# The Hubble Constant and the Hubble Space Telescope

**Shoko Sakai Ph.D.**

**Jet Propulsion Laboratory**

## Introduction:

According to the standard evolutionary model of the Universe, it started from the Big Bang and has been expanding ever since. But how long ago did this Big Bang occur? How large is the Universe at present? How old is the Universe? These are the fundamental questions in cosmology. And answers to many of these questions are embedded in determining the value of the Hubble Constant.

The expansion of the universe is quantified by a surprisingly simple equation known as the Hubble relation: $v = H_0 d$. Here, $v$ is the recession velocity of a galaxy, $d$ is its distance from us and $H_0$ of course is the Hubble Constant measured in units of km $s^{-1}$ $Mpc^{-1}$ [1]. The basic observation is that the further away the galaxy is, the faster it is receding from us. Thus if we can accurately measure the distance to galaxies and how fast they are moving, we should be able to determine the value of the Hubble constant. The age of the Universe is expressed as $t = (2/3)(1/H_0)$ for a flat universe and can be illustrated by a simple graph as in Figure 1 which illustrates the relationship between the size and age of the Universe. The Hubble constant defines the expansion rate of the Universe at present time, or the slope of these relations shown in Fig 1. If the Universe expanded uniformly since its beginning as defined by a thin straight line in the figure, the age would be estimated by extrapolating back in time and can be expressed simply by $t = 1/H_0$. However, in the

---

[1] Mpc stands for megaparsecs ($10^6$ parsecs). A parsec is approximately 3.26 lightyears, or $3.086 \times 10^{13}$ kilometers.

Einstein–deSitter model of the flat universe, the standard model that we use today, the expansion is not constant (the bold line) thus a correction of (2/3) is needed to define the age of the Universe.

Until recently, various estimates of the Hubble Constant varied by a factor of two, ranging from 50 up to 100 km $s^{-1}$ $Mpc^{-1}$. Fortunately, the observations of variable stars using the refurbished Hubble Space Telescope are starting to shed some light in finally making an accurate estimate of $H_0$. This article will summarize the studies undertaken to determine the Hubble Constant, focusing on the observations made with the Hubble Space Telescope.

**Background:**

We can determine relatively easily how fast a galaxy is moving away or towards us by measuring the doppler shifts in the absorption or emission lines in its spectrum. Galaxies that are receding from us (which include majority of them) will show spectral lines that are 'redshifted': that is, the wavelength of particular absorption/emission lines appear longer. By determining how much this shift is, the recession velocity of this galaxy can be calculated. Thus, if we can estimate the distance to the galaxy, we should be able to measure the value of Hubble constant by applying the Hubble relation.

The reality, however, is not so simple. This is because the distribution of galaxies is far from being smooth and uniform. Although the Universe is believed to be homogeneous and isotropic on scales of hundreds of megaparsecs, the gravitational perturbation from a slightly excessive mass concentration will amplify deviations from homogeneity, thereby promoting galaxy clustering on smaller scales. We do indeed observe clusters and superclusters of galaxies on scales $\sim$few megaparsecs.

The density inhomogeneity in turn induces perturbations in the smooth Hubble flow, usually referred to as peculiar motions. The Hubble relation is then expressed more accurately as: $v = H_0 d + v_{pec}$ where $v_{pec}$ is the peculiar motion of a galaxy in the line of sight, and on average amounts to few 100s of km $s^{-1}$. It is usually extremely difficult to examine the magnitude of $v_{pec}$ precisely, as that would require a good knowledge of the mass distribution in and around the clusters of galaxies, and this is complicated by the presence of large amounts of dark matter on these scales. If we attempt to measure the Hubble constant only by observing very nearby galaxies (at $\sim$ 10Mpc), the peculiar velocity accounts for a significant portion of the total velocity, leading to a very large uncertainty in $H_0$. So in this game, the trick would be to make distance and recession velocity estimates at large distances, preferrably at 100 Mpc or further, minimizing the error due to uncertain peculiar velocities. This idea is summarized in Figure 2. There are several distance estimators known as the "primary indicators" which include the Cepheid variables and RR Lyrae variables. This article will cover more extensively later on how Cepheid variable stars are used in the Hubble constant determination. The primary estimators require the observation of individual stars in galaxies, thus they can only be applied to nearby galaxies, out to $\sim$20 Mpc even using the powerful Hubble Space Telescope. Prior to HST, it was only possible to apply these methods to distances of a few megaparsecs, which included only a handful of nearby galaxies. These "primary indicators" can then be used to calibrate several "secondary distance indicators" such as Tully–Fisher relation for spiral and $D_n - \sigma$ relation for elliptical galaxies[2] The secondary distance indicators give reliable distances out

---

[2] These methods are very similar in their philosophy. For example, the Tully–Fisher relation is based on a basic idea that more massive galaxies rotate faster. Thus by measuring its maximum rotational velocity, the galaxy's absolute luminosity can be estimated using the Tully–Fisher relation. Its distance is then measured by comparing it with the apparent magnitude measured by surface photometry.

to 100 Mpc.

### Cepheid Variables:

As the name indicates, the Cepheid variable stars show variations in the luminosity. Their periods range from 2 up to 150 days. In 1907, Henrietta Leavitt discovered that these stars' absolute luminosity and period followed a very tight correlation: the periods of brighter Cepheids are longer. If one can observe a Cepheid variable star periodically, the period, and thus its absolute luminosity can be estimated. Given apparent and absolute luminosities, the distance can then be determined[3].

It was in fact Edwin Hubble himself who applied the period–luminosity (PL) relation of Cepheids to determine the distances to various galaxies, which were used to measure the Hubble Constant. Figure 3 is Hubble's original "Hubble diagram", showing the relation between the recession velocity and distance. The slope of this correlation represents Hubble constant. Hubble's original value of $H_0$ in 1929 was 450 km s$^{-1}$ Mpc$^{-1}$. This value of $H_0$ implied the age of the Universe of only 1.8 billion years. It seems extremely young, but at the time, this estimate was in excellent concordance with the age of the Earth measured from radioactive dating.

However, subsequent studies raised the age of the Earth up to 4.3 billion years. It was not until 1952 this age discrepancy was resolved: Walter Baade noticed that there were in fact two types of Cepheid variables – those found in the spiral galaxies were brighter than those found in globular clusters. Furthermore, in 1956, Allan Sandage noticed that some of the brightest stars in the nearby galaxies were in fact star clusters or HII regions (clouds of mainly ionized hydrogen). Sandage's value of Hubble constant in 1956 was 75 km s$^{-1}$

---

[3] If m and M represent apparent and absolute magnitude respectively, the distance ($d$) is determined by: $\log d = 0.2(m - M + 5)$

$\mathrm{Mpc}^{-1}$. He and his colleague, Gustav Tamann, started publishing a series of papers on the subject of the Hubble constant later on in the 60s and 70s and they consistently obtained a low $H_0$ value of around 50 km $\mathrm{s}^{-1}$ $\mathrm{Mpc}^{-1}$. Although this low $H_0$ value seemed to solve the age discrepancy, the controversy did not end. Numerous astronomers including Gerard de Vaucouleurs, Jeremy Mould, Marc Aaronson, Brent Tully and J. Fisher, argued for a high Hubble constant around 80 up to 100 km $\mathrm{s}^{-1}$ $\mathrm{Mpc}^{-1}$. Sandage and de Vaucouleurs remained at the center of what became known as the H0 debate over the next 20 years. It was hoped that observations with the Hubble Space Telescope would eventually solve the controversy.

### Measuring The Hubble Constant with the Hubble Space Telescope:

The Hubble Space Telescope (HST) is a 2.4m telescope on which several instruments are mounted on the HST The HST was deployed in xxx 1990; however, the flaw in its mirror configuration became obvious shortly after the launch. The telescope could not be focused accurately enough to meet the expected specifications. In December 1993, the Space Shuttle retrieved the HST into its cargo bay and the astronauts executed a spectacular servicing mission, placing new instruments and a corrective mirror in it. As the readers are aware, the HST had a second servicing mission in February this year, at which time two new instruments were installed including an infrared camera.

About ten years ago, a team of astronomers was formed with a goal to determine the Hubble Constant with 10% accuracy by detecting Cepheid variable stars in ~20 nearby galaxies. At present, the team consists of close to 25 astronomers, including several graduate students and postdocs, and is directed by three co–principal investigators: Dr. Robert Kennicutt of Steward Observatory in Tucson, Arizona, Dr. Wendy Freedman of Carnegie Observatories in Pasadena, CA and Dr. Jeremy Mould of Mount Stromlo Siding Springs Observatory in Australia. I was fortunate enough to join the team two years ago as a postdoctoral fellow at JPL in Pasadena, CA.

The schematics of this HST Key Project on Extragalactic Distance Scale is very similar to that shown in Figure 2. We are directly measuring distances to 25–30 nearby galaxies by detecting Cepheid variables in them. These distances are then used to calibrate several secondary distance indicators, including the Tully–Fisher relation for spiral galaxies, surface brightness fluctuation method in elliptical galaxies and planetary nebulae luminosity function method, in order to probe the distribution and velocity field of galaxies out to $\sim$100 megaparsecs.

One of the first target galaxies observed by the refurbished HST was M100, a grand–design spiral galaxy located in the Virgo cluster. The images were spectacular, showing individually resolved stars in this galaxy; the detection of Cepheid variables was immediately confirmed possible. On the left-hand side of Figure 4 is an image of M100 taken from a ground–based telescope. On the right, part of that same galaxy imaged using the Wide Field Planetary Camera 2 (WFPC2 – used for imaging purposes) is shown. We also show in Figure 5 an example of a Cepheid variable star whose brightness variation is clearly observed here. For each of 20 target galaxies in the HST Key Project, the same field is observed 12 times, spaced so as to maximize the probability of detecting Cepheid variables of periods ranging from 10 up to 50 days. In M100, more than 80 Cepheid variables were detected, placing it at 16.1 megaparsecs, or 52.5 million lightyears.

The Virgo cluster, in which M100 is located, has always been the center of attention in observational cosmology, and has been regarded as one of the stepping stones in reaching out to the distant clusters for the determination of $H_0$. Using the distance of 16.1 Mpc to Virgo, and stepping out to another cluster Coma located at $\sim$100 Mpc, the Key Project obtained the $H_0$ of 80 km s$^{-1}$ Mpc$^{-1}$[4]

---

[4] The *relative* distance between these two clusters is very well known from various

The problem, however, is that the Virgo cluster itself has a huge depth. This means that the distance to M100 is not necessarily that of the Virgo cluster; i.e., the error associated with the Virgo distance measured by M100 is large enough to make the $H_0$ determination uncertain. Also the $H_0 = 80$ results is based on a single galaxy observation. To overcome this problem, the Key Project is observing 3 galaxies in the Virgo cluster. Also, it is making observations of 3 galaxies in another cluster called Fornax cluster, which is located in the opposite direction of our own Galaxy from the Virgo, and believed to be another good step in the cosmological distance scale. The Fornax is more compact in size, thus its distance can be estimated more accurately by detecting Cepheid variables in a couple of galaxies in this cluster.

The Key Project is observing ∼25 galaxies in total. As mentioned above, these Cepheid distances are used to calibrate several secondary distance indicators such as the Tully–Fisher relation for spiral galaxies. The preliminary absolute calibration, shown in Figure 6, consists of 11 galaxies. Applying this relation to galaxies in clusters out to 100 megaparsecs, our preliminary results give $H_0 = 70 - 75$ km s$^{-1}$ Mpc$^{-1}$.

There are groups, other than the HST Key Project, that are making effort in measuring the value of $H_0$ using the HST. A team led by Allan Sandage is one of them, who has always been an advocate for lower $H_0$ estimates. His team has also been measuring distances to nearby galaxies by detecting and measuring the brightness and periods of Cepheid variable stars. But instead of Tully–Fisher relation, they apply another secondary distance indicator which utilizes the luminosities of supernovae. These are very bright objects and enable you to probe the Universe out to distances hundreds of megaparsecs, much farther than

---

secondary distance indicators including the Tully–Fisher relations. The relative distance is the offset between two distances and does not depend on the absolute zero point calibration of the secondary indicators.

that reachable by the Tully–Fisher relation. Although their earlier reports on their HST observations indicated $H_0$ of only slightly higher than 50 km s$^{-1}$ Mpc$^{-1}$, their recent reports conclude $H_0$ of 60 - 65 km s$^{-1}$ Mpc$^{-1}$. The gap between various $H_0$ estimates is indeed narrowing down.

$H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ would place the age of the Universe at 9 billion years for a flat Universe. However, as some readers might be aware of, the oldest stars in globular cluster in our own Galaxy have been estimated to be at least 15 billion years old. How could stars be older than the Universe itself? Are there ways to make a more consistent picture?

First question would be to ask if the age estimates of the globular cluster stars may be wrong. No theories are perfect but physics do set firm limits as to how much you can push some of these numbers. The 95% confidence lower limit for the age of these stars is 12 billion years. Although the non–zero uncertainty associated with present $H_0$ estimates could possibly lower the Hubble constant down to the lower 60s, unlike ten, twenty years ago, the errors are decreasing rapidly as more and more high–quality *HST* observations are made.

There are, however, several ways to resolve this age–discrepancy issue by introducing two other constants that play major roles in cosmology: density parameter, $\Omega_0$, and cosmological constant, $\Lambda$. The former represents the amount of matter in the Universe. For an open model in which the Universe expands forever, $\Omega_0 \leq 1$; on the other hand, a closed model ($\Omega_0 \geq 1$) in which the Universe, after reaching its maximum value, shrinks to a 'big crunch'. A flat Universe is represented by $\Omega_0 = 1$ and is the most favored model at present as it is predicted by the inflation theory, which seems to explain the observed state of the Universe quite well. Dynamical studies of galaxies in clusters and superclusters predict $\Omega$ of around 0.1 – 0.2.

The cosmological constant, $\Lambda$, arises due to a vacuum energy in space. This term has no effect on individual clusters of galaxies gravitationally, but does impose a significant weight on the expansion of the Universe if it is non–zero. It is still very debatable whether this constant should be greater than zero at all.

In Figure 7, we show the relations between $H_0$, $\Omega$ and $\Lambda$. In both figures, bold lines represent the correlation corresponding to the age found by the Globular cluster stars, 15.8 ± 2.1 billion years. On the left–hand side, correlations for a $\Lambda = 0$ universe are shown. We see that it would be very difficult to accommodate $H_0 = 70$, unless $\Omega_0$ is near zero. For more realistic values of $\Omega_0$, the Hubble constant of less than 50 km $s^{-1}$ $Mpc^{-1}$ is needed. On the right–hand side, correlations for flat universes with nonzero cosmological constant are shown. Here, the density parameter is divided into two terms – matter and vacuum. Although the high $H_0$ values become more acceptable in this picture, for $H_0 = 70$, we need $\Omega_{matter} \leq 0.2$ and $\Omega_{vac} \geq 0.8$.

Recently in February 1997, Michael Feast reported that the Cepheid distance scale itself might have a systematic uncertainty of about 10% based on parallax results obtained by Hipparcus satellite observations. Although this may decrease $H_0$ by up to 10%, this is still a very preliminary results. We must wait for further analysis; many more Hipparcus results will be released later this year.

It is a very exciting and challenging time for both observational and theoretical astronomers. The HST Key Project on the Distance Scale is planning on reporting our final estimate of the Hubble constant, accurate to 10%, in about one year.

## References:

1. Kennicutt, Freedman & Mould, 1995, Astronomical Journal, Volume 110, Number 4, p.1476

2. Freedman et al. 1994, Nature, Volume 371, p.757

3. “The Extragalactic Distance Scale”, 1997, conference proceedings edited by Livio & Donahue

**Figure Captions :**

**Figure 1:** Relationship between the size and age of the Universe. See text for details.

**Figure 2:** “Distance ladder” showing show the different distance indicators are calibrated and subsequently used to eventually determine the value of the Hubble constant.

**Figure 3:** The original Hubble diagram by Edwin Hubble.

**Figure 4:** An image of M100 taken from a ground–based telescope. The HST image is overlayed. *Courtesy: Laura Ferrarese (California Institute of Technology)*

**Figure 5:** One of the Cepheid variable stars found in M100, showing its brightness fluctuation. *Courtesy: Wendy Freedman (Observatories of the Carnegie Institution of Washington) and NASA*

**Figure 6:** The preliminary absolute calibration of Tully–Fisher relation between the absolute magnitude and rotation velocity of spiral galaxies.

**Figure 7:** (a) Correlations between $H_0$ and $\Omega$ for an open Universe, and (b) those between $H_0$, $\Omega$ and $\Lambda$ for a flat Universe with non–zero cosmological constant.