

Observing the Expansion of the Universe

Using the Hubble Space Telescope

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Can you figure out how old the Universe is? How would you carry out such an experiment? Even more, what does the Universe look like? How did it begin? And most of all, what is going to happen in the future, a very distant future? If you are remotely curious, you have probably wondered at some point where everything in the world came from.

Cosmology deals precisely with questions as those, and we, astronomers, attempt to solve these puzzles by collecting data using powerful telescopes and by developing theories. Observational cosmology has seen enormous changes in the past two decades, thanks to the dramatic improvement in technology, allowing us to work with an amount of the data that was unthinkable just a decade ago.

The Universe started out from a primordial explosion, the Big Bang. This is perhaps the most important scientific discovery of the 20th century. During the 1920s, Edwin Hubble discovered that the galaxies are indeed receding from us, in a sense that galaxies located further away are moving away at a faster speed. This is a direct evidence of the expanding Universe. A stunning confirmation of the Big Bang theory was the discovery of the cosmic microwave background radiation (CMB) by Arno Penzias and Robert Wilson in the 1960s, which is a remnant of the Big Bang fireball.

Today, 70 years after Edwin Hubble's first discovery of the expansion of the Universe, the basic picture of the history of the Universe has been verified. However, perhaps to a

surprise to most of the readers, the most fundamental questions such as the scale and ages of the Universe are only now being settled.

Answering these questions is closely connected to determining the expansion rate of the Universe, which is represented by a number called the Hubble constant. And appropriately enough, a powerful telescope named after Edwin Hubble himself, Hubble Space Telescope (HST), plays the key role here.

In June 1984, a conference on Hubble constant was held at the Aspen Center for Physics in Colorado, during which a group of astronomers gathered ideas together to form a project, that later developed into one of the HST Key Projects. In fact, determining the value of the Hubble constant was one of the major objectives for building the HST. The goal of the Key Project is to observe 25 to 30 spiral galaxies and estimate their distances accurately using stars called Cepheid variable stars. The project moved into full gear after the HST refurbishment mission in December 1993, and today, it has grown to a large group consisting of 27 astronomers, including quite a few postdoctoral associates and graduate students, and is led by three co-principal investigators: Robert Kennicutt Jr. of Steward Observatory, Wendy Freedman of Carnegie Observatories and Jeremy Mould of Mount Stromlo Siding Spring Observatory. As a postdoctoral fellow at Jet Propulsion Laboratory, I joined this team in fall of 1994. Although the team members are spread out on three continents, the internet keeps us updated on a day-to-day basis.

In this Science Series, I will describe how we are carrying out this experiment to measure the age of the Universe and what the impacts of HST are with regard to our project.

Expansion of the Universe

During the 1920s, using the 2.5-meter telescope on Mount Wilson near Los Angeles, Edwin Hubble and Milton Humason carried out the observations of nearby galaxies that led to the discovery of the expansion of the Universe. Gas in general emits and absorbs

light from stars at certain wavelengths. When the light from these galaxies are observed through a prism, we see a “spectrum” of light, consisting of various emission and absorption lines. Different elements show different spectral lines; in fact, they are analogous to fingerprints and astronomers can obtain enormous amount of information about gases and stars by examining their spectral features. Using these data, Hubble and Humason found that the absorption lines observed in nearby galaxies were shifted to longer wavelengths. This shift is referred to as Doppler-shift or redshift, and the size of the shift in wavelength is correlated with the recession velocity. They also found that the redshifts for galaxies are correlated well with their distances.

$$\text{velocity} = H_0 \times \text{distance} \quad (\text{Hubble Law})$$

This correlation between the distances and recession velocities is known as the Hubble Law, and H_0 here is the Hubble constant (Figure 1). This equation suggests that the faster moving galaxies travel further in a given time. This is analogous to a bomb explosion in which thousands of pieces fly away from the same point; those that travel faster end up further away from the starting point. Imagine a movie showing the galaxies separating further and further away from each other with time. If you played this film backwards, the galaxies would come closer to each other, eventually into a single point. This indicates the beginning of the Universe in the distant past, the Big Bang. The time that has elapsed since the Big Bang is related to the Hubble constant, so if we can measure its value accurately, we can actually determine the age of the Universe itself.

The Hubble Law is one of the direct evidences confirming the expansion of the Universe. Here, the expansion means that the space itself is expanding. This may be a difficult concept to grasp at first, but it can rather easily be demonstrated by an analogy illustrated in Figure 2, in which the expanding Universe is compared to an inflating balloon. On the surface of the balloon, the coins are placed which could be thought as the galaxies. As the balloon expands, distance between the coins become larger, just as the galaxies recede from each other while maintaining the constant size themselves in an expanding Universe.

It is important to determine the Hubble constant accurately. It leads to knowing a correct scale of the Universe, and thereby distances of objects such as the galaxies. Distances are extremely important as without their good measurements, characteristics such as the mass or energy output of galaxies cannot be estimated accurately. It is also important to have a good estimate of the Hubble constant because many of the fundamental quantities, such as the age of the Universe, is embedded in knowing accurately the expansion rate of the Universe. The age of the Universe is expressed in terms of the Hubble constant; it is inversely proportional to H_0 for flat Universe. That is, the larger the Hubble constant is, the smaller the age becomes (see Figure 3). Here, the 'flat' Universe refers to the shape of the Universe itself. This topic itself is beyond the scope of this article, but is one of the fundamental questions that need to be answered in cosmology. I will discuss briefly towards the end of this article what effects the shape has on the determination of the age of the Universe.

Structure of the Universe and Peculiar Velocities

As in any other scientific problem, measuring the expansion rate and the age of the Universe is similar to solving a puzzle. You need to first identify what pieces should be collected, and then you need to solve how you put all of them together. For the Hubble constant, these pieces are the expansion velocities of the galaxies and their distances.

We have now learned that H_0 is a constant that connects velocities and distances to galaxies, and also that knowing the value of H_0 would help in estimating how old the Universe is. Recession velocities can be measured from spectra of galaxies. Thus, what we are missing is a tool to accurately measure distances. However, there is yet one more complication that needs to be considered before measuring H_0 . The real world is much more sophisticated, mainly because the Hubble Law does not *fully* explain the velocities of the galaxies, in particular the way they interact with their immediate neighborhood.

As we know, the gravitational force plays an important role in the physical world, and it also has a significant effect on the motions of galaxies and on the structure of the

Universe, making the distribution of galaxies far from smooth and homogeneous. Shortly after the Big Bang, the Universe was relatively smooth, but there were small unevenness in its mass distribution. The gravitational perturbation from a small mass concentration amplified the clumping, which later grew to form clusters and superclusters of galaxies.

The gravity forces from these galaxy 'clumps' subsequently produce motions of galaxies, usually referred to as peculiar motion, that do not follow the smooth Hubble expansion. On average, the peculiar velocities amount to few hundreds of km s^{-1} (the recession velocities of galaxies range from thousands up to tens of thousands of km s^{-1}), but the accurate measurement of these motions is extremely difficult, as that would require a precise knowledge of the matter distribution in the clusters and superclusters, which is hindered by the presence of large amounts of dark matter on these scales. Fortunately, the typical peculiar velocities are small when compared to the cosmological expansion if you observe distant enough galaxies. But for very nearby galaxies, the peculiar velocities can be comparable to or even larger than the expansion speeds. For example, one of our nearest neighbor galaxies, such as the Andromeda Galaxy (M31), are known to be moving towards us, instead of receding from us as expected by the Hubble Law. This is not because the Universe behaves differently locally, but because of the significant gravitational pull among nearby galaxies. (see Box 1). In order to determine H_0 as accurately as possible, the trick is to measure velocities and distances of as many galaxies as possible, as far out as possible, such that the velocities are large enough that the magnitude of peculiar velocity is only a few percent and can be ignored with respect to them.

These structures such as the clusters and superclusters of galaxies are indeed observed on scales of few megaparsecs (clusters) up to few tens of megaparsecs (superclusters). They are extremely interesting objects as close examination of such structures reveal much information about their formation and their implications with regard to the history of the Universe itself. In fact, the Milky Way is a member of a small group of galaxies called the Local Group, consisting of ~30 galaxies. The morphological types of these galaxies span a wide range -- from spiral galaxies such as our own Milky Way, to elliptical

galaxies, to dwarf irregular galaxies which are much smaller in size and their morphology do not follow any pattern as other two. Although the edge of the Local Group is only ~3 million lightyears away from the Milky Way, distances to some of these galaxies are yet undetermined, which imposes questions when investigating the dynamical history of the Group.

My colleagues, Drs. Barry Madore and Wendy Freedman, and I have been involved in a long-term project to measure distances to all of the galaxies in the Local Group using one particular type of distance estimator. Later in this article, I will spend a significant amount discussing the Cepheid variable stars, the most accurate extragalactic distance estimating tool. However, here, we use a different method which uses the magnitude of the brightest red giant branch stars which are an old population of stars. The method is an excellent tool for such project; because the red giant branch stars are old stars, they can be found in any types of galaxies. Cepheid variable stars on the other hand are only found in or near the regions that have recently formed stars, which means that they are not detected in stellar systems such as elliptical galaxies that are composed of only older stars.

Of course, the disadvantage is that these red giant branch stars are about 10 times fainter than Cepheid variables so the method can be applied to only nearby galaxies (less than 6 million lightyears). However, using the 5-meter Hale telescope at Palomar Observatory, we have been very successful so far in measuring distances to the Local Group galaxies. In 3-4 years, we hope to complete this project, providing more data points for modeling the dynamics of the Local Group, how the galaxies have interacted with each other and formed the present Local Group.

Measuring Extragalactic Distances: Distance Ladder

Since the Hubble Law tells us that the recession velocities of galaxies are proportional to their distances, we can use the redshift velocities to make maps of the distribution of

galaxies in space. During last ~20 years, numerous galaxy redshift surveys produced a detailed map showing the distribution of galaxies (see Figure 4). Since the velocities and distances are correlated, the basic picture of the structures -- clusters and superclusters -- can be discerned from redshift survey maps. However, the problem is that these maps have no known scale associated with them; that is, we do not know whether 1 cm on this map corresponds to 50 million or 100 million lightyears.

Of course, an accurate measurement of the value of H_0 would solve this problem, and in order to achieve that, we need the last piece of the puzzle -- accurate distance measurement. However, distance determination is easier said than done. There are several paths to measuring distances to galaxies, and each path requires several steps. The basic idea is that we directly measure distances to certain types of stars located extremely nearby in our own Milky Way very accurately. Then these stars are used to calibrate another distance estimator which allows the measurement of more distant objects. In general, we refer to these steps as a “distance ladder.” (see Figure 5).

One of the more fundamental distance indicators, that is applicable to very nearby objects, is the parallax. As the Earth orbits around the Sun, a closeby star appears to move with respect to background distant stars. This is analogous to looking at the moon while taking a walk at night; the foreground nearby trees seem to shift back and forth with respect to the distant moon. The angular shift of this apparent motion is inversely proportional to the distance to the star. The disadvantage of the parallax is that it can only be applied to very nearby stars. For distant objects, the angular shift would be much too small to be detected.

The Cepheid variable stars turn out to be superior distance indicators. The brightnesses of these stars vary with periods ranging from 2 up to about 150 days. As shown in Figure 6, the shape of the light curve of a Cepheid variable star resembles a sawtooth, characterized by an abrupt rise followed by a slow decline. These stars brighten and fade as their outer envelopes expand and contract like a pump. In 1907, Henrietta Leavitt discovered that the period of the Cepheid variable stars showed a strong correlation with their absolute luminosity; the brighter Cepheids have longer periods (Figure 7). Thus by observing a Cepheid variable star over some time, we can measure its period and

apparent brightness¹. From its period, the absolute brightness is estimated using the Cepheid's period-luminosity (PL) relation. A star becomes dimmer as it moves further away. Thus, its distance is then estimated by comparing absolute and apparent brightnesses. The calibration of the PL relation is determined by measuring distances to very nearby Cepheid variable stars in the Milky Way using, for example, a more fundamental distance estimator such as the parallax.

The Cepheid variable stars are the most accurate extragalactic distance indicator. However, because of the need to resolve individual stars in a galaxy, Cepheids can only be detected in a handful of nearby galaxies, out to a few Mpc (megaparsecs = million parsecs, about 3 million lightyears) using ground-based telescopes. For galaxies further away, other distance estimators, called secondary distance indicators, are required. They include methods such as the rotation velocity-luminosity relation for spiral galaxies (Tully-Fisher relation). The Tully-Fisher relation is an empirical law that is based on the idea that the bigger galaxies rotate faster. By estimating the rotational velocity of a spiral galaxy which can be measured from its spectrum, one can apply the Tully-Fisher relation to determine the absolute magnitude of this galaxy. By comparing the absolute and apparent magnitudes, the distance can be measured. Another secondary distance indicator that is often used utilizes luminosities of supernovae.

The Tully-Fisher relation is the most widely used secondary distance indicator for spiral galaxies out to 100 Mpc. It correlates the intrinsic brightness of spiral galaxies to their maximum rotational velocity attained. An example of Tully-Fisher relation is shown in Figure 8. It is a powerful tool especially in terms of estimating *relative* distances of galaxies by comparing the Tully-Fisher relation of one cluster of galaxies with another. In order to determine the *absolute* distance, however, one needs an *absolute* zero point calibration of Tully-Fisher relation. This can be done by observing Cepheid variable stars in nearby galaxies which are also good candidates for the Tully-Fisher application.

¹ Apparent magnitude (m) is the magnitude we observe from Earth. On the other hand, absolute magnitude (M) is the intrinsic brightness of the object and is related to apparent magnitude via the relation $m - M = 5 \log(d) - 5$ where d is the distance.

Hubble Constant

Edwin Hubble first measured H_0 by observing Cepheid variable stars and using their period-luminosity relation. His original value of H_0 in 1929 was $550 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which implied the age of the Universe of only 1.8 billion years. This seems extremely short by today's standard, but as the reader will soon discover later on in this article, back in the 20s, the age of 1.8 billion years was in excellent agreement with the age of the Earth derived from radioactive dating.

Later studies however raised the age of the Earth up to 4.3 billion years, which meant that the Earth was much more older than the Universe. This was just the beginning of the 'age discrepancy' controversy which would keep astronomers busy for next half a century. During the 50s, the age problem seemed to have been resolved. In 1952, Walter Baade discovered that there are in fact two types of Cepheid variables; one type is much brighter than the other. Misidentifying these two types of Cepheids had led to wrong distance estimates. In addition, Allan Sandage in 1956 noticed that some of the brightest stars in nearby spiral galaxies were in fact star clusters of HII regions (clouds of mostly ionized hydrogen). Sandage concluded then that the value of Hubble constant was $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Subsequently, Sandage and his collaborators, Gustav Tammann, published a series of papers on the value of H_0 in the 1970s, consistently advocating a low value around $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Although $H_0 = 50$ seemed to solve the age discrepancy, the controversy did not end so fast. This was because many astronomers favored higher value of the Hubble constant around 80 up to $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, values different from the Sandage's estimate by almost a factor of two. The 'branch' of astronomers advocating high H_0 value included Gerard de Vaucouleurs, Jeremy Mould, Marc Aaronson, John Huchra, Brent Tully and Sidney van den Bergh. For next 20 years, Sandage and de Vaucouleurs remained at the center of what became known as the H_0 debate.

HST and H_0

The H0 conference in 1984 in Aspen, Colorado, brought several astronomers together to design an ambitious project, which later became one of the HST Key Projects. HST would revolutionize the H0 problem, because with its superb imaging capability, it would be capable of detecting and measuring Cepheid variable stars in tens of galaxies, to distances 10 times larger than was possible from the ground. The objective of the Key Project was to observe 25 to 30 spiral galaxies in the nearby Universe (< 20 Mpc), search for Cepheid variable stars in them, accurately obtain their periods and magnitudes and estimate their distances. These spiral galaxies would then be used to calibrate the zero point of the Tully-Fisher relation and other secondary distance estimators, which in turn can be used to probe the Universe out to ~ 100 Mpc, far enough to determine the Hubble constant to 10% accuracy.

Using the ground-based telescopes, the Cepheid observations are possible only to 3 Mpc or so. Unfortunately, within this distance, there are only a handful of galaxies. Searching for Cepheid variables and eventually calculating their periods and magnitudes is an especially time-consuming job. Indeed, some of these efforts did often require more than 10 years of observations in order to determine one galaxy's distance. The ground-based observations also are hampered by the presence of atmosphere, which degrades the quality of photographic images significantly, making it hard to resolve individual stars.

The Hubble Space Telescope (HST) was launched from the cargo bay of the Space Shuttle in 1990. To everyone's dismay, its 2.4-meter primary mirror suffered from a major problem called the spherical aberration; that is, the telescope could not be focused. Very fortunately in December 1993, the Space Shuttle retrieved HST back into the cargo bay, and the astronauts executed a magnificent servicing mission. Some instruments were replaced by better, new ones and a corrective mirror was placed. This mission was televised live, and many of us still remember how awestruck we were watching such intricate maneuvers done in space.

The first pictures taken with the refurbished HST were nothing short of spectacular. Shortly after the first servicing mission in January 1997, a winter meeting of American Astronomical Society was held in Washington D.C. There, a series of refurbished-HST pictures were shown to an audience of about 2000 astronomers for the first time. When

the first set of images were shown, we were all simply stunned, and we bursted out into a long standing ovation (which does not happen often in the astronomy-world). The images shown there included a spiral galaxy in the Virgo Cluster, M100, one of the Key Project target galaxies. In Figure 9, we show both the ground-based and HST images of M100. An image taken with a Wide Field Planetary Camera 2 (WFPC2)² is overlaid on top of the ground-based, less resolved image. Such HST images of unprecedented quality revealed details in every object observed that had never before seen, confirming that the observation of Cepheid variable stars in galaxies as far out as 15 - 20 Mpc was possible. It became immediately clear that the goal of the Key Project was not impossible to reach: to determine the value of Hubble constant with 10% uncertainty, by observing Cepheid variables in galaxies using the HST.

The HST is far superior for Cepheid variable searches. Because it is in space, the weather is not a problem, allowing us to schedule precisely the dates of observations, maximizing the probability of detecting variable stars with periods between 10 and 60 days.

Cepheids can be distinguished from other types of variable stars by their distinct sawtooth-like, lightcurve shapes. However, it is not an overnight task to search for Cepheid variable stars, even when using spectacular images taken by HST. Dr. Randy Phelps of Carnegie Observatories and I have recently led the search for Cepheid variable stars in a spiral galaxy, NGC 2090 (Figures 10a and b). This galaxy was observed 12 times between January 18th and March 8th, 1996. In addition, it was observed once one year prior to this period, on February 15th, 1995. Each of these 'visits' consisted of taking two 1100-second exposures of NGC 2090 using V (green) filter (~5500A), and during five of these 13 visits, we observed the galaxy also using an I (near-infrared) filter (~8000A) for 1300 seconds each. So, we have 2x13 V images and 2x5 I images, a total of 36 pictures. These images are first sent from the HST down to Space Telescope

² WFPC2 (Wide Field Planetary Camera 2): was developed by Jet Propulsion Laboratory as a spare instrument in 1985. During the first servicing mission, it replaced the original Wide Field Planetary Camera. The WFPC2, as seen in Figure 5, consist of L-shaped three wide-field sensors and a smaller but higher resolution planetary camera placed in the fourth corner.

Science Institute in Baltimore, MD where the data are first processed. Then the tapes containing the data are sent to us within a few days.

Using special software, we automatically find stars on each of these frames and measure magnitude of each individual stars. We find on the average 80,000 - 100,000 stars on each picture -- so that translates into $80,000 \times 36 = 2,880,000$ stellar brightness measurements! Needless to say, this requires an enormous amount of computer time (and patience).

Once we have brightnesses of all the stars on all the pictures, all 13 sets of data are combined. In the days before the computers became readily available, the Cepheid variable search was rather a painstaking labor. It was done by visually comparing two pictures of the same field taken some time apart. While most of the field remain unchanged when blinking the two pictures back and forth, your eyes would pick out those stars whose brightness change. Although this was an effective method, it was a very subjective one. Today, we rely on the speed and objectiveness of computers enormously.

After calculating brightness of all the stars in the HST field, we then do a statistical analysis to pick out those whose brightness vary significantly with time (see Figures 10c and d). In addition, we need to look for not just any variable stars, but those whose lightcurves resemble a 'sawtooth'. Once candidate Cepheid variables are selected, we measure their periods by trying out every period between a few days up to 50-60 days and judging which period is the most likely solution. Figure 11 demonstrates an example, in which I show lightcurves of one of the Cepheid variable stars found in NGC 2090. On top, the brightness of this Cepheid is plotted against the day of observation. This particular Cepheid fluctuates its brightness by about 60 percent from its brightest peak to the faintest phase. You can also see that this Cepheid is fluctuating its brightness in a cycle of about 20 days. As a test, we try out a period of 18 days; this is done by basically dividing the top graph into bins of 18 days each. Then each bin is stacked on top of each other. The result is represented by the middle lightcurve. This is by no means a good Cepheid lightcurve, showing no characteristic of a 'sawtooth'. On the very bottom, however, is shown the result of trying out the period of 20.7 days. The sawtooth

lightcurve becomes prominent. This series of exercise -- measuring magnitudes of individual stars, searching for Cepheids, and finally measuring their periods accurately -- is carried out independently by both of us, Dr. Phelps and myself, using two different software packages in order to confirm each other's results. The whole analysis takes at least few months -- just running software on all of the images require two to three weeks. However, realizing what lies ahead and knowing what we are solving for keeps us motivated.

We found 34 Cepheids in NGC 2090 and their periods and luminosities place it at distance of 12.1 Mpc. In Figure 13, their periods and apparent magnitudes are plotted (*bottom*), showing a very tight period-luminosity (PL) relation. The distance to this galaxy is determined by comparing its PL relation with that of Large Magellanic Cloud (*top*), a galaxy that is right next to us. The distance to LMC is well determined via various methods and plays a role as a cornerstone in the Key Project Cepheid distances -- that is, distances to all the other galaxies are measured with respect to LMC, including NGC 2090. In order to deduce the distance, we basically slide the LMC PL relation up until it “matches” with that of NGC 2090. We place this galaxy at distance of 12.1 Mpc. Although this galaxy is not associated with any clusters of galaxies, as a Tully-Fisher calibrator, it provides another step towards the H_0 determination.

M100, whose spectacular image was shown in Figure 9, was determined to be located at 16.1 megaparsecs, or 52.5 million lightyears. The discovery of Cepheid variables in M100 was first reported in October 1994. Since then, the Key Project has obtained WFPC2 images of many more spiral galaxies including NGC 2090. Currently, we are working altogether on 25-30 galaxies; for each one, two astronomers do individual analysis that are compared in the end before reporting a new distance. We are also working on several other sub-projects other than the Cepheid searches themselves, in order to prepare for the final measurement of the Hubble constant. One such subproject which I am leading is to establish a good database for the calibration and application of the Tully-Fisher relation, which consists of compiling database of magnitudes and rotational velocities for all the Key Project galaxies. This itself is a large enough project to keep a group of us occupied. By the completion of the project that is expected in

about 1 year, we will have measured accurate distances to 25 spiral galaxies. Our ‘midterm’ application of the Tully-Fisher relation showed that using the galaxies out to 100 Mpc, the value of Hubble Constant is $72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with 20% uncertainty. Figure 14 shows the distance-velocity relation for distant clusters of galaxies from our Tully-Fisher analysis. For each cluster of galaxies applied, their distances -- measured by the Tully-Fisher relation which was calibrated using our new Cepheid distances -- and their recession velocities are plotted. The *slope* of the solid line represents the value of H_0 . In this case, it is $\sim 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The Key Project team is not the only one who is attempting to measure the Hubble Constant using the HST. Allan Sandage, who is a long-time advocate for a low H_0 value, leads a group that is also observing Cepheid variable stars in nearby spiral galaxies. Instead of using the Tully-Fisher relation, his team uses Type Ia supernovae, whose progenitors are white dwarfs that explode as a consequence of accreting matter from companion stars. These stars show a remarkable homogeneity in their light and color variations with time, and their maximum brightness obtained at the time of explosion is shown to be constant, satisfying a criteria to be a good distance indicator. Sandage’s group has successfully searched for Cepheids in galaxies which have had a Type Ia supernova event in recent years. The recent reports indicate values between 55 and $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Spiral galaxies in general contain not only stars, but lots of dust and gas. The latter often obscure the stars, dimming their apparent magnitude. So in order to determine the star’s intrinsic luminosity, one needs to estimate exactly how much of light is lost before reaching us due to the dust. This is not an easy task, and often turns out to be one of the major obstacles in distance determination. Drs. Adam Riess, Robert Kirshner and Bill Press of the Center for Astrophysics in Cambridge, MA, recently developed a powerful method which increases significantly the precision of the Type Ia supernovae distance indicator. By effectively combining observations of supernovae in multiple wavelengths, Riess and collaborators were able to distinguish supernovae that are intrinsically faint from those that are faint due to dust. They were also able to calibrate small variation in brightness of supernovae. Figure 15 shows a velocity-distance diagram for galaxies with

observed Type Ia supernovae after applying Riess's method; the tight correlation observed here is impressive. Their analysis yields $H_0 = 64 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

There are of course other estimates of Hubble Constant made during past year or two. Listing them here would probably take up a whole page! In Figure 16, we show various estimates of the Hubble constant as a function of time spanning from 1974 up through 1996. Many of the recent estimates have suggested H_0 between 65 and 75 $\text{km s}^{-1} \text{ Mpc}^{-1}$. The gap between estimates is indeed narrowing down, in comparison to the time before the HST observations began.

Hubble Space Telescope

The Hubble Space Telescope (HST) was deployed from the Space Shuttle cargo bay in early 1990. Ever since, it has been sending unprecedented spectacular images back to the earth.

The idea of the HST, to place a telescope in earth's orbit, has been around for a long time. The first serious justification, however, was made in 1946 by late Lyman Spitzer who submitted a proposal for the extraterrestrial observatory. His idea is now viewed as the birth of the HST itself.

The HST orbits the Earth, at an altitude of 515 km, and completes this orbit in 90 minutes. It was placed in a low orbit, so that it would be easily accessible with the Space Shuttle for servicing missions. After the telescope takes a picture of an object, the data takes quite a trip before it reaches the observer. It is first sent to two orbiting satellites which stay in a much higher orbit (at 35,400 km) called geostationary orbit. It means that each one of them remains above the same Earth location at all times. The data are then relayed from these satellites down to White Sands, New Mexico. From there, it is relayed to the Goddard Space Flight Center (GSFC) in Maryland via communication satellite. The raw scientific data finally reaches the Space Telescope Science Institute in Baltimore from the GSFC by telephone link.

Soon after its deployment from the Shuttle, it became clear that the mirrors of the HST were made to the wrong shape; the quality of the pictures was far below the original specifications of the telescope. After much discussion on how to repair this faulty mirror, it was decided that a corrective optics would be put in such that the light would be focused before reaching the instruments. In December 1993, seven astronauts participated in this incredible servicing mission which consisted of some of the longest space walks. The servicing mission was nothing but a success.

Recently in February 1989, the second servicing mission was executed. This time, a spectrometer was replaced by a new instrument. In addition, an infrared instrument (NICMOS) was placed in the HST. Infrared light penetrates through dust more than optical light, which fills interstellar space in the galaxies. Observations with infrared helps to view certain regions that are heavily obscured by surrounding dust, such as the center of the Galaxy. It turns out that NICMOS will not last as long as planned, but it has already brought back remarkable images, revealing structures of galaxies that were not possible to see until now.

The Universe is Younger than the Stars?

Although there are still much more work left for us for next year or so, the consensus in the value of H_0 might have reached a reasonable point. However, the puzzle is not completely solved yet. $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ indicates that the age of the Universe is 9 billion years for a flat Universe (recall Figure 3). Some of the readers who have been keeping up with the latest news in cosmology might remember that the oldest stars in our own Milky Way Galaxy have been estimated to be at least 15 billion years old. Could the stars which are located **in** the Universe be older than the Universe itself?

There are several ways to resolve this age-discrepancy issue, one of which is to introduce a density parameter, Ω . The density parameter indicates how much matter there is in the Universe, or more accurately, it refers to how dense that Universe is. When you throw a ball up in the air, it will eventually come down to the ground. However, there is a critical velocity you can attain (called escape velocity), with which you would be able to leave the Earth. Indeed using a powerful rocket, it has been possible to send an object

out into the space. The density parameter is analogous to this idea. Although the Universe is expanding, there are gravitational pulls among matter. If there is enough matter, the gravitational pull would eventually overpower the expansion of the Universe; in this case, the Universe would expand to a maximum size, but then start shrinking its size. At a particular density called critical density, however, the Universe is just sparse enough to expand forever. The density parameter is the ratio of the actual density of the Universe to the critical density. Thus for an open model, the Universe expands forever, (density is less than the critical density, thus $\Omega < 1$); on the other hand, a closed model ($\Omega > 1$) is the one in which the Universe, after reaching its maximum value, collapses to a 'big crunch'. A flat Universe is represented by $\Omega = 1$ and it had been the most favored model until recently as it is predicted by the inflation theory, which seems to explain the observed state of the Universe quite well. However, recent observations of galaxies in clusters and superclusters seem to be most consistent with a value of Ω that is much less than 1.

Recently, however, Hipparcos satellite released parallax measurements for some of the nearby stars. This satellite was launched in 1989 by European Space Agency, designed to measure direct distances to stars using parallax. Neil Reid of Palomar Observatory estimates that the new data would decrease the age of the Globular cluster stars down to 11 to 13 billion years. Independent analysis using Hipparcos data by Brian Chaboyer of Steward Observatory (University of Arizona) and his collaborators also indicated that the mean age of the oldest Galactic globular clusters could be 11.7 billion years. Michael Feast, on the other hand, reported that the Cepheid distance scale itself might have a systematic uncertainty of about 10%, decreasing H_0 by up to 10%, again using the Hipparcos data. However, the Hipparcos data are still preliminary and we need to wait for more accurate data. As one can see, even if the H_0 is measured with high accuracy, making sense out of the value itself, bringing both theory and observations into an agreement, is a challenging task.

Another constant that could possibly play a significant role in resolving the age discrepancy issue is the cosmological constant, Λ , which was first introduced by Albert Einstein in 1917. At this time, the Universe was believed to be static on cosmological

scale -- it was not expanding nor collapsing. In order to explain such world, Einstein introduced this cosmological constant which is equivalent to repulsive force that opposes the force of gravity. Within a decade, however, the expansion of the Universe was observationally verified and it was no longer necessary to consider Λ . Nonetheless, the cosmological constant is being discussed today as a possible device to solve the age discrepancy problem. The cosmological constant 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 later than zero.

In Figure 17, we show the relations between H_0 , Ω , and Λ . In both figures, the lines represent the correlation corresponding to the age found by the Globular cluster stars, 12 ± 1 billion years. In both cases, the solid line corresponds to the 12-billion year Universe, and two dotted lines below and above the solid line correspond to 13 and 11-billion years respectively. 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 Ω is much less than 1. For more realistic values of Ω , the Hubble constant of less than $55 \text{ km s}^{-1} \text{ Mpc}^{-1}$ 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 $0.4 < \Omega < 0.6$.

Where do we go from here?

As part of the HST Key Project on the Extragalactic Distance Scale, we will obtain our last HST observations later this year, and are planning on reporting our final estimate of the Hubble constant, accurate to 10%, in about one year. We are also working on various other problems associated with the Cepheid PL relation; it is not a perfect distance indicator by any means. One of the outstanding question is whether the Cepheid variables are sensitive to their metal contents. We are hoping to provide an upper limit of such an effect, if there is any.

It is a historical time right now as the closure to the Hubble constant is approaching quickly. This does not signify that we now know everything there is to know about the Universe. There are still countless questions to be investigated in astronomy and cosmology. We still need to resolve fundamental questions such as the value of Ω and Λ . By now, astronomers have a reasonable understanding of how galaxies formed in the early universe. However, a full picture of how they *evolved*, the history of galaxies from their birth until now, still remains as one of the outstanding issues in astronomy.

In order to solve these mysteries, astronomers worldwide are constructing large-scale telescopes which will be used as tools to examine above questions. Japan is building an 8.3-meter Subaru telescope on Mauna Kea in Hawaii, which will be in full operation by XXX, 199X (Doi-san, please fill this in for me!). United States is also building a couple of 8-meter class telescopes in Northern and Southern hemispheres. There is also an ambitious plan in US to build the Next Generation Space Telescope, which will host an 8-meter mirror. The objective of the NGST is to observe the galaxies at the time of their birth. We are all patiently waiting for the completion of these telescope. It will be undoubtedly a remarkably exciting time when the spectacular data from Subaru and other telescopes start pouring in!

Figure Captions

Figure 1: Hubble's original diagram showing the distance-velocity relation of nearby galaxies. The solid line indicates the best fit to the data, whose slope represents the Hubble constant. Hubble's estimate of H_0 was around 500 km/sec.

Figure 2: A balloon depicting the expansion of the Universe. The coins located on the surface of the balloon represent galaxies. As the Universe expands, the space between the galaxies increase, while their intrinsic size remain constant.

Figure 3: shows the relationship between the size and age of the Universe. The value of H_0 at a given time is defined by the slope of this age-size relationship. If the Universe has been expanding uniformly since the Big Bang, its size is described by a thin straight solid line and the age would be $1/H_0$. According to the standard cosmological model that we use today, the Einstein-deSitter model for a flat Universe, the size—age relation more correctly follows that indicated by a bold line. Thus, the age estimate becomes age = $(2/3)(1/H_0)$.

Figure 4: A 'slice' of the Universe. Each dot in this map represents an individual galaxy. We are located at the apex of the slice, and the distance from this point is correlated with the actual distance to the galaxies. Clusters of galaxies often show an elongated feature such as the prominent one near the apex which is the Virgo cluster. When the value of Hubble constant is determined, we will know the scale of this map. *Courtesy: John Huchra (Center for Astrophysics).*

Figure 5: "Distance Ladder", showing how some of the distance indicators are calibrated. RR Lyrae variable stars are another type of primary distance indicator. These stars are found in old stellar systems, unlike Cepheids which are found in spiral galaxies. This diagram is by no means complete. There are several other methods that are used to measure distances to galactic and extragalactic objects.

Figure 6: An example of a Cepheid variable star, showing its brightness variation as a function of time. It is characterized by its appearance which resembles a 'sawtooth' shape.

Figure 7: A period-luminosity (PL) relation for Cepheid variable stars found in Large Magellanic Cloud, the closest galaxy to our own Milky Way.

Figure 8: Examples of Tully-Fisher relation for spiral galaxies. The relation shown in top is for a nearby cluster of galaxies, whereas the one on the bottom is for a distant cluster. The difference between these zero points of two relations infers the *relative* distance between the two clusters.

Figure 9: An image of M100 taken from a ground-based telescope. The HST image is overlaid. *Courtesy: Laura Ferrarese (California Institute of Technology).*

Figure 10: (a) A ground-based picture of NGC 2090. A footprint of an HST WFPC2 field is overlaid. (b) A stunningly detailed picture of NGC 2090 as observed by the HST WFPC2. (c) A closeup view of Wide Field Camera 3. Cepheid variables are indicated by circles. (d) One of the Cepheid variables found on WFC 3, showing how its brightness changes with time. The Cepheid variable star is located in the middle of each field. Other objects that seem to appear and disappear are cosmic-ray hits (*note to Kubota-san: This Cepheid is the one located right below the "EAST" arrow*).

Figure 11: An example of a Cepheid variable found in NGC 2090. See text for detailed discussion.

Figure 12: Examples of Cepheid variable stars in NGC 2090.

Figure 13: Comparison of period-luminosity (PL) relations of Large Magellanic Cloud (LMC) and that of NGC 2090. By sliding the LMC PL relation down and matching it with that of NGC 2090, we can estimate the distance to NGC 2090.

Figure 14: Distance-velocity relation for distant clusters. The Hubble constant is determined by measuring the *slope* of the fit to the data. Here, it is estimated to be 72 km/s/Mpc.

Figure 15: Hubble diagrams for galaxies whose distances were estimated by the Type Ia SN method. The new technique of Riess et al. has been applied. (*adopted from Riess et al. ApJ December 1996*). PLEASE USE THE BOTTOM PART ONLY!

Figure 16: demonstrates the ‘history’ of Hubble constant estimates. Beginning 1990, these estimates started showing some convergence. The HST Key Project is planning on reporting its final number in a couple of years. (*courtesy: Robert Kennicutt, Jr., Steward Observatory*)

Figure 17: shows relations between Hubble constant, density parameter and cosmological constant. Notice that in order to accommodate $H_0 = 70$ km/sec/Mpc, and the age of 12 billion years, we need a density parameter that is much less than 1.0.