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The Hubble constant

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Abstract. In this talk the history of Hubble's constant is reviewed from the discovery of the velocity-distance relation to the present day measurements with the Hubble Space Telescope. The problems encountered in fixing the true value of Hubble's constant are briefly discussed. The implications of the present measured values of this constant for cosmology, in particular for the hot big bang models, are discussed.

1. Hubble's law

In 1929 Edwin Hubble (Hubble 1929) announced a result that has subsequently become well known as *Hubble's Law.* The result described the relationship between the radial velocity V and D of extragalactic nebulae, which can be written in the form:

$$V = HD,$$

H being a constant, now called the *Hubble's constant.*

In the actual observations, the astronomer measures the redshift z and the apparent magnitude of a typical galaxy and infers the radial velocity from the Doppler effect and the distance from the inverse square law of illumination. During 1929-36 Hubble and Milton Humason carried out several such measurements. Their estimates of the constant H were around the value 530 km/s/Mpc.

How does this value compare with the present value of Hubble's constant? To give the answer in a proper perspective we may review a few historical landmarks in the measurement process.

2. A historical flashback

First we must recognize that two (possibly major) corrections have to be made to any raw data of redshifts and apparent magnitudes. Redshifts measure the relative radial motion between the source and the observer. The Earth has motion round the Sun, the Sun goes round the galactic centre, the Galaxy moves within the Local Group, the Local Group may have an infall velocity towards the centre of the Virgo cluster .... We still do not know where this series of relative motion ends; much less did the astronomers in Hubble's time and in the subsequent years know about these corrections. For, Hubble's constant is concerned with velocity in the cosmological rest frame. The second correction also has several uncertainties. To get distance from apparent magnitude, the astronomer needs to know the absolute magnitude of the source galaxy, the extent of possible absorption of radiation enroute and the spectrum of the source. In the absence of actual information, the assumption is made that the source observed is similar to a known source near us. This assumption is also prone to biases and errors.

On the latter count, in the 1940s came the realization that Hubble may have used the wrong standard candle for his data reductions. He was observing what he thought were Cepheid variable stars in other nearby galaxies. These stars have a definite known relationship between their pulsating period and median absolute magnitude. Thus by observing the period, the absolute magnitude of the Cepheid can be estimated. Then knowing its apparent magnitude one can estimate its distance and hence the distance of the galaxy it is located in. Hubble, however, mistook another class of variable stars called the *RR Lyrae* stars for the Cepheids. This led to a gross under-estimation of the distance of the galaxy and hence to an over-estimate of H.

It was Hubble's student Allan Sandage who during 1956-58 applied the distance correction in a realistic way and came up with a Hubble constant of 98 km/s/Mpc with about 15% quoted error. Sandage found that Hubble had made another error in his distance estimates. What Hubble had considered as single stars were in fact *H II* regions illuminated by several stars. In his Warner lecture Sandage stressed the need for accurate distance scale for extragalactic objects and expected that the way the possible systematic errors may be operating, the value of H may be as low as 75 km/s/Mpc.

As methods improved in extragalactic astronomy, the Hubble constant also steadily came down. In 1974 Sandage and Gustav Tammann obtained a value of 57 km/s/Mps with an error σ = 6km/s/Mpc. During 1975-95 they carried out several observations and have stabilized the value between 50-60 km/s/Mpc.

But the story does not end here! Other observers who have also been measuring Hubble's constant keep getting higher values. Till recently, the late Professor G. de Vaucouleurs was championing a high value of H, in the range 80-100 km/s/Mpc. It is sufficient that in the sixties when Sandage's estimate was close to this value, de Vaucouleurs was finding almost twice that value! This means that both groups have been reducing the value of H while keeping their ratio constant, thus indicating that perhaps both have been reducing their systematic errors while differing on some issues of calibration.

In 1992, a review by S.van den Bergh suggested a middle way, with the value of H = 76 km/s/Mpc with σ = 9 km/s/Mpc.

3. Methods of measurement

I will not have time to go through all the different methods of measurement of H : see Narlikar (1993) for details. The methods use a distance-ladder with calibration proceeding from our immediate neighbours in the Local Group (LG) like the Large Magellanic Clouds, followed by others in the LG, followed by galaxies in nearby clusters and then going up to distances of 10-20 Mpc. A few general comments may be made.

The observers who get the low values of H use the methods based on Type Ia Supernova models for the most distant sample, Cepheids for intermediate distances coupled with Cepheids in the LMC.

Those who get the high values start with the Cepheids in the LMC and nearby galaxies, followed by luminosity function of planetary nebulae, followed by surface brightness fluctuations, then Tully Fisher relation, then Type II Supernovae expanding photosphere method or the Type la Supernovae method.

A comparatively recent realization of a possible source of error has come from the large scale motions over and above the Hubble flow (Narlikar 1993). Thus we cannot confidently assert that we are observing the Hubble flow till we go to distances larger than 20 Mpc, or so. Till then the situation is confused by these peculiar motions. Since the accurate measurements of the cosmic microwave background, there is a standard cosmological rest frame (i.e., the frame in which the MBR shows no dipole anisotropy) available. This allows us to assess the extent of large scale non-Hubble flows in our local neighbourhood.

4. Distance to the Virgo cluster centre

In 1994 two independent determinations of distances of galaxies, in the direction of the centre of the Virgo cluster, were made. Pierce *et al.* used the ground based Canada-France Hawaiian telescope while the other of Wendy Freedman *et al.* (Freedman 1994) used the Hubble Space Telescope. The two groups obtained values on the high side: 87 ($\sigma = 7$) and 80 ($\sigma = 17$) km/s/Mpc.

The *HST* result which looked directly at Cepheids in the galaxy M 100 near the centre of the Virgo cluster is particularly impressive as Cepheids could not be seen at such distances by the ground based telescopes. To avoid getting mixed up with the peculiar motions both groups calibrated via the more distant Coma cluster. The Freedman *et al.* distance of M 100 is 17.1 ($\sigma = 1.8$) Mpc. By way of comparison Sandage and Tammann find the distance to the centre of mass of the Virgo cluster to be 21 Mpc.

Table 1 gives a summary of the various distance measurements.

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Table 1. Estimates of the distance to the Virgo cluster.

Method		Distance	
	Sandage (1995)	van den Berg (1992)	Jacoby *et al.* (1992)
Globular clusters	21.1 ± 2	19.7 ± 2.3	18.8 ± 3.8
Novae	20.6 ± 4	18.2 ± 2.5	21.1 ± 3.9
Supernovae	21.2 ± 2.2	19.1 ± 6	19.4 ± 5
		22.9 ± 5	–
$D_n - \sigma$	23.4 ± 2	–	16.8 ± 2.4
21 cm line widths	20.9 ± 1.4	15.0 ± 1.4	15.8 ± 1.5
Size of the Galaxy	20.0 ± 1.8	–	–
Size of M31	–	17.0 ± 4	–
Size of M33	–	10.5 ± 2.5	–
Size of LMC	–	12.0 ± 2.5	–
Surface Brightness Fluctuations	–	14.9 ± 0.9	15.9 ± 0.9
Planetary Nebulae	–	14.1 ± 0.3	15.4 ± 1.1
Red Supergiants in NGC 4571	–	13.8	–
Red Supergiants in NGC 4523	–	13.2	–

5. Implications for standard cosmology

The values of Hubble's constant given above range generally from 50 to 80 km/s/Mpc. The reciprocal of H gives a time scale that is intimately related to an important result of standard cosmology, viz. the age of the big bang universe. In general we can write the age of the universe as

$$
\begin{aligned}
T &= H^{-1}\, f(\Omega, 1) \\
&= 9.8^{-1}\, h\, f(\Omega, 1) . 10^{9} \text{ years}
\end{aligned}
$$

where we have expressed the Hubble constant as 100km/s/Mpc. The parameters Ω and λ are respectively the density parameter and the cosmological constant; f is model dependent.

For the most popular big bang model which has zero cosmological constant λ and unit density parameter, the function f has value 2/3. Thus the age of the universe lies between 8.3 (for $h = 0.8$) and 13.2 (for $f = 0.5$) billion years. How does this age compare with ages of globular clusters or the age estimates of our Galaxy based on nuclear cosmochronology? These are in the range 12-18 and 13-20 billion years respectively. Thus only with the lowest value of H in the observed range and with the lowest value of the astrophysical ages given above can we manage consistency.

Clearly with the HST estimates of the Hubble constant this model will be ruled out. This possibility has led to the revival of interest in the cosmological constant. With λ positive and suitably chosen, we can raise the theoretical age of the universe. But there are other constraints also, from primordial nucleosynthesis, gravitational lensing, the measurements of deceleration of the expansion, the abundance of clusters, the numbers of high redshift object etc. which put constraints on how large λ can be. In a recent study of all such constraints Bagla, *et al.* (1996) have concluded that the parameter window is shrinking fast under these restrictions and something like a crisis situation is approaching for standard cosmology.

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