THE HUBBLE PARAMETER - A STATUS REPORT AT EPOCH 1994.5

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ABSTRACT. New observations obtained during the last two years have slightly shifted the balance of evidence towards larger values of H_0. A compilation of recent determinations shows reasonable agreement and suggests that $H_0 \geq 75$ km s^{-1} Mpc^{-1}.

1. Introduction

The Hubble parameter H_0 is usually expressed in units of km s^{-1} Mpc^{-1}, i.e. it has a dimension $(time)^{-1}$. If $H_0 \geq 1000$ km s^{-1} Mpc^{-1} then $t_H \leq 1$ Gyr. This would not allow enough time to form galaxies, stars, planets and the carbon that is required for all known forms of life. On the other hand for $H_0 \leq 10$ km s^{-1} Mpc^{-1}, corresponding to $t_H \geq 100$ Gyr, almost all gas in galaxies will have been used up long ago to form stars - most of which would by now have exhausted their fuel supply and become white dwarfs. As a result few sites that are congenial to life as we know it would remain in the Universe. Such *a priori* arguments suggest that $10 \leq H_0$ (km s^{-1} Mpc^{-1}) $\leq$ 1000. A compilation of H_0 values by Okamura & Fukugita (1991) shows that the overwhelming majority of recent determinations of H_0 fall in the narrower range $50 \leq H_0$ (km s^{-1} Mpc^{-1}) ≤ 100.

Turner, Cen & Ostriker (1992) have suggested that H_0(local) might differ significantly from H_0(global). Using first-ranked galaxies in rich clusters van den Bergh (1992) concluded that H_0(global) = (0.94 ± 0.07) H_0(local), in which H_0(local) refers to the region with V < 10000 km s^{--1}. By applying the same technique to a full-sky sample of Abell clusters Lauer & Postman (1992) find that H_0 is globally constant to ± 7% for the region of space with V < 15000 km s^{-1}. Due to local streaming velocities of a few hundred km s^{-1} it is, however, necessary to derive "cosmological" redshifts of local clusters such as Virgo and Fornax, from the Coma redshift and the distance ratio D(Coma)/D(cluster).

2. Meter Sticks and Standard Candles

2.1 GLOBULAR CLUSTERS

Shapley (1953) first pointed out that the mean luminosity of globular clusters might turn out to be a good "standard candle". This conclusion appears to be supported by modern observations of globulars in the Galaxy, M31 and the Large Cloud. It has, however, not yet been proven beyond reasonable doubt that the mean luminosity of globular clusters around distant giant E galaxies is identical to that of the globular cluster systems surrounding spiral galaxies such as M31 and the Milky Way System.

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Recently Sandage & Tammann (1994) have compared Virgo globulars with local ones to obtain $H_o = 55 \pm 5$ km s^{-1} Mpc^{-1}. *Using the same technique* van den Bergh (1994b) finds $H_o \geq 73$ km s^{-1} Mpc^{-1}. Reasons for this difference are the following: (1) Sandage & Tammann used the rather bright luminosity calibration of RR Lyrae stars adopted by Sandage (1993), which results in a high luminosity for Galactic globular clusters. On the other had van den Bergh adopts a more conservative value $M_V(RR) = +0.6$. Even fainter luminosities for Galactic RR Lyrae stars have been derived by Storm, Carney & Jones (1994), who use the Baade-Wesselink technique to obtain $M_V(RR) \approx +0.8$. Such faint RR Lyrae magnitudes appear to be supported by Hubble Space Telescope color-magnitude diagrams of two globulars in M31 (Ajhar et al. 1994). However, the issue will remain clouded until it is understood (Walker 1992) why $M_V(RR) = +0.44$ (at [Fe/H] = -1.9) in the Large Cloud. Furthermore (2) Sandage & Tammann (1994) adopt a small cosmic velocity [V(cosmic) = 1179 ± 17 (sic) km s^{-1} Mpc^{-1}] for the Virgo cluster, whereas van den Bergh (1994b) derives a larger value V(cosmic) = 1311 ± 132 km s^{-1} Mpc^{-1} from the Coma velocity and the Coma/Virgo distance ratio. Finally (3) new observations by Fleming (1994) suggest that the peak of the M87 globular cluster luminosity function is 0.2 mag brighter than the value previously obtained by Harris *et al.* (1991). It is not yet known (Harris 1994) whether a similar correction also applies to the globular cluster systems surrounding other Virgo giant E galaxies. All three of the effects discussed above will tend to *increase* the value of H_o derived from globular clusters.

2.2 GALAXY DIAMETERS

Sandage (1993a) has derived a value $H_o = 43 \pm 11$ km s^{-1} Mpc^{-1} from a comparison of the diameter of M101 with the diameters of other, more distant, galaxies of DDO type Sc I. However, intercomparison of the Sc I galaxies NGC 309 and M100 (van den Bergh 1992) shows that Sc I galaxies have a range of 2 - 3 in their diameters, i.e. they are not good standard "meter sticks". Similarly Sandage (1993b) compares M31 to other Sc I galaxies at larger redshifts to obtain $H_o = 45 \pm 12$ km s^{-1} Mpc^{-1}. However, van den Bergh (1994a) finds $H_o \sim 76$ km s^{-1} Mpc^{-1} by comparing M31 with similar objects in the Virgo cluster. A comparison of M33 with Sc II-III galaxies in Virgo yields $H_o \sim 124$ km s^{-1} Mpc^{-1}. From the examples cited above it is concluded that the dispersion of diameters of spirals of any given luminosity class is too large for galaxy diameters to be useful tools for precision distance determinations.

2.3 SUPERNOVAE OF TYPE Ia

In a recent review Branch & Tammann (1992) conclude that the intrinsic scatter in M_B(max) for supernovae of Type Ia (SNe Ia) is less than 0.25 mag. This would make such objects excellent standard candles. Just after their paper was submitted SN 1991bg, which was subluminous by 2.5 mag in B, exploded in the Virgo elliptical M84. Furthermore the Type Ia supernova 1991T was found to probably be of above-average luminosity. More recently Branch, Fisher & Nugent (1993) and Branch et al. (1994) have found that SNe Ia with strongly deviant luminosities are spectroscopically abnormal and can therefore be weeded out. However, Maza et al. (1993) find that the supernovae 1992bc and 1992bo, which were both spectroscopically normal, differed in luminosity by 0.8 ± 0.2 mag. The use of SNe Ia as standard candles is also suspect because recent high quality spectra obtained at Lick (Lynch et al. 1992) and at Cerro Tololo (Phillips 1993a) reveal a range of lightcurve and spectroscopic characteristics that had not previously been appreciated. An additional problem (Branch & van den Bergh 1993) is that the expansion velocities of SNe Ia in galaxies that have experienced recent star formation appear, on average, to be higher than those of SNe Ia in galaxies with an old stellar population.

Phillips (1993b) has suggested that M_V(max) and the rate of decline of supernovae are correlated. However, observations of SN 1992bc (Hamuy et al. 1994) and of S Andromedae (van den Bergh 1994a) indicate that the dispersion around Phillips' luminosity versus rate of decline relation may be large. Finally Phillips (1993c) also finds evidence which suggests that the Si II $\lambda5979/\lambda6355$ intensity ratio near maximum may be closely correlated with luminosity. If this suspicion is supported by future observations, then SNe Ia might yet fulfil their promise as standard candles that could be used to calibrate the extragalactic distance scale.

2.4 SUPERNOVAE OF TYPE II

Recently Schmidt (1993) has used the expanding photosphere (Baade-Wesselink) method, in conjunction with detailed model atmosphere calculations, to determine distances to individual supernovae of Type II (SNe II). For the two most distant objects in their sample (SN 1990ae, cz=7800 km s^{-1} and SN 1992am, cz = 14500 km s^{-1}), for which the effects of deviations from a smooth Hubble flow should be small, Schmidt (1994) and Schmidt et al. (1994) obtain D = 115 Mpc and D = 180 Mpc, respectively. The corresponding values of the Hubble parameter are H_o = 68 km s^{-1} Mpc^{-1} and H_o = 81 km s^{-1} Mpc^{-1}. The good agreement between distances derived to individual SNe II, and the Tully-Fisher distances to their parent galaxies, indicates that expanding photosphere distance determinations have probably not been significantly affected by deviations from spherical symmetry in expanding supernova envelopes.

2.5 THE TULLY-FISHER RELATION

Recent applications of the Tully-Fisher relation (e.g. Pierce & Tully 1988) to spiral galaxies generally yield relatively large values of H_o. The fact that the dispersion in the luminosity-line width relation is small for linewidths $\geq$ 200 km s^{-1} suggests that the effects of Malmquist bias ($\Delta M = 1.38\ \sigma_M^2$) on determinations of H_o from giant and supergiant spirals are probably small. From studies of galaxies in two volume elements, one in the direction of (but beyond) the Virgo cluster, and another in the opposite direction Lu, Salpeter & Hoffman (1994) find H_o = 84 ± 8 km s^{-1} Mpc^{-1}. This value includes a small correction for Malmquist bias and is, to first order, independent of the adopted infall velocity (retardation) of the Local Group into the Virgo cluster.

2.6 SURFACE BRIGHTNESS FLUCTUATIONS

Tonry & Schneider (1988) have shown that surface brightness fluctuations in galaxies containing old stellar populations can be used to determine the distances to such objects. Using this technique Jacoby et al. (1992) derive a distance modulus $(m-M)_o$ = 30.88 ± 0.2 for the elliptical-rich core of the Virgo cluster, from which H_o = 87 ± 12 km s^{-1} Mpc^{-1}. Since different early-type galaxies may have experienced differing evolutionary histories the brightest stars in different old galaxies might not all have exactly the same luminosities. This may account for the fact that Lorentz et al. (1993) find a small range in Virgo distance moduli for individual galaxies. These distance moduli appear to correlate with the Mg_2 indices observed for individual objects.

2.7 PLANETARY NEBULAE

The luminosity function of planetary nebulae appears to have the same shape in all galaxies in which it has so far been studied. Planetary nebulae therefore provide a powerful tool (see Jacoby et al. 1992 for a review and references) for the determination of extragalactic distances. Possible problems with the use of planetaries as distance indicators have recently been reviewed by Tammann (1993). It is, however, encouraging that McMillan, Ciardullo & Jacoby (1993) find no evidence for a correlation between galaxy luminosity (and hence metallicity) and the *differences* between Fisher-Tully distances to objects in four clusters of galaxies and the distances to these same galaxies derived from the luminosity functions of planetary nebulae. Jacoby, Ciardullo & Ford (1990) find $82 \leq H_0$ (km s^{-1} Mpc^{-1}) ≤ 94 from observations of planetary nebulae in Virgo galaxies. A somewhat smaller value $H_0 = 75 \pm 8$ km s^{-1} Mpc^{-1} has been obtained by McMillan, Ciardullo & Jacoby (1993) from observations of planetary nebulae in the Fornax cluster.

Table 1. Recent Determination of the Hubble Parameter.

Method	H_0 (km s^{-1} Mpc^{-1})
SNe Ia	75 (± 12?)
SNe II	68 - 81
Tully-Fisher	84 ± 8
Surface brightness fluctuations	87 ± 12[a]
Planetary nebulae (Virgo)	86 ± 18[a]
Planetary nebulae (Fornax)	75 ± 8
Galaxy diameters	76 - 124
Globular clusters (Virgo)	$\gtrsim 73$[b]
Surface brightness profiles (Fornax)	99 ± 16
Gravitational lens	< 87
Sunyaev-Zel'dovich effect	~ 55 ± 17
Compact radio sources	~ 100

[a] A 10% uncertainty in the cosmological distance of the Virgo Cluster has been added in quadrature.

[b] Reduction of the mean luminosity of Virgo globulars (Fleming 1994) would increase the value of H_0.

3. Summary and conclusions

A compilation of recent determinations of the Hubble parameter is given in Table 1. In view of the difficulty of extragalactic distance determinations the agreement between the individual values of H_0 listed in this table is encouraging. Taken at face value these data appear to indicate that H_0

≥ 75 km s^{-1} Mpc^{-1}. Successful observations of Cepheid variables in Virgo spirals with the Hubble Space Telescope would greatly add to our confidence in the reliability of the extragalactic distance scale. However, such observations will probably not prove to be a panacea. This is so because (1) the cosmological redshift of the Virgo cluster remains uncertain at the ~10% level, and (2) the zero point (and possibly the metallicity dependence) of the Cepheid period-luminosity relation remains uncertain. Observations with Hipparcos should, however, reduce such uncertainties in the not too distant future.

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