New measurements of the Hubble constant and its implications*

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One of the key projects on the Hubble Space Telescope (HST) is to determine the distance to the Virgo cluster of galaxies using classical Cepheid variables as standard candles. The refurbished HST has resolved and measured the periods and magnitudes of twenty odd Cepheids in M100, a spiral galaxy near the core of the Virgo cluster. Coincidentally, ground-based observations from Hawaii with the help of a high resolution camera, under subarcsecond seeing conditions, have also succeeded in the identification of a few Cepheids in NGC 4571, another Virgo spiral. The distance to the Virgo cluster from these two sets of measurements turns out to be 17.1 ± 1.8 Mpc and 14.9 ± 1.2 Mpc respectively and implies a value of the Hubble Constant H_o equal to 80 ± 17 km s^{-1} Mpc^{-1} and 87 ± 7 km s^{-1} Mpc^{-1}. The result implies that the age of the Universe is in the neighbourhood of 10 ± 2 Gyr. Some of the globular clusters in the Milky Way system are known to be older (age ~ 14–18 Gyr) from stellar evolutionary calculations. Secondly, another important standard candle, the Type Ia supernova, has now been accurately calibrated using HST data on Cepheids in IC 4182 and NGC 5253, the host galaxies for SN 1937C and SN 1972E respectively. These calibrations yield a much lower value of H_o from the Hubble diagram of SNe Ia.

Though there may still be uncertainties of the order of 10–20% in the measurements, the low value of H_o from SN Ia measurements focuses attention on the class of objects classified as SN Ia, and their suitability as standard candles. Significantly, the high value of H_o from the measurements of classical Cepheids may indicate that we live in a Universe somewhat different from the one we have been thinking we do.

EVER since Hubble's discovery of the universal recession of galaxies as a result of the cosmological expansion, measurement of the rate of this expansion, that is its current value has been a subject of intense investigation. The Hubble parameter H_o, referred to as the Hubble Constant is related to the factor $R(t)$ which determines the rate of the isotropic expansion of a homogeneous Universe through the relation

$$H_o = \dot{R}/R\,. \tag{1}$$

H_o is an observationally determinable parameter as it appears in the velocity–distance relation of receding galaxies given by

$$V_r = H_o \times D\,. \tag{2}$$

Here V_r is the velocity of recession usually measured as a redshift of the spectral lines from distant galaxies and D is the distance to the galaxies. As velocities are measured in km s^{-1} and the distances in megaparsecs (1 parsec = 3.085×10^{13} km) H_o is usually expressed in the units of km s^{-1} Mpc^{-1} and has the dimension of inverse time. The reciprocal of H_o is the age of the Universe. In the present century, measurement of H_o has been one of the most important goals of observational astronomy.

To derive H_o two measurements are needed, the velocity of recession of a faraway galaxy and its distance. Though the velocities are estimated quite accurately from the redshift of the spectral lines, distances to astronomical objects are difficult to determine. And it is the uncertainty in the distance estimates that has hindered an accurate determination of H_o since the 1930s. Hubble's original estimate of 500 km s^{-1} Mpc^{-1} for H_o (ref. 1) was revised to about 250 km s^{-1} Mpc^{-1} by Baade[2] when he recognized the population differences between classical Cepheid and RR Lyrae variables and revised the luminosities of the former upward by $1^m.5$. A further revision to H_o = 75 km s^{-1} Mpc^{-1} was effected by Sandage[3] when he discovered that on the photographic plates objects, thought earlier to be the brightest stars in distant galaxies were, in fact, small clusters of stars or compact knots of ionized hydrogen regions around these clusters. Since the 1960s the estimated values of H_o have ranged between 50 km s^{-1} Mpc^{-1} and 100 km s^{-1} Mpc^{-1}, creating an uncomfortably large range of a factor of two in the inferred size and age of the Universe. A curious feature of these estimates is that the value of H_o shows a bimodal distribution with peaks at approximately 50 and 90 km s^{-1} Mpc^{-1} which is directly related to the two widely different values of the distance to the Virgo cluster obtained by the use of methods falling in two mutually exclusive categories. The 'short' distance to Virgo (D ~ 15 Mpc) leads to the larger value of H_o while the 'long' distance to Virgo leads to an H_o in the neighbourhood of 50 km s^{-1} Mpc^{-1}. Each is supported by measurements involving secondary distance calibrators. Although almost all these methods yield consistent results in the Local Group and beyond, they seem to suddenly

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fall out with one another at the nearest cosmologically significant distance, that is the distance to the Virgo cluster.

Galaxies are known to cluster on various scales. The Local Group of twenty odd galaxies, which the Milky Way is a member of, is part of a larger group, the Local Supercluster containing within it several groups and clusters including the Virgo cluster. Within the group, galaxies evince a complex pattern of motion that has little to do with the uniform Hubble flow. Thus to obtain an estimate of H_o astronomers have to look at clusters of galaxies at distances large enough that the random motions of the galaxies within the group are a tiny fraction of their recessional motion as part of the uniform Hubble flow. Since direct trigonometric methods do not carry us far enough even within the Milky Way, astronomers have always relied heavily on indirect methods to estimate distances to faraway objects. Using direct trigonometric methods to obtain distances and hence the luminosities of bright stars, they have extended distance estimates to remote regions of the Galaxy and nearby galaxies using the bright stars as the standard candles. At distances where the bright stars are too faint to be seen, secondary standard candles like globular clusters, SN Ia, HII regions, etc. have been devised and used to estimate distances. Farther out a tertiary standard candle like the brightest galaxy, or the largest galaxy, in a cluster has been used and eventually large enough distances are reached where the unperturbed uniform expansion can be clearly discerned. A velocity estimate at this distance obtained from the redshift of the spectral lines of the test object then leads to H_o. This stepwise process, wherein new distance indicators are calibrated using indicators from the previous step, is liable to accrue both random and systematic errors lending a large uncertainty in the value of H_o that is eventually estimated. Elimination of a step in the process could improve the accuracy of the distance determination considerably and ways and means of effecting this have occupied the attention of astronomers.

Direct measurement of magnitudes and periods of classical Cepheid variables in the Virgo cluster was long recognized to be a potentially powerful way that leapt over a crucial step in the cosmological distance ladder by eliminating the need of secondary calibrators to obtain the distance to this cluster. The use of Cepheids involves only one step – the calibration of their period–luminosity relation by direct trigonometric means, known since the days of Harlow Shapley. Since the Earth's atmosphere hampers attempts at resolving Cepheid variables at the distance of the Virgo cluster, the need for observations from a satellite-based telescope was recognized. The Hubble Space Telescope (HST) has now performed this task by resolving a large number of classical Cepheids in the spiral galaxy M100, a member of the Virgo cluster. Near-simultaneous advances in optical and detector technologies have enabled astronomers to beat the 'seeing' to a large extent and using a high resolution camera at the Canada–France–Hawaii Telescope (CFHT) atop Mauna Kea, Hawaii, a group has been able to resolve a handful of the brightest classical Cepheids in NGC 4571, another member spiral of the Virgo cluster. The distance estimates to both the spirals, whose positions in the sky are close to the assumed dynamical centre of the cluster, support the long distance scale, implying a value of H_o close to 80 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This direct distance estimate to the Virgo cluster suggests a Universe no older than 12 Gyr.

Such a young Universe is bothersome since stellar astronomers have gathered ample evidence of stars and clusters of stars in our Galaxy which appear to be older. Are all stellar age estimates then wrong? A second equally important problem has been thrown up by measurements from the very same HST, this time of supernovae of Type Ia. While these supernovae are only secondary distance indicators, their luminosities have now been directly calibrated by using classical Cepheid variables in the galaxies NGC 5253 and IC 4182 where the prototype SNe Ia 1972E and 1937C were observed. Using SN Ia as a standard candle one obtains quite a different value of H_o, namely $H_o = 52\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ which is in full agreement with the 'long' distance scale and hence an older Universe. Finally, a value of H_o, in the neighbourhood of $80\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ will rule out any preferred cosmological model with the density parameter $\Omega_o = 1$ unless the cosmological constant is nonzero.

Classical Cepheids as primary distance indicators in an expanding Universe

Although classical Cepheid variables had been known since the late eighteenth century, their prime importance as distance indicators was first realized in the 1910s when Henrietta Leavitt published the results of her study of these stars in the Small Magellanic Cloud (SMC). Leavitt noticed that in the SMC the Cepheid variables with longer periods had higher average apparent brightness. Since all stars in the SMC were logically at about the same distance from us, it was immediately obvious that Leavitt's correlation implied the existence of a period–luminosity (P–L) relation for these variables. The significance of this discovery was realized soon by Harlow Shapley then working at Mt. Wilson, California. Shapley used the method of statistical parallaxes on a handful of Galactic Cepheids, for which proper motion data were available, to obtain a calibrated P–L relation. Shapely had noticed that the globular clusters invariably contained short period variables called the RR Lyrae variables whose light curves were no different from those of the classical Cepheids. He extended the P–L relation to include the RR Lyrae variables obtaining thereby their intrinsic luminosities. His next step was to use these variables to obtain the distances to globular clusters and then to map their distribution as part of our galactic system. The sequence of discoveries by Shapley which finally gave a reasonable idea of the size and shape of our Galaxy and the position of the solar system in it has often been likened to the Copernican revolution which ushered in the scientific renaissance in the 1600s.

In the 1920s when the nature of the spiral nebulae was still hotly debated upon, Edwin Hubble using the newly commissioned 100" telescope at Mt. Wilson was able to resolve Cepheids in the Andromeda nebula and provided the first measurement of a distance beyond our Galaxy. The existence of external galaxies was proved beyond doubt. Armed with the powerful tool of Cepheid variables as standard candles, Hubble and then others extended distance measurements to the Local Group galaxies and beyond. Using Cepheids in the nearby regions and then devising secondary indicators (e.g. brightest stars, supernovae, globular clusters, etc.) which were calibrated with respect to the Cepheids and RR Lyr variables to go further, and finally by using these secondary indicators to calibrate galaxy diameters and galaxy magnitudes in clusters, astronomers, during the decades following Hubble's work were thus able to reach out to cosmological distances. The series of efforts resulted in the refinement and extension of the calibrated velocity distance relation that was first given by Hubble in 1929.

Cepheid variables are thus seen to have played a seminal role in setting up the extragalactic distance scale by being the first step of the cosmological distance ladder.

Cepheids are a class of regular pulsating variable stars with periods ranging from a couple of days to well over a hundred days. They are of spectral types F to G and are intrinsically bright, belonging to the luminosity classes of bright giants and supergiants. Their internal structure and evolutionary status as core-He burning stars are well understood and highly sophisticated models are available that reproduce all of their observed properties. On the HR diagram they occur in a narrow strip somewhat inclined to the temperature/colour axis and it was observationally shown that their period depends both on the luminosity and the colour. The P–L–C relation, which is of fundamental importance in measuring extragalactic distances, has also been derived theoretically from the models and it is in excellent agreement with the P–L–C relation determined empirically. The best calibration of the relation comes from Cepheids in open clusters whose distances are known to great accuracy through the fitting of their main sequences to the Hyades main sequence, the latter being calibrated directly in absolute magnitudes through the method of moving cluster parallaxes. Thus the study of Cepheids is very secure both theoretically and observationally and hardly any substantial change will occur in any of the results based on the properties of these stars.

Distances to the Local Group galaxies and to other galaxies slightly beyond have been estimated using Cepheid variables as standard candles. A variety of other calibrators have also been used to estimate the distances to these galaxies. The best measurements to date are available for the Magellanic Clouds. In their case the distance moduli obtained by different methods agree to within $0^m.10$. Until the HST and the CFHT measurements the farthest the Cepheids were seen were in M101 at a true distance modulus $(m-M)_0 \sim 29^m.5$. Even at this distance the other methods led to distance estimates in good agreement with the ones obtained through Cepheids. However, the distance is yet too small to see an unambiguous Hubble flow. Determination of cosmologically significant distances for deriving H_o had depended totally on the use of secondary distance calibrators.

Distance estimates to the Virgo cluster

The Virgo cluster forms the core of the Local Supercluster. Its role in the determination of the extragalactic distance scale has been crucial. The cluster is large and it contains the full complement of galaxies of different morphological types allowing for the application of almost all the methods of distance estimates at hand including those using novae and supernovae of different types since the richness of the cluster ensures that even these rather rare events are not too infrequent in it. Further the cluster is at a high galactic latitude such that the foreground extinction to it is not a problem. It is ideally located for observations from both hemispheres of the globe. And lastly it is sufficiently distant so that most of its recessional velocity derives from the Hubble expansion.

Before 1994 the distance estimates to this cluster were all based on secondary and tertiary calibrators since technology did not allow yet the discovery of Cepheids in its member spirals. Table 1 lists these estimates from a variety of sources. Dichotomy of the results is quite evident. While surface brightness fluctuations, the planetary nebula luminosity function and the Tully–Fisher relation lead to a short distance to the cluster

Table 1. Distance of the Virgo cluster

Method	Author and ref.	$(m-M)_o$
Planetary nebulae	Jacoby *et al.*[12]	30.74 ± 0.05
Surface brightness fluctuations	Tonry *et al.*[13]	30.86 ± 0.13
Tully–Fisher	Pierce and Tully[14]	30.88 ± 0.22
Globular clusters	Harris *et al.*[15]	31.47 ± 0.25
Novae	Capaccioli *et al.*[16]	31.30 ± 0.36
SN 1979C in M 100	Schmidt *et al.*[17]	31.40 ± 0.60

$(m-M)_0 \sim 30.7$, SN Ia, the globular cluster luminosity function and novae lead to a long distance with $(m-M)_0 \sim 31.4$. The long distance is also supported by measurements that use diameters or scale lengths of Sc I galaxies as calibrators. The difference in the distance moduli between the two sets, which is nearly a full magnitude, translates to a distance ratio of about 1.4. This large difference has been principally responsible for the controversy surrounding the value of the Hubble parameter H_o, since the dispersion in the velocity estimates of the member galaxies of the Virgo cluster produces a much smaller uncertainty. It has also been noted in the literature[4,5] that though the absolute distance to the Virgo cluster was in dispute, the relative distances of distant clusters with respect to Virgo were not. A variety of methods yielded very similar relative distances to the Coma cluster with uncertainties in D(Coma)/D(Virgo) which are less than 10%, more typically on the order of 5%. It was thus realized that an accurate distance estimate to the Virgo cluster using a primary calibrator could lead to an equally accurate absolute distance to the Coma cluster where the Hubble recessional velocity is easily an order of magnitude larger than the typical random of motions of galaxies within the cluster. This would then lead to an accurate determination of H_o. One of the key projects assigned to the Hubble Space Telescope was thus the discovery and measurement of classical Cepheid variables in the spirals of the Virgo cluster. It is my personal belief that the eventual naming of the Space Telescope was consciously or unconsciously influenced by this very important task that it was to undertake.

HST and CFHT observations of Cepheid variables in Virgo cluster

In 1994 two independent groups[4,6] announced the first discovery of classical Cepheid variables in the spiral galaxies NGC 4571 and NGC 4321 (M 100) which are members of the Virgo cluster. While twenty odd Cepheids were resolved by the Hubble Space Telescope in M 100, ground-based efforts using a sophisticated high resolution camera (HR Cam) on the Canada–France–Hawaii Telescope atop Mauna Kea, could discover three Cepheids in NGC 4571.

Cepheids in M 100

M 100 is a giant Sc galaxy with a projected location 3°.9 away from the centre of the cluster defined by the giant elliptical galaxy M 87 (Virgo A, NGC 4486). The HST measurements have covered full cycles of about twenty Cepheids in this galaxy with periods ranging from 20 to 65 days. Both V band and I band measurements were made. The mean V and I magnitudes and the measured periods define a nearly perfect linear relation that was indistinguishable in its slope from the absolute P–L relation of the LMC Cepheid sample. The reddening-corrected true distance modulus led to $D(\mathrm{M\ 100}) = 17.1 \pm 1.8$ Mpc based on an LMC $(m-M)_o = 18.5$. This direct estimate is close to the value obtained by the use of the Tully–Fisher relationship ($D = 18.4 \pm 2.2$ Mpc), but very different from Sandage's values of $D = 27.7$ Mpc based on a calibration of the diameters of Sc I galaxies.

Cepheids in NGC 4571

The ground-based sample of Pierce *et al.*[4] contained certain identification of two classical Cepheids and one suspected one in NGC 4571. This galaxy is located at less than 2°.5 from M 87 as projected in the sky. Further it shows evidence of significant HI stripping. Its kinematics shows that it is close to the cluster core and most likely is in orbit around the dynamical centre of it. The periods of Cepheid variables range from 50 to 90 days and again define a linear relation with their mean R magnitudes, the slope of which is the same as found in the LMC Cepheid sample. The distance $D(\mathrm{N4571}) = 14.9 \pm 1.2$ Mpc.

Observations of classical Cepheids in two of the spirals of the Virgo cluster seem thus to support the so-called short distance scale to this cluster ($D_{\mathrm{Virgo}} \sim 15 \pm 2$ Mpc). But before deriving H_o based on these distances the measurement of velocities of the cluster galaxies should be critically examined to infer the true Hubble velocity of the cluster.

Cosmic velocity of the Virgo cluster

Our local region of space, cosmologically speaking, shows a complexity of motion that needs to be disentangled before the true Hubble flow of the Virgo cluster can be estimated. It has been known for several years now that our own Local Group has a Virgocentric flow of a few hundred km s^{-1}. Observations of the 3 K Cosmic Microwave Background (CMB) show a dipole anisotropy, implying a motion towards its warm pole, but the direction does not coincide with the direction of the Virgo cluster in the sky. Some years ago it was postulated that there is a Great Attractor (GA), a large hidden clump of mass towards which all galaxies in the local superbubble (defined as a cell within $V_r \leq 6000$ km s^{-1}) are attracted. More recent and extensive data by Mathewson *et al.*[7] have demolished the GA concept and it is now well established that the nearly bulk peculiar motion of the local superbubble gradually peters out beyond 6000 km s^{-1}, merging gradually into the unperturbed Hubble flow.

In the currently accepted picture of the dynamics of the local region consistent with all kinematic data, there are two components to the motion of the Local Group relative to the frame of CMB: (i) the perturbation of the free expansion of it from the Virgo region due to the mass of the Virgo cluster complex and (ii) the large scale nearly bulk motion of the local bubble of size $V_r \leq 6000\,\mathrm{km\,s^{-1}}$ relative to the CMB, carrying the Local Group and the Virgo complex with it. Figure 1 displays a vector diagram of the velocities in the local region, adapted from Sandage and Tammann[8]. These authors assert that the peculiar dipole motion toward the CMB within the Local Supercluster and beyond is so small that it can be neglected in the determination of H_o.

The most direct method of determining the true Hubble velocity of the Virgo cluster is to use the Hubble diagram with redshifts of remote clusters in the kinematic frame of the CMB plotted against the relative distance of these clusters with respect to the Virgo cluster expressed as a difference in their distance moduli. This is a line with a slope of 5. An extrapolation to zero in abscissa then gives the cosmic redshift at the distance of the core of Virgo cluster, devoid of all streaming motions. In this way Sandage and Tammann[8] (*op. cit*) estimate the true Hubble velocity of the Virgo cluster to be $1179 \pm 17\,\mathrm{km\,s^{-1}}$.

Hubble parameter H_o

There are two independent ways of obtaining H_o from the recent measurements of the distance modulus to the two spirals. It is assumed, of course, that both the spirals belong to the Virgo cluster and are not foreground or background objects.

(1) Using the result, $V_{\mathrm{Virgo}} = 1179\,\mathrm{km\,s^{-1}}$, we find $H_o = \frac{1179}{17} = 69\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ based on the distance to M 100 and $H_o = \frac{1179}{14.9} = 79\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from the distance to NGC 4571.

(2) Using the argument from the section 'Distance estimates to the Virgo cluster', described above, that the relative distance D(Coma)/(Virgo) is very secure and that its value is 5.5, we obtain D(Coma) = 94 Mpc and 82 Mpc respectively from the two distance measurements and then using $V_{\mathrm{Coma}} = 7{,}100\,\mathrm{km\,s^{-1}}$ to reach $H_o = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $87\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

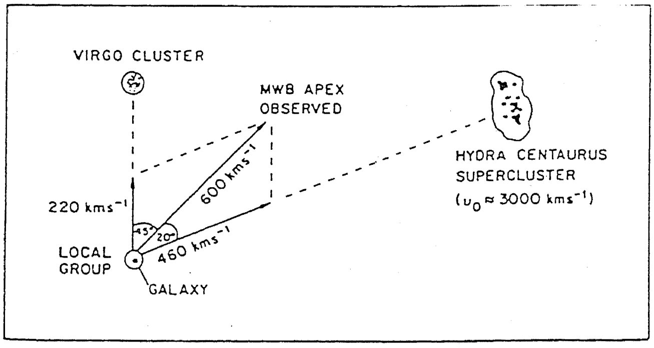

Figure 1. Schematic diagram of the combination of the 'infall' of the Local Group toward Virgo of $220\,\mathrm{km\,s^{-1}}$ and the 'infall' of the 'local cell' of size $\sim 6000\,\mathrm{km\,s^{-1}}$ (including the Virgo complex and the Local Group) toward Hydra–Centaurus at $460\,\mathrm{km\,s^{-1}}$, giving an apparent motion of the Local Group of $600\,\mathrm{km\,s^{-1}}$ toward the warm pole of the CMB.

Since there is still disagreement on the true cosmic velocity at the distance of the Virgo cluster, while as stated before the various methods of obtaining distances yield reliable results for the relative distance of the Coma cluster to the Virgo cluster, the second option of determining H_o would seem to be more prudent. Thus direct measurement of the distance to the Virgo cluster appears to indicate that the true value of the Hubble parameter is close to $80\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, implying that the Universe is no more than 12.5 Gyr old if its expansion has been uniform in the past.

Disagreement with estimates based on SN Ia

Although great confidence is placed on the estimate of distances using classical Cepheids as the standard candles, secondary calibrators still occupy a very important place in setting up the extragalactic distance scale. Beyond the Virgo cluster it is the use of these secondary calibrators which lead to any distance measurement at all. Among the secondary calibrators, SN Ia occupies a unique position. These supernova are extremely luminous as point sources and they occur in all kinds of galaxies. Their observed light curves in all these galaxies appear to be remarkably uniform. The shape of the light curve is theoretically well understood. According to the currently accepted view, these supernovae are thermonuclear explosions of white dwarfs which accrete matter from a binary companion and ignite carbon in their degenerate cores which then disrupts the star completely. The characteristic light curve shape is theoretically reproduced by trapping and thermalization of the decay products of radioactive ^{56}Ni and ^{56}Co in $1.4\,M_{\odot}$ of ejected matter. This model brings with it a self-calibration of the peak luminosity. An impressive amount of theoretical work has been done over the years on SN Ia explosions and these lead to a computed peak luminosity in the neighbourhood of $M_B = -19.5$. Empirical calibrations of SN Ia luminosities have depended upon observations of these supernovae in various galaxies whose distances are estimated by other methods. Those supernovae for which prepeak B and V light curves are available had their peak luminosities calibrated with reasonably good accuracies.

Since two well-known SNe Ia occurred in galaxies near enough for the HST to look at their Cepheid population, an equally important project for HST was to use the Cepheids in these galaxies to calibrate the peak luminosity of SN Ia. Saha *et al.*[9,10] observed a number of Cepheids in NGC 5253 and IC 4182 the host galaxies of the well observed SN 1972E and 1937C respectively. Using the Cepheid distances to these galaxies the peak luminosities of the SNe Ia were calibrated in B and V. The final values of $M_B(\max) = -19.65 \pm 0.13$ and $M_V(\max) = -19.60 \pm 0.10$ are in good agreement with the theoretical self-calibrated values.

To obtain the Hubble parameter from SN Ia measurements it is customary to use the SN Ia Hubble diagram which is a plot of the velocities of receding galaxies versus SN Ia V magnitudes in them. From Sandage and Tammann[8] one obtains: $\log V_r = 0.2V + 0.658$, and hence $\log H_0 = 0.2\, M_V(\max) + 5.658$. The value of H_0 obtained from these measurements is 52 ± 9 km s^{-1} Mpc^{-1}. This value disagrees with the high value obtained directly from the Cepheid variables. Thus there is discrepancy between the Cepheid measurements and SN Ia measurements and it is sure to focus attention on the estimates of SN Ia magnitudes used in producing the SN Ia Hubble diagram and also on the suitability of SN Ia as standard candles.

Implications of the new measurement

The HST is carrying out further measurements of classical Cepheid variables in other member spiral galaxies of the Virgo cluster and though it may take some more time to pin down the distance to the Virgo cluster with much higher accuracy, it may not be totally out of place now to discuss the implications of a high value of H_0, should it come to stay.

The Hubble parameter in a simple sense determines how big the Universe is and how old it is. The inverse of it, which has the dimensions of time, characterizes the time scale for the expansion of the Universe at any epoch. Thus if the Universe expanded uniformly, $1/H_0$ would be the age of the Universe in Gyr (1 Gyr = 10^9 yr). However, since the Universe contains matter, it is natural to assume it has decelerated since the expansion began and in the most popular cosmological model, known as the Einstein-de Sitter model (also the Standard Model) with $\Omega_0 = 1$ and $\Lambda = 0$, the age is $2/3\,H_0$. The question of the age is thus intimately related to three parameters H_0, Ω_0 and Λ. Ω_0 is a dimensionless measure of the density of matter in the Universe and determines the deceleration of its expansion. Formally, $\Omega_0 = 8\pi G\rho/3H_0^2$, where ρ is the density of matter and G the universal gravitation constant. Λ is known as the cosmological constant, first introduced by Einstein in 1917 to obtain static solutions to the field equations of general relativity as applied to the Universe. It represents the energy density of the vacuum. So far it has not been possible to obtain either Ω_0 or Λ from observations. While all cosmological models (Friedmann Universes) set $\Lambda = 0$, a variety of arguments and deep philosophical convictions have led to the belief that we live in a Universe where $\Omega_0 = 1$ (see ref. 11 for a detailed discussion of these premises). Since visible matter perhaps makes up for only 1–5% of the total density required for Ω_0 to be unity, it has been commonly assumed that most of the matter in the Universe is dark or invisible. Investigation into the nature and distribution of this dark matter is one of the most active fields of research today. The measurement of H_0 described earlier therefore leads to $T \simeq 8$ Gyr.

There have been independent estimates of the age of the Universe. These are based on the estimates of the ages of the constituents of the Universe. Amongst the oldest objects in the Galaxy are the globular clusters. Their ages have been determined by a combination of theory and observation related to the evolution of stars. The current best estimates indicate that many of these globular clusters are at least 16 ± 2 Gyr old. This result is in conflict with the age of the Universe quoted above. Probably some uncertainties lurk in the background of the otherwise highly successful theory of stellar evolution requiring these ages to be revised downward but the general consensus is that it will never be to the extent of a factor of two that is required by the new estimates of H_0. If the assumption of $\Omega_0 = 1$ were relaxed and only the value of it consistent with early nucleosynthesis (abundances of D, ^{3}He, ^{4}He) and the virial masses of clusters of galaxies were adopted, which is a number between 0.1 and 0.2, even then the age of the Universe could hardly be increased beyond 11 Gyr for an $H_0 \sim 80$ km s^{-1} Mpc^{-1}. The only choice that remains, therefore, is to abandon the assumption of $\Lambda = 0$. If a positive cosmological constant were allowed, the age of the Universe can be lengthened sufficiently to accommodate the ages of globular clusters and of oldest stars.

Thus the implication of the new measurement of H_0 seems to be rather profound and would indicate that our preferred cosmological model needs fundamental revision. Further it may open up new directions of research and spur the observational quest for the value of Λ.

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