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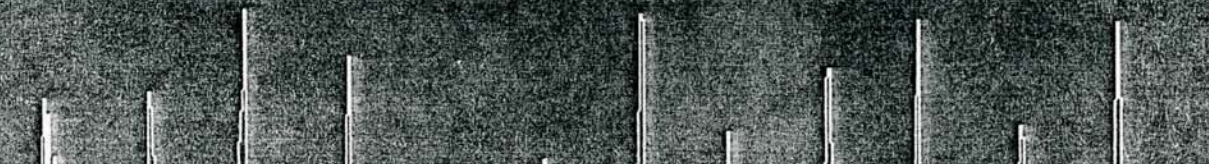

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Distance Scale of the Universe and its Implications for Cosmology

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Abstract

The cosmological distance scale is set by the Hubble's constant. Ever since the enunciation of the velocity distance relation by Edwin Hubble in 1929, observers have attempted the measurement of this constant. Naively speaking, the velocity of an external galaxy is determined by its redshift and its distance by its apparent faintness. In reality the measurements of these quantities are beset with many difficulties and uncertainties. This talk will begin with a review of the current status of these measurements against the backdrop of previous attempts.

The Hubble constant is used for estimating the time elapsed since the big bang, i.e., the so-called age of the universe. The age depends on the specific model chosen. The second part of the talk will discuss this age-model relationship.

How does this age compare with ages of some important components of the universe? Examples will be given from nuclear astrophysics to compare these ages with the age of the universe. The implications of such a comparison for the standard big bang cosmology will be discussed.

1. Hubble's law

In 1929 Edwin Hubble [1] announced a result that has subsequently become well known as *Hubble's Law.* The result described the relationship between the radial velocity V and distance 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 get the answer in 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 motions 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 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/Mpc with an error $\sigma = 6$km/s/Mpc. During 1975-95 they carried out several observations and have stabilized the value between 50-60 km/s/Mpc. For a review see Sandage's lectures in 1995 [2].

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 the high value of H, in the range 80-100 km/s/Mpc. It is significant that in the sixties when Sandage 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 [3] suggested a middle way, with the value of $H = 76$ km/s/Mpc with $\sigma = 9$km/s/Mpc. A recent review of several methods by Jocoby et al. [4] is also of interest. They find values of H in the range 80 ± 11 or 73 ± 11 km/s/Mpc depending on weights given to different results. See Table 1 for a listing.

3. Methods of measurement

I will not have time to go through all the different methods of measurement of H: see Ref [5] for details. the methods use a distance-ladder with calibration proceeding from our immediate neighbours in the Local Group 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 Ia Supernovae method.

TABLE 1

Estimates of the distance to the Virgo Cluster

Method	Distance		
	Sandage	van den Berg	Jacoby et al.
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 22.9 ± 5	19.4 ± 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	-

A comparatively recent realization of a possible source of error has come from the large scale motions over and above the Hubble flow (see Ref [5]). 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 and other galaxies

In 1994 two independent determinations were made of distances of galaxies in the direction of the centre of the Virgo cluster. One group [6] of Michael J. Pierce et al used the ground based Canada-France Hawaiian telescope while the other of Wendy Freedman et al [7] used the Hubble Space Telescope. The two groups obtained values on the high side: 87 (σ=7) and 80 (σ=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 (σ=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 (see [8]). We list there three columns representing three sets of measurements. The range of values is representative of the divergence of opinion that has existed over the last few decades.

However, it is perhaps a significant development that the more recent measurements of Hubble's constant show a tendency to converge to a relatively compact (if not a very narrow) interval. For a summary of such measurements see Ref.[9]. The key project of the *HST*, which began with the above measurement of M 100, [7] has now yielded more distances including that of NGC 1365 in the Fornax cluster. These measurements lead to H in the range 68 to 77 kms^{-1} Mpc^{-1}. On the other side a group headed by Sandage has yielded $H = 55$ to 61 kms^{-1} Mpc^{-1}, using the Type Ia Supernovae.

Other methods have also been refined. Thus, using the surface brightness fluctuation method, the planetary nebula luminosity function, the Tully-Fisher relation and supernova photosphere method yield H in the range 65 to 82 kms^{-1} Mpc^{-1}. Most are consistent with the primary Cepheid distances for nearby objects. Thus, the systematic errors are either being eliminated or narrowed down.

5. Implications for standard cosmology

The values of Hubble's constant given above range generally from about 60 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

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

where we have expressed the Hubble constant as $100h$km/s/Mpc. The parameters Ω and λ are respectively the density parameter and the cosmological constant. f is a function depending on the model.

For the most popular big bang model which has zero cosmological constant and unit density parameter, the function f has value 2/3. This is the well known Einstein de Sitter model. 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.

In addition to the nearby old galaxies, in recent times the deep *HST* images are also showing *distant* galaxies that are too old to be consistent with the standard big bang model [9]. For, when we look at a distant part of the universe we have to allow for light travel time, and so the object being seen is at a very early epoch. Dunlop et al. [10] have reported a galaxy 53W091 at a redshift of $z = 1.552$. The magnitude of the galaxy is as faint as 26^m and so these measurements are a remarkable achievement of faint object astronomy by the new 10m Keck Telescope. At the epoch of observation the Einstein de Sitter universe would have been about 2 – 2.6 Gyrs old for H in the range 60–80 kms^{-1} Mpc^{-1}. However, from the visible and infrared colours and the absorption spectrum of the galaxy 53W091 the authors arrive at an estimate of its age of ≥ 3 Gyr, their best value being 3.5 Gyr. Allowing 1 Gyr for stars to form, the age of the galaxy appears to exceed the then age of the universe by a factor 1.5 – 2.

Clearly with the current estimates of the Hubble constant the standard Einstein de Sitter 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 objects etc. which put constraints on how large λ can be. In a recent study of all such constraints Bagla et al [11] 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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