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The Global Hubble Constant*

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Abstract

A review of large-scale investigations of the determination of H is presented. The infrared period–luminosity relation of Cepheids gives distances accurate to ~2% to nearby galaxies. Based on the distances of M31, M33, N300 and N2403, a DM of $31 \cdot 30 \pm 0 \cdot 20$ has been derived to the nearby Virgo cluster from the TF relation of spirals at four wavebands. Distances to more distant clusters extending up to a redshift of ~10000 km s^{-1} obtained through the CM relation of E galaxies, the TF relation of spirals and the velocity dispersion–luminosity relation of E galaxies give a value of H of 71 km s^{-1} Mpc^{-1} when these distances are normalised to a Virgo DM of $31 \cdot 30$. The scatter in the redshift–distance relation of these clusters is ~500 km s^{-1} arising from the presence of unaccounted peculiar motions of individual clusters. The magnitude limited all-sky samples of galaxies also give a value of H near 70 km s^{-1} Mpc^{-1} once the data are corrected for Malmquist bias. The best value of the global Hubble constant obtained from the redshift–distance data of Virgo and farther clusters, as well as the magnitude limited samples involving various methods of determining distances by different observers, is 73 km s^{-1} Mpc^{-1}. Taking into account the error in the calibration of our DM of Virgo we can set a generous error of 10 to this value of H.

1. Introduction

The global Hubble constant H_0 and the deceleration parameter q_0 are the two important parameters that define the dynamics of the universe and can be determined from observations at the telescope. The rate of expansion of the universe H_0 is related to the timing of the creation event in which the universe was formed, while the change of expansion rate with (lookback) time q_0 tells us the average density of matter in the universe and hence the geometry of the universe. Thus the determination of the expansion rate at different times in the history of the universe has been one of the major goals of the observational cosmology.

Since Hubble's (1929) announcement that the redshifts of galaxies linearly vary with their distances, further observations (continued to the end of the 1960s) by Hubble, Humason, Mayall and Sandage have established that this linear relation is the same in all directions and at various depths in the universe (Sandage *et al.* 1975). The classic determination of Hubble's relation between the velocities and distances of the brightest galaxies in clusters by

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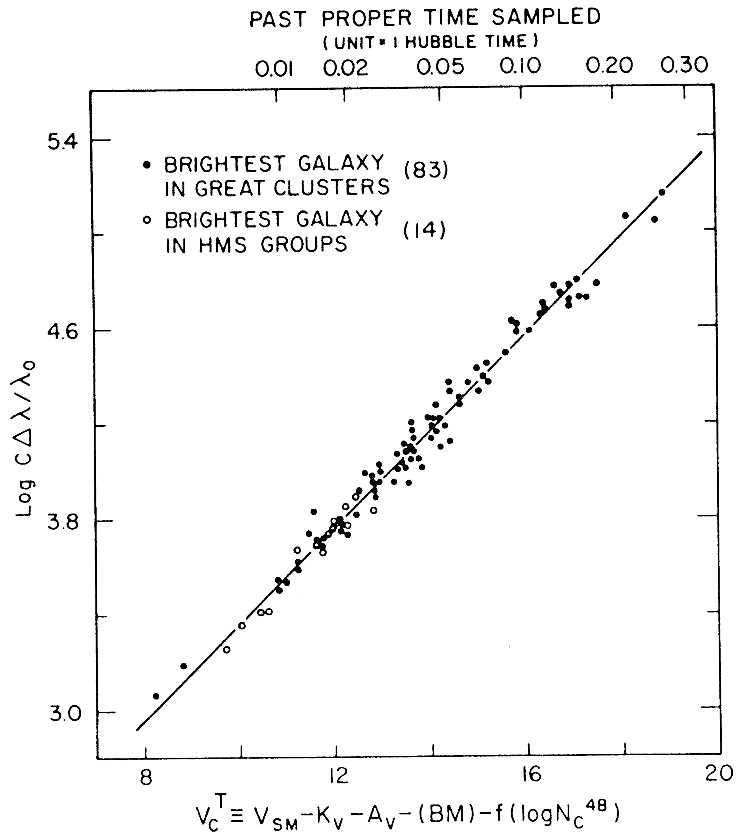

Fig. 1. The redshift–magnitude diagram (Hubble diagram) for first-ranked E galaxies in clusters (from Sandage and Hardy 1973).

Sandage and Hardy (1973) is given in Fig. 1. This aspect of the kinematic field and the discovery of the 3 K blackbody background radiation (Penzias and Wilson 1965) are the two important lines of evidence which support the view that the universe originated in a gigantic exploding fireball.

2. The Hubble Constant in the Period 1936–60

Hubble's (1936) best value for H in the original paper was 526 km s^{-1} Mpc^{-1} based on the study of the brightest stars in the field galaxies and the Virgo cluster as well as of the total magnitude of the fifth brightest galaxy in 10 clusters. The Virgo cluster's distance and redshift were found to be 2·3 Mpc and 1230 km s^{-1}. The value of H was halved in 1952 after Baade's (1952) 1·5 magnitude zero point correction for the Cepheid period–luminosity (PL) relation. Sandage (1958) applied the new magnitude scale of Stebbins *et al.* (1950) to the brightest stars in external galaxies, corrected the several errors made in the identification of the brightest stars (many of Hubble's identifications were H II regions or association of stars) and derived a value of $H \sim 75$ km s^{-1} Mpc^{-1}. *Thus since Hubble's first announcement, the revisions* *made by Baade and Sandage are responsible for the change from 526 to 75 km s^{-1} Mpc^{-1} (by a factor of 7 in 25 years!).*

3. The Hubble Constant in the Period 1970–80

Sandage and Tammann (1976) using Cepheids, diameters of H II regions as well as the Tully–Fisher (1977) (TF) relation derived distances to nearby late-type spirals and the Virgo cluster and obtained a value for H of $50 \cdot 3 \pm 4 \cdot 3$ km s^{-1} Mpc^{-1}. Kennicutt (1981) reanalysed the H II region data using more accurate isophotal Hα diameters and arrived at nearly the same value for H. van den Bergh (1975) reviewed the methods to determine distances to the Local Group galaxies and out to the Virgo cluster and beyond. He concluded that the best value of H is 95 ± 14 km s^{-1} Mpc^{-1}. de Vaucouleurs (1979*a*, 1979*b*) reassessed the galactic reddening and absorption as well as the zero points of the primary distance indicators and redetermined the value of H as 100 ± 10 km s^{-1} Mpc^{-1} using tertiary distance indicators and the luminosity index of external galaxies. Aaronson *et al.* (1980) observed spirals in the infrared ($1 \cdot 6\mu$) and used IR magnitudes in conjunction with H I linewidths to derive distances to Virgo and four other distant clusters. They calibrated the TF relation with the known distances of M31 and M33 and derived a value for H of 95 ± 4 km s^{-1} Mpc^{-1}. Visvanathan (1979*b*) and Visvanathan and Griersmith (1979) obtained values for H of 60 and 59 km s^{-1} Mpc^{-1} using the colour–magnitude (CM) relation for E galaxies and H II regions of spirals respectively.

In this review, we have only given selected large-scale investigations on the determination of H during this period. At the beginning of the 1980s it could be said that there was no general consensus among different authors except that the values were in the range 50 to 120 km s^{-1} Mpc^{-1} with a pronounced dichotomy favouring either $H = 50$ (long distance scale) or $H = 100$ (short distance scale).

4. The Hubble Constant From 1980 Onwards

Redshifts and independent distances of distant galaxies, required to evaluate H, have been found to have many systematic errors. In the past 10 years, the extension of the observed wavebands to infrared, the use of CCD images and the availability of larger all-sky samples have enabled the identification of many of these errors and correction of the data. These in turn have improved the accuracy of the determination of H.

(a) Systematic Errors in Redshifts

The observed redshift of a galaxy contains not only the expansion redshift but also a component due to peculiar motion of galaxies which depends on the position of the galaxy. The presence of peculiar motions in the local region are indicated by:

(i) the anisotropy of the microwave background which is interpreted by assuming that the Local Group (LG) has a peculiar motion of 614 km s^{-1} toward $l = 267°$, $b = 30°$ (Smoot and Lubin 1979);

(ii) gravitational pull due to Virgo which induces a peculiar velocity of 200–300 km s^{-1} at the LG (Schechter 1980; Visvanathan 1981*a*; Aaronson *et al.* 1982; Tammann and Sandage 1985);

(iii) gravitational pull due to the Great Attractor which generates a velocity of 570 km s^{-1} at the LG (Lynden-Bell *et al.* 1988; Aaronson *et al.* 1989; Visvanathan 1989).

The value of the peculiar motion increases for galaxies nearer to Virgo or to the Great Attractor. In the past the redshift data have not been corrected for these peculiar motions. For example, the correction of the Virgo redshift (1151 km s^{-1}) for the infall of the LG (200 km s^{-1}) changes the value of H from 57 to 69 if a distance of 20 Mpc is assumed. As the peculiar motion component is a function of the direction and the distance of the galaxy, it is necessary to understand the peculiar velocity fields present in the observed region and correct each redshift of the galaxy and the cluster before computing H.

(b) Systematic Errors in Distances

(1) Uncertainties in the distances to nearby calibrating galaxies introduce large errors in the zero point of the distance scale.

(2) Luminosity determinations of galaxies at B,V wave bands are affected by uncertain corrections for aperture and dust in our Galaxy and in the program galaxy.

(3) The mean error in the distances derived from different distant indicators and from different samples varies greatly from one to the other and leading to selection bias in the field samples chosen. If the data are not corrected for the bias (Teerikorpi 1987; Sandage 1988) the distances are underestimated. This makes it necessary to choose the distance indicators with small intrinsic scatter. The sample chosen for observation should be an all-sky sample covering a large volume in space.

(4) The present practice of deriving distances to galaxies involves the assumption that the galaxies are identical in their properties wherever they are located in the region. This assumption could introduce systematic errors in the measurement of distances as the possibility exists that galaxies differ in evolutionary history, metallicity etc.

The use of CCD images and the extension of the observed wavebands to the infrared, as well as the availability of new large samples of data, provide better luminosities for the distance indicators with minimum corrections for dust and metallicity variations (Aaronson *et al.* 1980*a*; Visvanathan 1981*b*; Burstein *et al.* 1987; Pierce and Tully 1988). These in turn have improved the accuracy of distances derived.

In Sections 4*c* and 4*d* a discussion is given of primary distance indicators used to derive distances to nearby galaxies and of secondary distance indicators for deriving distances to farther galaxies. In Section 4*e* the local velocity field is described and in Section 5 the value of *H*, indicated by different observers' data, is given. Finally conclusions are drawn in Section 6.

(c) Primary Distance Indicator

Classical Cepheids, RR Lyr stars, Mira variables and Novae are generally used to determine the distances to nearby galaxies.

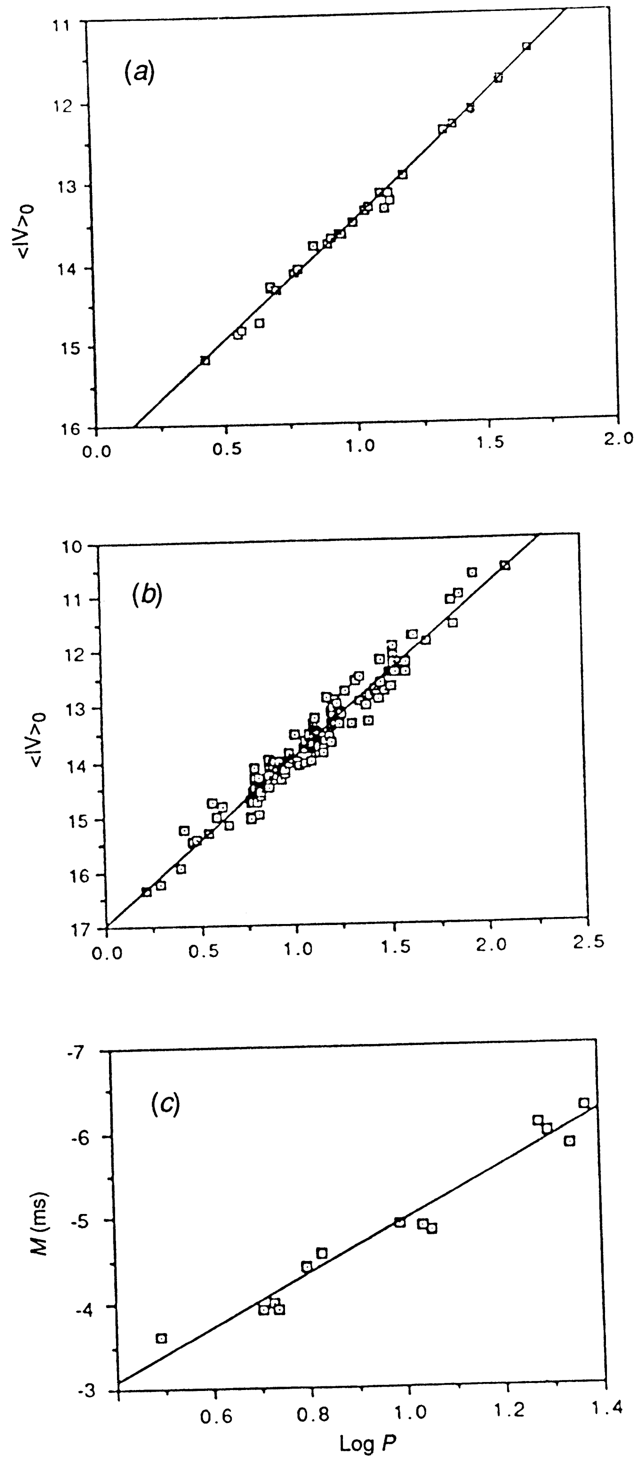

Fig. 2. The period–luminosity relationship in IV (10600 Å) for Cepheids in (*a*) the LMC, (*b*) the SMC (data are from Mathewson *et al.* 1986), and (*c*) galactic clusters. The lines are least-squares fits to the points (see Visvanathan 1989).

Classical Cepheids. These are ideal extragalactic distance indicators because as supergiants they are luminous enough to be observed up to 7 Mpc away. Recent observations of the infrared PL relation of Cepheids show small scatter (Visvanathan 1985, 1989; Laney and Stobie 1986; Welch *et al.* 1987) which makes them insensitive to selection bias. The choice of the near infrared wavebands ($1\cdot06\,\mu$; $1\cdot6\,\mu$) reduces the systematic errors due to uncertain corrections for dust and abundance variations in the measurement of luminosity of the Cepheids. Hence we concentrate only on IR Cepheid distances here. The luminosities have been measured at random phases and corrected to mean phase through the V mag observations. The absolute calibration of the PL relation has been achieved through the galactic cluster Cepheids. The distances to the clusters are determined through the ZAMS fitting and referenced to a Pleiades distance modulus of 5·57 (this corresponds to a Hyades modulus of 3·27 with a metallicity correction of −0·22 mag).

Fig. 2*a* is the PL relation for LMC Cepheids (Visvanathan 1989). A least-squares fit gives a slope of −2·95 with a dispersion of ±0·09 mag. This low dispersion makes the Cepheids one of the most accurate distance indicators. It is also to be noted that this dispersion includes the line of sight scatter in the distances of the Cepheids as well as any variation in the reddening across the galaxy.

Fig. 2*b* is the PL relation for the SMC Cepheids (Visvanathan 1989). The slope of the relation is −3·04 which is nearly the same as that obtained in the LMC. However, the dispersion is large (±0·23 mag) due to the depth of the distribution of Cepheids in the line of sight (Mathewson *et al.* 1986). We adopt the mean value of the slopes in the LMC and SMC (−3·0) as the best value of the slope of the PL relation.

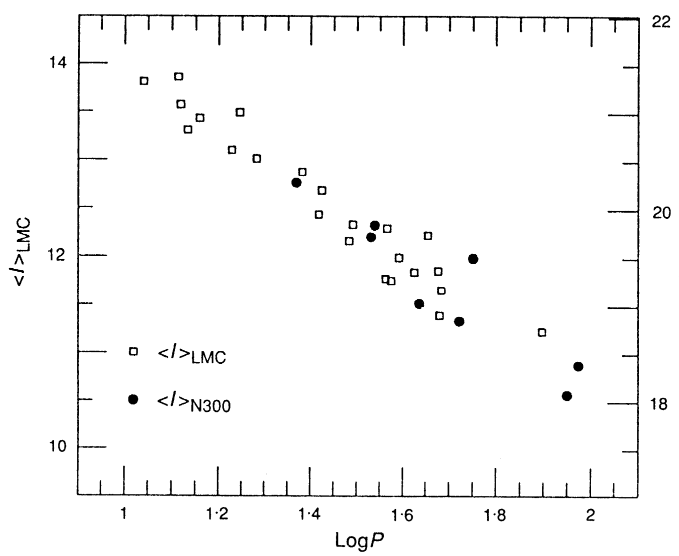

Fig. 3. The period–luminosity relationship in I (9000 Å) for Cepheids in the galaxy N 300 (plotted as solid points). The LMC data for Cepheids in the I band are also plotted (open squares) (see Visvanathan and Mackie 1990).

Fig. 2*c* is the PL relation for the galactic Cepheids. A slope of $-3\cdot0$ has been fitted to the points. The absolute calibration of the PL relation is $M(\mathrm{IV}) = -1\cdot94 -3\cdot0\log P$. It is to be pointed out that M(IV) is nearly equal to M(bol) as the bolometric correction in the IV wave band is small.

Eight Cepheids in NGC 300 have been observed in the I waveband using a CCD detector (Visvanathan and Mackie 1990) and the observed PL relation along with the LMC Cepheids data is given in Fig. 3.

RR Lyrae stars. These stars have been observed in nearby galaxies and distances derived using the zero point as $\langle M_V \rangle = 0\cdot6\pm0\cdot1$ (Feast and Walker 1987). The disadvantages of RR Lyr stars as distance indicators are that they are intrinsically much fainter than Cepheids and their luminosity is a function of metallicity. The distance moduli (DM) derived for the LMC, SMC and M 31 through RR Lyr stars are 18·5, 18·85 and 24·16 respectively (Walker 1985; Pritchet and van den Bergh 1987) and are in agreement with IR Cepheid distances.

Mira variables. These are also found to follow a PL relation. However, the applicability of Mira variables is restricted to the LMC whose DM is derived as 18·48 (Feast and Walker 1987).

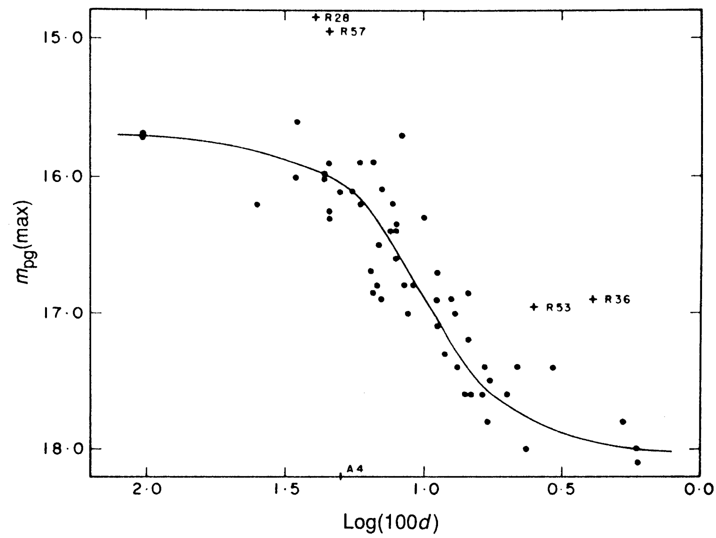

Fig. 4. Plot of m_{pg}(max) against decline rate d for M31 novae (solid points) (see van den Bergh 1986).

Novae. Novae exhibit a correlation between absolute magnitude M_B(max) and decline rate (van den Bergh 1986). However, the decline rate and M_B(max) are not well determined; hence the DM are uncertain. Fig. 4 shows the relation between m_{pg}(max) and decline rate for novae in M31.

Distance moduli to the LMC, SMC, M31, M33, N 6822, I 1613, N 300 and N 2403. The DM to the LMC, SMC, N 6822 and N 300 obtained by us using the IV PL relation for Cepheids, as well as those obtained by other observers to the LMC, SMC, M31, M33, N 6822, I 1613, N 300 and N 2403 using the IR

PL relation of Cepheids, are given in Table 1. The DM derived from different distance indicators for various galaxies are also compared in the same table.

Table 1. Distance moduli for nearby calibrating galaxies

References: 1. Visvanathan (1989); 2. Feast and Walker (1987); 3. McAlary *et al.* (1983); 4. McAlary *et al.* (1984); 5. Madore *et al.* (1985); 6. Freedman *et al.* (1985); 7. Welch *et al.* (1986); 8. Pritchet and van den Bergh (1987*a*); 9. Cohen (1985); 10. Freedman (1986); 11. McAlary and Madore (1984)

Name	$(m-M)_0$				References
	Cepheid	RR Lyr	Mira	Novae	
LMC	18·45; 18·47	18·42	18·48	18·99	1, 2
SMC	18·83; 18·78	18·80		18·90	1, 2
M31	24·3	24·16		24·03	7, 8, 9
M33	24·19; 24·07				5, 6
N 6822	23·32; 23·18				1, 3
I 1613	24·07				4
N 300	25·87; 25·90				1, 10
N 2403	27·9; 27·47				10, 11

The Cepheid distances obtained by different observers for the LMC, SMC and M31 agree well with one another and with those derived from other distance indicators. We believe that the derived IR Cepheid distances to the nearby galaxies are accurate to 0·1 mag and free from the systematic errors due to corrections for dust as well as metallicity variations, and hence they are the best available calibrators. One of the important goals in the coming years will be to derive IR Cephid distances for many more nearby galaxies.

(d) Distances to Galaxies beyond 7 Mpc

Global properties. Many global properties of galaxies have been proposed as secondary distance indicators:

(1) H II regions in spiral galaxies (Sandage and Tammann 1974; Kennicutt 1981);
(2) Peak of the luminosity function of globular clusters (van den Bergh *et al.* 1985);
(3) Luminosity classification of spiral galaxies (van den Bergh 1960);
(4) First ranked cluster galaxies (Sandage and Hardy 1973);
(5) Luminosity index as a derivative of the luminosity classification (de Vaucouleurs 1979*a*);
(6) CM relation of ellipticals (Visvanathan and Sandage 1977; Visvanathan 1986);
(7) TF relation (H I line width–luminosity relation) of spirals in optical and IR (Aaronson *et al.* 1979; Visvanathan 1981*a*);
(8) Velocity dispersion–luminosity relation of ellipticals (Faber and Jackson 1976);
(9) Supernovae Ia at maximum (Cadonau 1986).

The last five relations have been well studied and tested as regards the zero point of the relation, the intrinsic scatter and the applicability of the relation to large distances.

Luminosity index Λ. de Vaucouleurs (1979*b*) used the luminosity index, which is equal to 1/10th of the sum of the galaxy type plus its luminosity class, to determine distances to external galaxies. The luminosity index has been calibrated through primary distance indicators such as Cepheids, RR Lyrae stars, novae etc. The luminosity index–absolute luminosity relation derived for 309 galaxies is shown in Fig. 5.

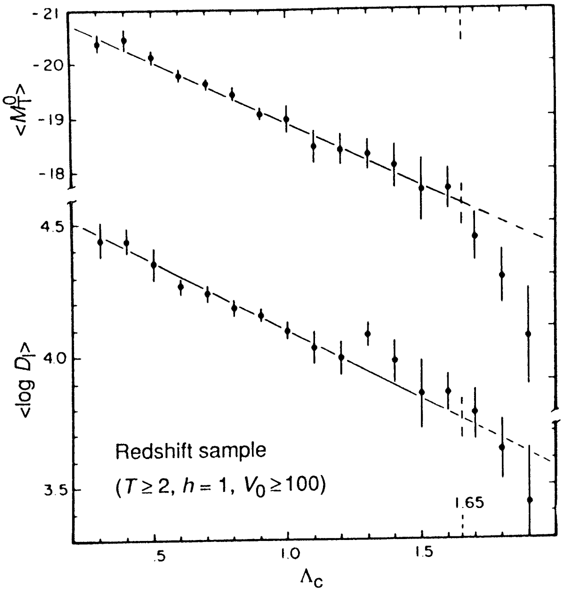

Fig. 5. Luminosity index Λ_c (de Vaucouleurs 1979*a*) plotted against the mean corrected absolute magnitudes $M_T{}^0$ and linear diameters D_l.

Colour-magnitude (CM) relation of E, S0 galaxies. The colours (u-V) and (V-IV) are found to be linearly correlated with the total luminosity of the galaxy for E, S0 galaxies and this relation is found to be universal (Visvanathan and Sandage 1977; Visvanathan 1990*b*). Fig. 6 is a plot of u-V (lower panel) and V-IV colour (upper panel), corrected for aperture, K effect and absorption in the Galaxy for Virgo E, S0 galaxies against log D_n (Dressler *et al.* 1987) which is a measure of the luminosity of the galaxy. The scatter in the relation is $\pm 0 \cdot 06$ in log D_n which corresponds to $0 \cdot 3$ mag. The CM relation of the E, S0 galaxies has been used to derive distances to 500 E, S0 galaxies (Sandage and Visvanathan 1978; Visvanathan 1979*a*).

Tully-Fisher (TF) relation. H I linewidths of spiral galaxies are found to be correlated with their total luminosity (Tully and Fisher 1977). Investigations of this relation in many wave bands ($1 \cdot 6$, $1 \cdot 06$, $0 \cdot 67$, $0 \cdot 55$ and $0 \cdot 45\,\mu$) show that the slope varies with wavelength and the intrinsic scatter in the relation is $\sim 0 \cdot 4$ mag in all wave bands (Aaronson *et al.* 1979; Visvanathan 1981*a*; Pierce and Tully 1988). However, as the corrections for the internal absorption for spirals, as well as the extinction in our Galaxy especially in low latitudes, are high and uncertain (Sandage and Tammann 1981*a*; Burstein and Heiles 1984), the distances derived from luminosities in the I to H wave band region are usually given higher weight. Fig. 7 shows plots of the relation in the V, r, IV and H wave bands of spirals in Virgo. The small intrinsic dispersion in the relation (~0·4 mag) allows the determination of good distances to galaxies.

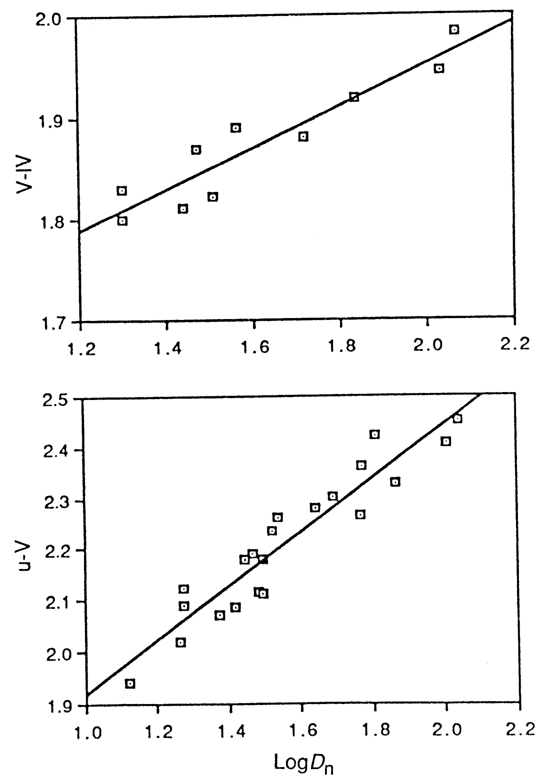

Fig. 6. CM relation of E, S0 galaxies: *lower panel*, colour (u-V) plotted against log D_n; *upper panel*, colour (V-IV) plotted against log D_n, where D_n is the diameter of the aperture in sec of arc within which the integrated surface brightness is 19·5 V mag per square arc second and is a measure of the magnitude of the galaxy (see Visvanathan 1990*b*).

Velocity dispersion–luminosity relation. Velocity dispersions of E galaxies are found to be well correlated with luminosity (Faber and Jackson 1976; Lynden Bell *et al.* 1988). This relation is found to be universal and the dispersion in the relation is ~0·4 mag (Dressler *et al.* 1987). Fig. 8 shows the log D_n–velocity dispersion for E,S0 galaxies in the Virgo and Coma clusters. Because of the high luminosity of E galaxies this relation can be used to derive distances to distant galaxies.

Supernovae. SN Ia at maximum brightness are found to have a small dispersion (~0·5 mag) in their absolute magnitudes (Tammann 1987). Fig. 9 shows the relation between the redshift and m_B(max). Once the absolute magnitude is known, the distances can be derived from these data. The present estimates of M_B vary from −20·5 to −19·2 (Tammann 1987).

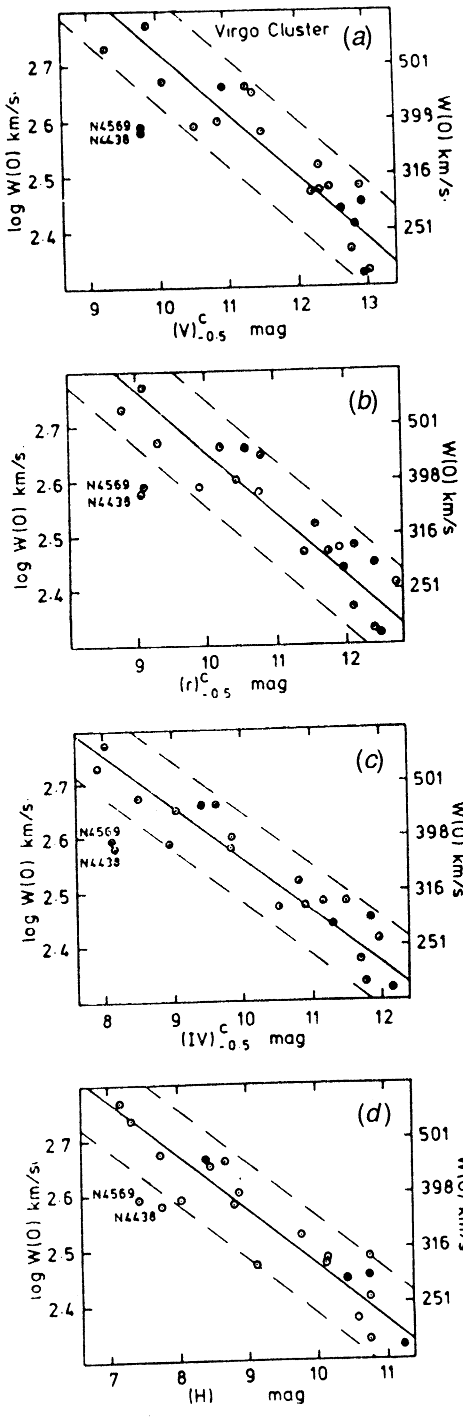

Fig. 7. TF relation for Virgo spirals: H I velocity width plotted against magnitudes at (*a*) V (5500 Å) (*b*) r (6738 Å) (*c*) IV (10600 Å) and (*d*) $1 \cdot 6\,\mu$ wave bands (see Visvanathan 1981).

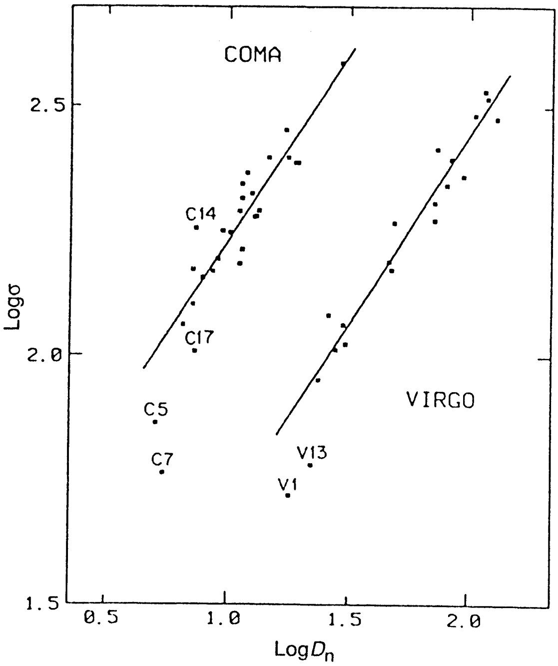

Fig. 8. Velocity dispersion (log σ) against log D_n plotted for the ellipticals in the Virgo and Coma clusters. Here D_n is the diameter of the aperture in sec of arc within which the integrated surface brightness is 20·75 B mag per square arc second and is a measure of the magnitude of the galaxy (see Dressler *et al.* 1987).

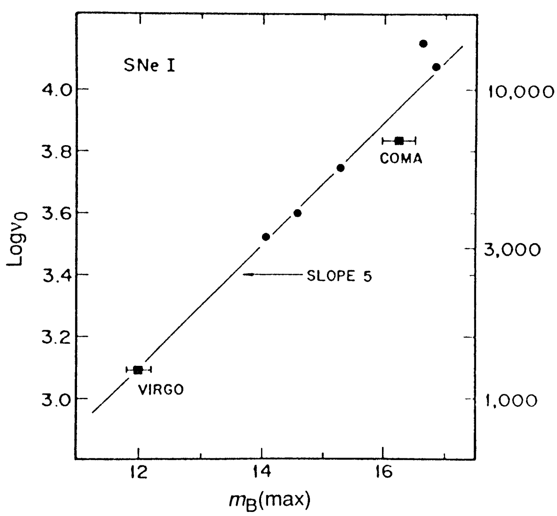

Fig. 9. The m_B(max) against redshift diagram of 11 SN Ia in E, S0 galaxies (see Sandage and Tammann 1985).

(e) Local Velocity Field

The observed redshift of galaxies contains not only the universal cosmological expansion component but also the peculiar motion component. The peculiar motion component has to be derived and subtracted from the observed redshift to compute the value of H. Two components of peculiar motion have been identified in the nearby region from the analysis of redshift–distance data of all-sky samples of galaxies extending beyond the Local Super Cluster (LSC).

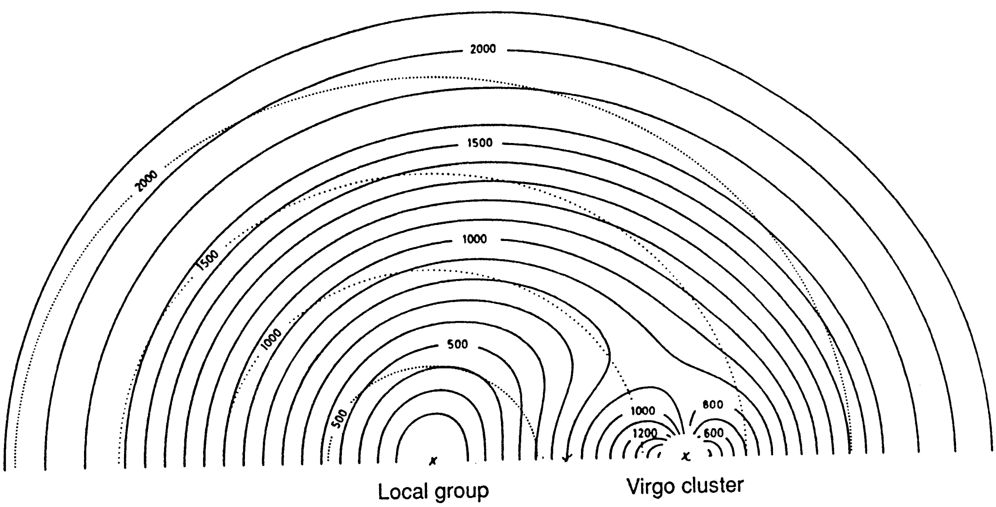

Fig. 10. Velocity contours as seen from the centroid of the Local Group in a plane containing the LG and the Virgo cluster. Lines of equal observed recession velocities (solid lines) are shown for an infall velocity of the LG towards Virgo of 220 km s^{-1} and for the unperturbed Hubble flow (dashed lines) (see Sandage and Tammann 1981*b*).

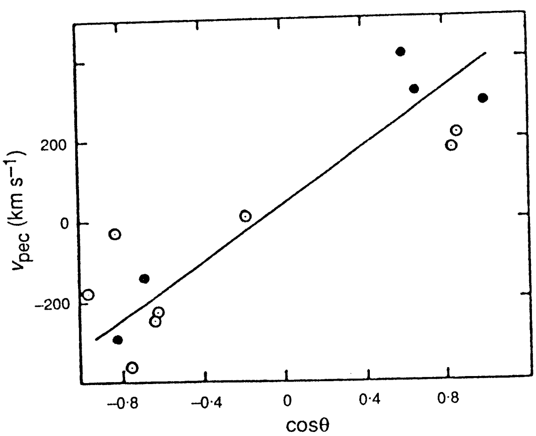

Fig. 11. The Local Group infall motion component exhibited by each distant cluster (v_{pec}) is plotted against cos θ where θ is the polar angle of the cluster from Virgo (see Visvanathan 1981*a*).

Virgo complex. One component is due to the Virgo complex which induces a velocity of ~220 km s^{-1} at the LG towards the Virgo cluster and decelerates the expansion of the galaxies within the LSC (Schechter 1980; Aaronson *et al.* 1982; Tammann and Sandage 1985). The values obtained for this component from a self-consistent flow model (Yahil 1985) of different field galaxy samples are 220±75 (Yahil 1980), 250±64 (Aaronson *et al.* 1982), 150±60 (Stavely-Smith and Davies 1989) and 200±50 km s^{-1} (Visvanathan 1986). It seems that a value of 220±50 km s^{-1} is quite acceptable for the infall at the LG. The resulting velocity contours in the Virgo complex as seen from the centroid of the LG are shown in Fig. 10. Visvanathan (1981*a*) found a value of 232±31 km s^{-1} for the infall velocity by mapping the peculiar motion component of nearby clusters and groups as a function of the polar angle of the cluster from Virgo (Fig. 11). This can be taken to support the infall value obtained from the Virgo flow models.

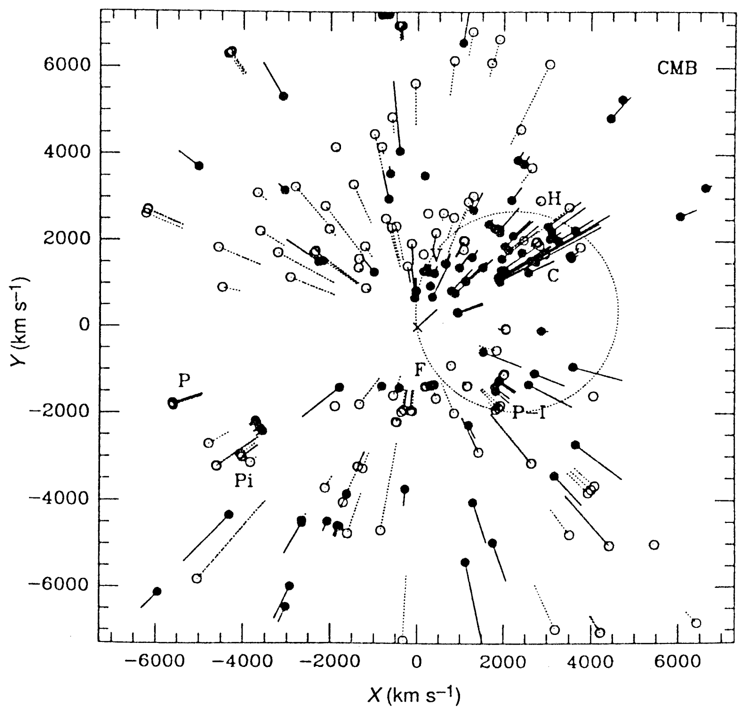

Fig. 12. Peculiar radial velocity vectors for galaxies within 45° of the supergalactic plane are plotted in the rest frame. Each galaxy is placed at its distance *R* and a line of length proportional to the peculiar velocity is drawn. Outward moving points are filled. The proposed Great Attractor would produce positive residuals within the sphere drawn (see Lynden-Bell *et al.* 1988).

Great Attractor. The second component has been identified by Lynden-Bell *et al.* (1988) from the velocity dispersion–redshift sample of E, S0 galaxies. They have proposed that the nearby ellipticals reveal a large-scale velocity flow relative to the microwave background towards the point $l = 307°$, $b = 9°$.

They have also identified a massive concentration of galaxies located at a distance of 4350 km s^{-1} towards that direction, inducing a velocity at the LG of 570 km s^{-1} (Fig. 12). This component is assumed to fall away from the mass concentration as r^{-1}. Though supported by Aaronson *et al.* (1989), it is to be emphasised that there remain major discrepancies with other work (Lucey and Carter 1988; Mathewson 1990, present issue p. 167) and with predictions based on the IRAS and optical distributions of galaxies (Lahav *et al.* 1988). More data extending to a larger velocity interval of ~8000 km s^{-1} are needed to understand this component completely as well as any other components in the region.

5. Derivation of Hubble Constant

(a) Cluster Approach

The clusters and groups (Hickson *et al.* 1989) are identified in the observed sample. As all the galaxies in a group can be assumed to be at the same distance, the distances of the members of the same group are averaged and a mean distance is assigned to each group. This method has the advantage of reducing the error in the distance of each group to the desired level (5–10%) by observing many galaxies in each group, even though the error in the distance of a single galaxy is ~0·4 mag.

Virgo cluster. This cluster, observable through a dust free region of our galaxy, is nearby, well studied (Binggeli *et al.* 1985) and contains all types of galaxies with sufficient range in luminosity. Hence it has been used to derive the behaviour of the properties of different distance indicators as a function of luminosity and as a platform from which distances to farther galaxies and clusters are obtained. This latter aspect makes it important to know the distance of this cluster accurately.

Table 2. Absolute calibration data

Name	M_B	M_V	M_{IV}	M_H	A_V	A_V^i	$(m-M)_0$
M31	−21·63	−22·12	−23·82	−23·56	0·48	0·79	24·30
M33	−19·14	−19·37	−21·05	−19·88	0·60	0·35	24·13
N 300	−18·18	−18·70	−20·15	—	0·12	0·29	25·93
N 2403	−19·55	−19·87	—	−21·37	0·18	0·35	27·69

The TF relation using luminosities from B to IR wave bands has been applied to Virgo spirals by many observers to derive a mean distance modulus (Mould *et al.* 1980; Visvanathan 1981*a*, 1983; Richter and Huchtmeir 1984). As these observers used different zero points for the calibration of the TF relation, we have corrected the results to the mean zero point for M31, M33, N 300 and N 2403 given in Table 1. The details of our calibration, the assumed absolute magnitudes in B, V, IV and H wave bands, the galactic absorption in V, the internal absorption in V and the DM are given in Table 2. The distance moduli for Virgo obtained from H, IV, V and B wave bands data are 31·03, 31·38, 31·22 and 31·5 respectively. The error in these measurements (±0·20) is decided mainly by the fact we have used only four calibrating galaxies and it agrees with the error (±0·22) obtained from the intercomparison of the four values of DM. The uncertainties in the measurements of DM originating from the errors in the slopes of the TF relation (Richter and Huchtmeir 1984), from the Malmquist bias in the selected sample of the cluster (Kraan-Kortweg *et al.* 1988) and from the inclusion of the infalling galaxies (Pierce and Tully 1988) seem to be of the same order as our error. Hence we need at least twelve more calibrating galaxies with IR Cepheid distances to improve the accuracy of the calibration to $\pm 0 \cdot 10$ mag, before we can study in detail these systematic errors in the measurements of DM.

Pritchet and van den Bergh (1987*b*) compared the data for six novae in Virgo with that of the novae in M31, and found a DM difference of $6 \cdot 8 \pm 0 \cdot 4$ which translates into a distance modulus of $31 \cdot 74 \pm 0 \cdot 4$ for the Virgo cluster. Visvanathan (1978) derived a distance modulus of $30 \cdot 96 \pm 0 \cdot 4$ to Virgo from a comparison of the (u-V) colour of the dwarf elliptical M32 with the CM relation of the Virgo cluster.

Distance modulus of Virgo and the value of H. The best value of the DM to Virgo is $31 \cdot 30 \pm 0 \cdot 20$ which is the mean value measured from the TF data at the four wave bands mentioned in the last section. If we adopt the systematic velocity of Virgo as 1151 ± 38 km s^{-1} (Huchra 1985) and the value for the Virgo infall velocity as 220 km s^{-1}, we derive a value for H of 75 ± 7 km s^{-1} Mpc^{-1}.

Distances to distant clusters. Distances extending up to a redshift of ~11000 km s^{-1} have been obtained through the CM relation for 22 clusters (Visvanathan 1986, 1989), through the velocity dispersion–luminosity relation for six clusters (Dressler *et al.* 1987) and through the TF relation in IR for 20 clusters (Aaronson *et al.* 1989). The mean values for H obtained are $72 \cdot 7 \pm 2$, $69 \cdot 0 \pm 3$ and $70 \cdot 7 \pm 2$ respectively. We have normalised all distance moduli to a Virgo DM of $31 \cdot 30$. It is gratifying to note that the values of H obtained by different observers agree with one another, indicating the absence of any large-scale errors in the distance measurements. Indeed the ΔDM of Coma cluster from Virgo obtained by different observers using various methods agrees with one another (Tammann 1987). There is sufficiently large scatter in the redshift–distance relations (197, 583, 457 km s^{-1}) of the aforementioned data, arising probably from the presence of unaccounted peculiar motions of individual clusters. It is interesting that the observed scatter (550 km s^{-1}) in the redshift–distance relation of SN Ia (Tammann 1987) is nearly the same as that observed in the case of distant clusters. The redshift–distance relation extending up to a redshift of 11000 km s^{-1} obtained by three groups is shown in Fig. 13.

The average value of H determined from Virgo and distant clusters by different observers comes out as 71 km s^{-1} Mpc^{-1}. Taking into account the error in calibration of our DM for Virgo we can set a generous error of 10 to this value of H.

(b) All-sky Sample

Many studies of the determination of H have been done with apparent magnitude limited samples of galaxies. Visvanathan (1990) analysed the redshifts and distances (obtained via the CM relation) for 405 galaxies (Sandage and Visvanathan 1978). After correcting the sample for Malmquist bias according to the precepts given by Lynden-Bell *et al.* (1988) and correcting the redshifts for the infall of the LG towards Virgo (220 km s^{-1}), a mean value of 68 km s^{-1} Mpc^{-1} has been derived for H. The plot of H versus the corrected redshift for the sample is given in Fig. 14.

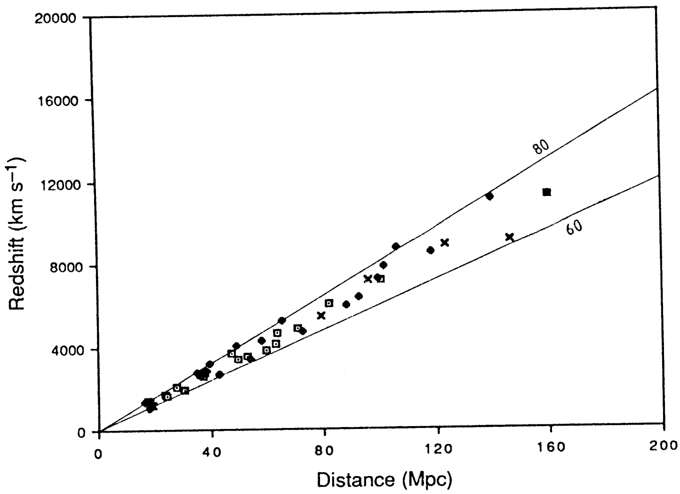

Fig. 13. Redshift–distance relation of groups and clusters. Distances of the clusters have been determined through the TF relation, CM relation and velocity dispersion–luminosity relation. Velocities have been corrected for infall of the LG towards Virgo. The two solid lines represent two values of H: 60 and 80 km s^{-1} Mpc^{-1}. Open squares are data from Visvanathan (1986); filled diamonds from Aaronson *et al.* (1989); and crosses from Dressler *et al.* (1987).

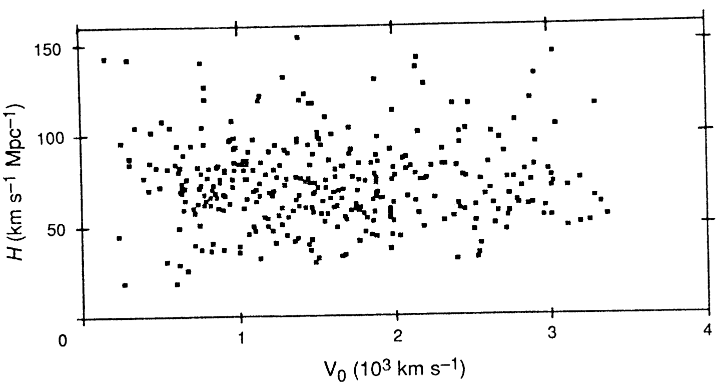

Fig. 14. The value for H for individual galaxies with known distances from the CM relation of E, S0 galaxies plotted against the velocity corrected for infall. The best estimate for the value of H is 70 km s^{-1} Mpc^{-1}. The data sample is E, S0 galaxies from Sandage and Visvanathan (1978).

Tammann (1987) has reanalysed redshifts and distances (obtained via the TF relation in IR) for 308 field spirals in an all-sky sample of Aaronson *et al.* (1982). A mean value of 79 km s^{-1} Mpc^{-1} for H has been obtained (Fig. 15, upper panel) after taking into account the Malmquist bias in the sample.

Redshift–luminosity index data of de Vaucouleurs (1979*a*) for 309 non-Local Group galaxies have been reanalysed by Tammann (1987). A bias has been identified and a value of 68 km s^{-1} Mpc^{-1} for H has been derived (Fig. 15, lower panel). Bottinelli *et al.* (1988) have also reanalysed these data and found H roughly in agreement with that obtained by Tammann (1987).

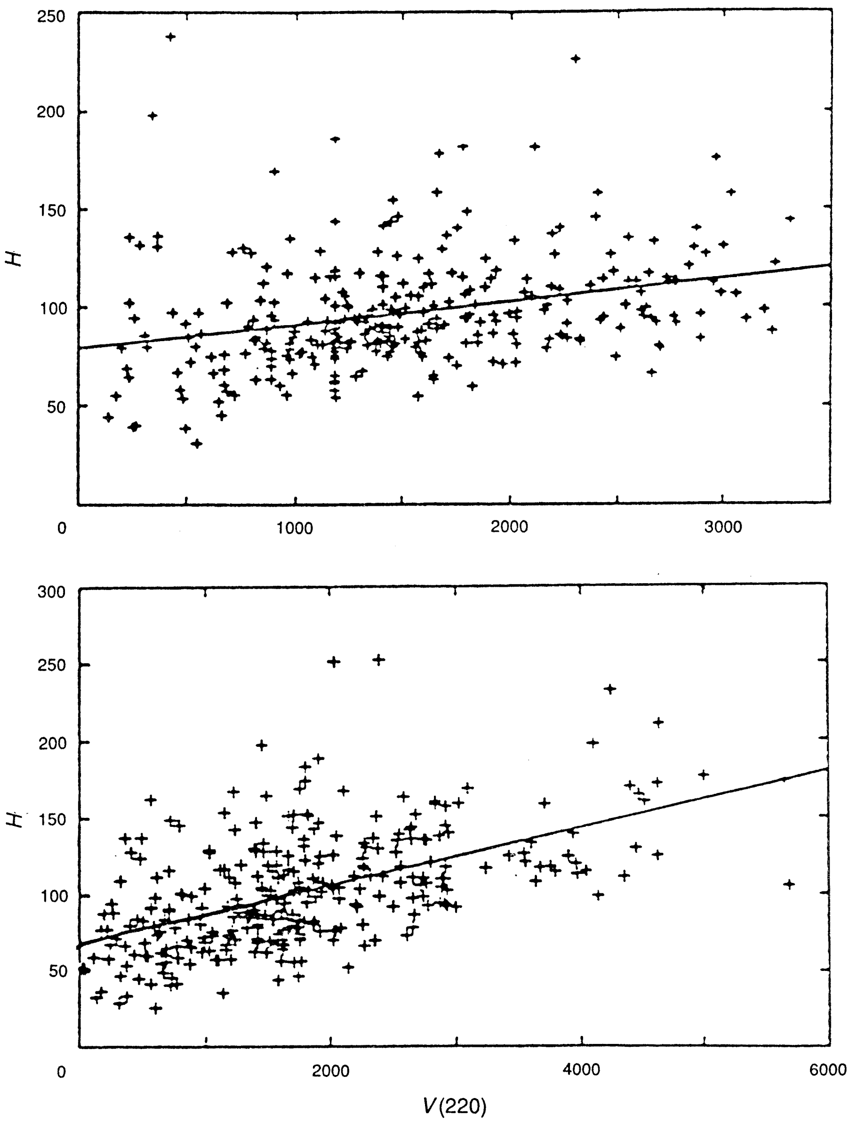

Fig. 15. *Lower panel*: The value of H for individual galaxies with published values of luminosity index distances (de Vaucouleurs 1979*a*) plotted against the velocity corrected for infall of the LG towards Virgo (Tammann 1987). The value of H increases with distance indicated by the line fitted to the points, due to Malmquist bias in the data. The best estimate of the value of H is 68 km s^{-1} Mpc^{-1}. *Upper panel*: The value of H for individual galaxies with known distances from IR-H magnitudes and HI widths from the Aaronson *et al.* (1982) data sample. The increase in the value of H is also seen in these data. The best value of H is estimated to be 78·8 km s^{-1} Mpc^{-1}.

The all-sky magnitude limited samples give a value of H of 72±8 km s^{-1} Mpc^{-1}.

6. Global Hubble Constant

The redshift–distance data of the clusters which reach out to $v = 5000$–10000 km s^{-1}, as well as the magnitude limited samples involving various methods of determining distances, give a value of 73 for H consistently. Hence the best value of the global Hubble constant H_0 is 73±10 km s^{-1} Mpc^{-1} and leads to an age of the universe of 14 billion years (assuming $\Lambda = 0$ and $q_0 = 0$).

Though the value of the global Hubble constant did not change dramatically in 1980s, the measurements of accurate IR distances to nearby galaxies have opened the way to improve the zero point of the distance scale. The large errors in the distance measurements of distant galaxies have remained the major source of the uncertainties in determining H. Also, the discovery of a nonuniform distribution of galaxies and large peculiar motions in the local regions have further complicated the determination of the expansion redshift of the galaxies accurately and hence a value for the global Hubble constant.

We believe that accurate IR Cepheid DM are needed for more nearby galaxies so that the error in the zero point of the absolute calibration of the TF relation for spirals can be reduced and the DM of the Virgo cluster can be decided accurately. We need data for at least sixteen nearby spirals to reduce the error to ~0·1 mag. A list of possible candidates for future work is given in Aaronson and Mould (1986).

The peculiar velocity component in the local region should be mapped better. It is true that the deceleration of the local Hubble flow within the LSC has been understood; the evidence is growing that the Centaurus–Hydra supercluster produces sizeable peculiar velocities in the galaxies of the local region. However, the effect of other mass concentrations like the Perseus and Coma superclusters and large voids like that in Sagittarius (Lahav *et al.* 1988) on the local velocity field are yet to be studied. A possible upper limit to the peculiar velocities in the local region derived from the dispersion in the velocity–distance diagram of supernovae is 550 km s^{-1} (Tammann 1987).

We need all-sky velocity–distance data for field samples with limiting magnitude to fainter values and for clusters sampled by a fixed magnitude interval at large distances. A complete mapping of the velocity field around the Coma cluster will help us greatly in understanding the behaviour of peculiar velocities around a large cluster. Here, the CM and log σ versus L relations for E, S0 galaxies and the TF relation for spirals are the promising distance indicators.

The supernovae which are intrinsically bright will give us distances to distant galaxies and clusters independently once we know the calibration accurately. At present the estimate of M_B(max) varies from −19·2 to −20·2 mag (Tammann 1987). Observations of Cepheids in the galaxies of the Virgo cluster with the Hubble Space Telescope will provide an estimate of the DM to Virgo directly without going through the TF relation.

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