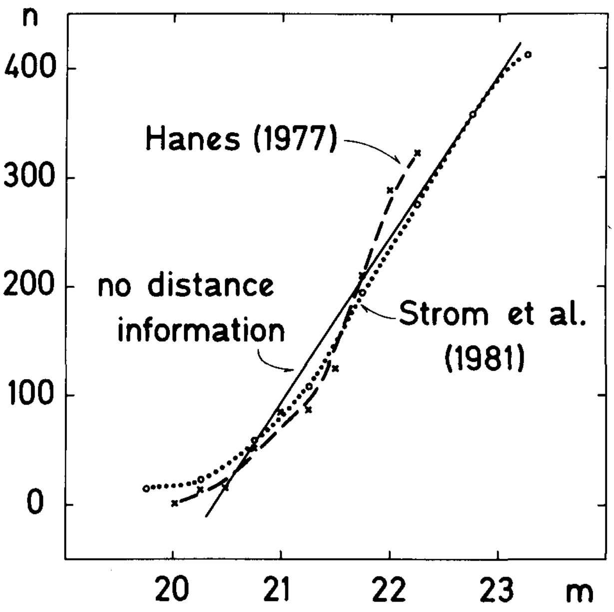

Fig. 5. The apparent-magnitude distribution of the globular clusters surrounding the Virgo cluster galaxy NGC 4486 (M 87) from Hanes (1977) and Strom et al. (1981). The former counts are normalized to contain the same total numbers as the latter ones down to 22^m. The straight line corresponds to the case where the counts contain no distance information.

VI. THE ROTATIONAL VELOCITY OF DISC GALAXIES

A three-parametric characteristics of the optical rotation curves of disc galaxies (v_{max}, some form parameter, and Hubble type) yields a good measure of the galaxian luminosity (Rubin 1983a; Thonnard 1983). Pending a reliable calibration (Rubin 1983b) and to the extent that sufficient numbers of first-class rotation curves will become available, the method will play an important role for the extragalactic distance scale.

An abridged, two-parametric, or even one-parametric (i.e. without distinction of Hubble type) analogue to this method is the correlation of the 21 cm line width Δv_{21} with the luminosity of a disc galaxy (Tully and Fisher 1977). The 50% intensity line width measures in fact $2\ v_{max}$ quite accurately (Rubin 1982a). Present results of this method cover a wide range of H_o, i.e. H_o = 55-60 (Sandage and Tammann 1976; Richter 1982; Huchtmeier and Richter 1982) to H_o = 103 (de Vaucouleurs et al. 1981), and cluster around H_o = 80 (e.g. Fisher and Tully 1977; Shostak 1978; Aaronson and Mould 1982). These results are still open to several questions:

1) The quoted standard deviation of the absolute magnitude at a given value of Δv_{21} is $\sigma_M \approx 0^m\!.4$. This would indicate that the above values of H_o should be decreased by roughly 10%. It is, however, not clear, whether the full intrinsic scatter has already been seen. A reliable determination of σ_M from faint cluster samples is still lacking (Sullivan 1982). The discrepancy of the slope of the log Δv_{21} - absolute magnitude relation between different authors (cf. de Vaucouleurs et al. 1982) could be interpreted as evidence for a considerable scatter σ_M.

2) The log Δv_{21} - absolute magnitude relation may depend on environmental effects. Data given by Mould et al. (1980) and Aaronson et al. (1980) for disc galaxies in five different clusters show that the distance-independent relation between log Δv_{21} and infrared surface brightness is not the same in these clusters, - assuming that the observational data are correct (Kraan-Korteweg 1982). Giovanelli et al. (1982) find that spirals at a given value of Δv_{21} are underluminous if they lie in a low-density environment, and are overluminous in cluster regions. Because the local calibrators lie in regions of relatively low density, present determinations of H_o may be too high by roughly a factor of 1.4 (Giovanelli 1982).

VII. THE LUMINOSITY OF TYPE I SUPERNOVAE AND THE VALUE OF H_o

A direct way to derive the value of H_o at large distances ($v_o > 3000$ km s^{-1}), i.e. H_o(cosmic), consists of only three steps (Sandage and Tammann 1982a, b):
1) Cepheid distances to 4 Local Group galaxies, to Sex A, and to 4 galaxies in the M 81-NGC 2403 group are used to calibrate the absolute visual magnitude of the brightest supergiants with (B-V) > $1\overset{m}{.}6$. Including data of the solar neighborhood the result becomes $M_V(1) = -7.91$ for the brightest and $M_V(3) = -7.72$ for the mean of the three brightest red supergiants. The small scatter of $\sigma_M = 0.17$ proves that the calibration is constant over a wide range of galaxian luminosity ($-14.0 > M_{Gal} > -19.4$), and that the effects of internal absorption are well-behaved. Since the calibration is accomplished within < 4 Mpc it is not surprising that the present value of $M_V(1)$ agrees within $0\overset{m}{.}3$ (i.e. 15% in distance) with the value of de Vaucouleurs (1978a; cf. § III).
2) The three brightest red supergiants are used to determine the distances to some nearby late-type galaxies, in particular of IC 4182 with $(m-M)^\circ = 28.21 \pm 0.2$ and of the galaxy pair NGC 4214/4395 with $(m-M)^\circ = 28.92 \pm 0.3$. IC 4182 and NGC 4214, respectively, have produced the well observed type I supernovae (SNeI) SN 1937c and SN 1954a. Their mean blue absolute magnitude at maximum light can therefore be determined to be $M_B(\max) = -19.74 \pm 0.19$. Here no correction for internal absorption has been applied for SN 1937c, and only a moderate one for SN 1954a. If anything, the true absolute magnitude is therefore still brighter.

The calibration implies a very reasonable distance of SN 1572 (Tycho) and of SN 1604 (Kepler) of 4 and of 3-4 kpc (cf. Dennefeld 1982). The value is also well bracketed by SNI expansion parallaxes yielding $-20.5 < M_B(\max) < 19.12$ (Branch 1977; Arnett 1981; Branch 1983). The expansion parallax of the type II SN 1979c in M 100 gives a Virgo cluster distance modulus of $(m-M)^\circ = 31.8$ (Branch et al. 1981), which leads for the six SNeI in this cluster to $M_B(\max) = -19.8$, and which again compares favorably with the present calibration.
3) The Hubble line in Fig. 6 defined by the apparent maximum magnitude of 16 SNeI with known velocity, is represented by

$$\langle M_B(\max) \rangle = (-19.73 \pm 0.24) + 5 \log (H_o/50). \quad (3)$$

Here only SNeI are used which occurred in E galaxies to avoid the effect of absorption within the parent galaxy. Inserting the calibration from step 2 into eq. (3) yields

$$H_o = 50 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

This is the cosmic value of H_o, because half of the SNeI defining eq. (3) have recession velocities of $v_o > 4000$ km s^{-1}, i.e. they lie at distances where any random velocities are expected to be relatively small.

There remains one crucial question: how much smaller is the true value of H_o due to selection bias of SNeI? First one should note that the SNeI in Fig. 6 are not strictly magnitude-limited; SNe are actually discovered as faint as $\sim 18^m$. Secondly the scatter of M_B(max), observed in Fig. 6 ($\sigma_M = 0\overset{m}{.}43$ for the 9 best observed SNeI) and in the Virgo cluster ($\sigma_M = 0\overset{m}{.}43$), is likely to be caused mainly by observational errors. And random observational errors, - contrary to intrinsic scatter, - do not introduce a Malmquist bias. The near identity of the infrared light curves of three SNeI (Elias et al. 1981) suggests that the intrinsic scatter of M_B(max) is $\sigma_M < 0\overset{m}{.}2$, and that selection effects are therefore negligible.

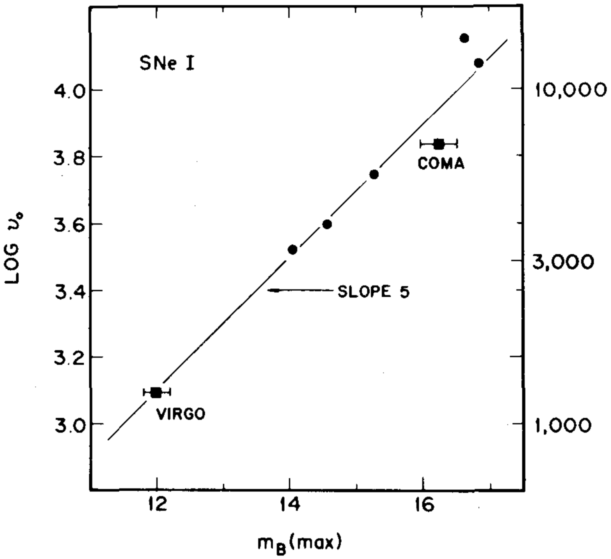

Fig. 6. The Hubble diagram of SNeI at maximum B light. The six SNe in the Virgo cluster ($<v_o> = 1187$ km s^{-1}, corrected for a local infall velocity of 220 km s^{-1}) and the five SNe in the Coma cluster are combined, respectively. The best linear fit has closely the expected slope of 5.

In agreement with quite different routes to H_o (Sandage and Tammann 1976; Tammann et al. 1980), the main conclusion here is that H_o(cosmic) = 50 ± 7 and that, from eq. (3), the 3σ confidence limits are $33 < H_o$ (cosmic) < 75 km s^{-1} Mpc^{-1}.

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