PHY 475/375
Lecture 2
(March 28, 2012)

The Scale of the Universe: The Shapley-Curtis Debate

By the 1920's a debate had developed over whether some of the "spiral nebulae" catalogued in the 18th century by Charles Messier and William Herschel and later astronomers were parts of our own Galaxy, or island universes (i.e., other galaxies, just like ours).

On April 26, 1920, Harlow Shapley of Mt. Wilson Observatory and Heber D. Curtis of Lick Observatory debated the nature of these spiral nebulae at a meeting of the National Academy of Sciences in Washington, D.C., by giving talks at a forum titled "The Scale of the Universe."

Based on the measurements of the distribution and distances of globular clusters using Cepheid variables, Shapley concluded that the diameter of our Galaxy was 300,000 LY. Cepheid variables have a well-known relation between their period of variation and luminosity, and hence can be used as "standard candles" for measuring distances (i.e., by measuring their period of variation, you can determine their intrinsic brightness, and by comparing intrinsic to observed brightness, you can derive the distance to the Cepheid). Shapley also believed that the Sun was not at the center of our Galaxy, but about 60,000 LY away (based on the distribution of globular clusters being asymmetric about the Sun; i.e., he observed many more globular clusters in one direction than in the other). Since the Milky Way was so large, he argued, it had to be the whole Universe, and the spiral nebulae were just gas clouds inside our Galaxy/Universe.

Curtis argued that the Milky Way Galaxy was 10 times smaller (hence around 30,000 LY in diameter), based on star count analysis and distance estimates from spectral types and intrinsic brightness of stars that suggested a smaller galaxy, with the Sun near to its center. He believed the spiral nebulae were outside the Milky Way, and were in fact galaxies just like our own. He based this partly on Vesto Slipher's measurement of high recessional speeds for nebulae (discussed in more detail later in this lecture); if the spiral nebulae were within our Galaxy, they would move with a much slower speed relative to the Sun. Also, his apparent sizes for the spiral nebulae were consistent with his estimate for the Milky Way when the nebulae were placed outside the Milky Way, at great distances from us.

A partial resolution was achieved in the 1920's, when Edwin Hubble identified Cepheid variable stars in Andromeda (M31). By measuring the distance to these Cepheid variables with the 100-in Hooker Telescope on Mt. Wilson, Hubble was able to show that the distance to the spiral nebulae was greater than the extent of our Galaxy proposed by Shapley, and hence the spiral nebulae were just other galaxies outside of our own.

However, Shapley was also proved partially correct when it gradually became clear by the 1930s that the size of our Galaxy had been grossly underestimated, and that the Sun was nowhere near the center of our own Galaxy. Therefore, our Galaxy turned out to be larger than previously believed with the Sun far from its center (as Shapley had claimed), but the Universe turned out to have many galaxies (as Curtis had claimed).

The Realm of the Nebulae

(with apologies to E. Hubble)

As we move outward from our Milky Way Galaxy, we find the Canis Major Dwarf at $\sim 45,000$ LY and the Sagittarius Dwarf Elliptical at $\sim 80,000$ LY. Both of these galaxies have been worked on by the gravitational field of our Milky Way, and are in the process of being cannibalized by it. A little farther out, the Large Magellanic Cloud (LMC) at 160,000 LY and the Small Magellanic Cloud (SMC) at 210,000 LY are two irregular shaped galaxies that are easily visible from locations in the the southern hemisphere of the Earth. The nearest large galaxy is the spiral galaxy M31, also known as Andromeda.

Eventually, we see that we have a cluster of 30-40 galaxies in our neighborhood, in a volume about 10 million LY in diameter. This cluster is called the *Local Group* of galaxies, and its largest members are the Milky Way and M31.

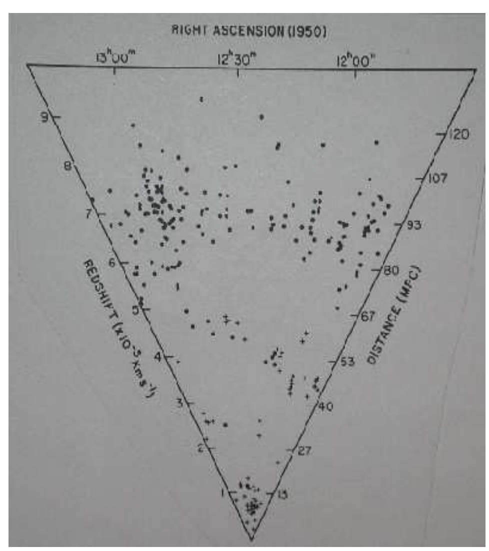
Within 50 million LY of the Sun, we have about 20 such groups of galaxies. Examples are M81 with 8 members at a distance of 10 million LY, Centaurus with 17 members at 11 million LY, and NGC 1023 with 6 members at 31 million LY.

At 50 million LY lies the nearest rich cluster of galaxies: the Virgo cluster, with about 250 large and 2000 smaller galaxies.

The Local Group and the Virgo cluster are members of the *Local Supercluster* of galaxies. Its approximate extent is about 60 million LY in diameter.

At this stage, it is well worth asking if we have reached our limit. Are there structures on scales larger than superclusters?

A remarkable discovery in the 1980s was there there exist significant voids between superclusters. Tantalizing evidence for this was first suggested by the work of Tifft & Gregory (1976) and Gregory & Thompson (1978). In the figure on the right, taken from Gregory & Thompson (1978), we see a pie-slice plot with right ascension along the top horizontal edge and declination information collapsed on to this slice (right ascension and declination are like longitude and latitude respectively in the sky, used to describe the locations of stars, galaxies, and other celestial objects). The radial direction of the pie shows the redshift on the left, and equivalently, the distance to the galaxies on the right. Each point in the plot is a galaxy, and we are located at the bottom tip of the pie. The Coma cluster of galaxies is at the top left, and the A1367 cluster is at the top right.



So, what is the redshift, and why should measuring it allow us to measure the distance?

The Hubble Law: Velocity-distance Relation

When we observe a galaxy at visible wavelengths, we are primarily detecting the light from the billions of stars contained in the galaxy. So, if we observe the spectrum of a galaxy at visible wavelengths, it will typically contain absorption lines that are due to the relatively cooler upper atmospheres of these stars (but note that galaxies containing Active Galactic Nuclei (AGN) will also have emission lines due to the hot gas in their nuclei).

Consider one of these absorption lines, whose wavelength as measured in a laboratory here on Earth is $\lambda_{\rm rest}$. Yet, when we measure the wavelength $\lambda_{\rm obs}$ of the same absorption line in the spectrum of a distant galaxy, we will find that $\lambda_{\rm obs}$ is not equal to $\lambda_{\rm rest}$. In fact, except for a few nearby galaxies in our Local Group, we will find that nearly all galaxies have $\lambda_{\rm obs} > \lambda_{\rm rest}$.

Since, in the visible spectrum, the wavelength of red light (∼630 nm) is longer than that of blue light (∼450 nm), this phenomenon of $\lambda_{\rm obs} > \lambda_{\rm rest}$ is generally described by the term *redshift*.

A quantitative measure of the redshift z is obtained using the formula

$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm rest}}{\lambda_{\rm rest}} \tag{2.4}$$

Between 1912-1925, Vesto Slipher at the Lowell Observatory measured the shifts in the wavelengths of spectral lines for about 40 galaxies, and found that almost all were redshifted ($z > 0$).

The exceptions were all nearby galaxies within the Local Group. By convention, $z < 0$ is usually described as a blueshift. Interestingly enough, Slipher's first measurement in 1912 was for M31 (Andromeda), which is one of the few galaxies that exhibits a blueshift.

The observed redshift or blueshift is usually interpreted as a Doppler shift due to the motion of the galaxy away from or toward Earth, respectively. So a galaxy with $z > 0$ would be moving away (receding) from us.

We can measure the redshift z by direct observation with telescopes. For galaxies in the local Universe, we can then use the classical nonrelativistic expression for the Doppler shift, $z = v/c$, to convert the measured values of z to the radial velocities of the galaxies v.

When we set up our cosmological models, we will learn that this cosmological redshift is not due to galaxies moving through space, but rather due to space itself stretching (carrying away the galaxies with it).

By 1929, enough redshifts had been measured that astronomers could seek the answer to the question of whether the redshift of a galaxy depended on its distance from the Earth. Edwin Hubble plotted the velocity (cz) of a galaxy versus the distance to that galaxy (r); Hubble's original plot is shown in Figure 2.4 (page 13) of your text, while an updated version of the plot with more recent data is shown in Figure 2.5 (page 15).

Hubble found that there is a linear relation between the two quantities given by

$$v = H_0 \, r \tag{2.6}$$

where H_0 is called the Hubble constant, or to purists, the Hubble parameter (since, as we will learn later, it is possible it may have had different values at different periods in the Universe). Equation (2.6) is now known as *Hubble's law*, and it marked a revolutionary advance in the study of cosmology.

- From equation (2.6), the units for H_0 are found to be km s^{-1} Mpc^{-1}.

- When Hubble first discovered his law, he found $H_0 = 500$ km s^{-1} Mpc^{-1}.

- However, it turned out that Hubble was severely underestimating the distances to galaxies (i.e., while the redshift z could be measured to great precision, the distance to the galaxy r could not, and was the major source of error).

- More recent determinations of the Hubble constant by groups employing independent methods and using data from the Hubble Space Telescope gives a consensus value (adopted in your text, and by us) of
$$H_0 = 70 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{2.7}$$

- So, this is the redshift that is shown in the pie-plots of Tifft & Gregory (1976) and Gregory and Thompson (1978; reprod), and why their slices can also be labeled in terms of the distance.

Let us return, therefore, to the matter of superclusters and voids.

The existence of voids was proven conclusively by extensive surveys following the initial work. We looked at two examples in lecture: the CfA redshift survey (Huchra & Geller 1998), in which the existence of voids is clearly seen, along with a contiguous sequence of superclusters that has come to be known as the "Great Wall." We also looked at a more extensive survey that concluded in the last decade. The 2dF Redshift Survey (so called because each pointing of the telescope covered a field of view of 2° in the sky) with the Anglo-Australian telescope observed over 220,000 galaxies in 1800 deg^2 of sky, and clearly shows these voids.

In summary, therefore, it appears that superclusters, together with the voids between them, constitute the largest scale structures in the Universe, at the level of 50 Mpc (or so).

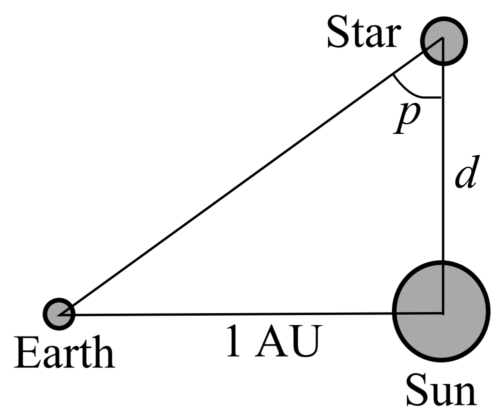
On the largest scales of 100 Mpc or greater, therefore, we will assume that the Universe is isotropic and homogenous; the meaning of these terms will be discussed in the next lecture.

For now, we must digress to learn about the distance unit known as parsec (pc).

The parsec (pc)

While LY is used more frequently in popular publications, astronomers prefer instead to use the parsec (pc) to measure distances, mainly because it is geometrically connected to observations.

The distance from the Sun to an object will be 1 pc if the Earth and Sun subtend an angle of 1 arcsecond (also called second of arc) at the object, where 1 arcsec is 1/3600 of a degree.



Therefore, if the Earth and Sun subtend an angle of p arcsec at an object, the distance from the Sun to that object will be d pc, where

$$d \text{ (in pc)} = \frac{1}{p \text{ (in arcsec)}}$$

The practical way to measure this is to observe the object against a background of distant objects six months apart, and measure the apparent angular shift in the position of the object in the sky. Half this angular shift will then be the parallax (p) in arcsecond, and $1/p$ then gives the distance d in pc.

Note that no real star has a parallax angle of 1 arcsecond; the nearest star is at a distance of 1.3 pc, so its parallax angle is $p = 0.8$ arcsec; more distant objects will clearly have smaller parallaxes.

Connecting to other units, 1 pc = 3.26 LY = 3.1×10^{16} m

It is a good idea to remember the following typical distances:

- The average separation between stars in a galaxy (like ours) is typically of order pc. (But note that there are so-called starburst galaxies where stars may be much nearer to each other).

- The diameter of a galaxy is typically of order several tens of kpc or $\sim$100 kpc; e.g., our Milky Way Galaxy has a diameter of about 30 kpc.

- The separation between galaxies in a cluster of galaxies (like our own Local Group) is typically several Mpc, where Mpc stands for a million pc, i.e., 10^6 pc; e.g., we are at a distance of 0.7 Mpc from M31 (Andromeda galaxy).

- The separation between clusters of galaxies is typically of order 10 Mpc. For example, we are about 15 Mpc from the Virgo cluster.

Scales in Time

The finite speed of light has an important consequence. Since we can only obtain information about an object by studying the light emitted or reflected from the object, therefore, we see objects the way they were when the light left the object. For example, it takes about 8 minutes for light to travel from the Sun to the Earth, so we see the Sun the way it was 8 minutes in the past. As we go farther, this period becomes longer and longer. So, when we observe the Orion nebula which is 1500 light years away, we see it the way it was 1500 years ago; the way it was during the time of the decline and fall of the Roman empire here on Earth. When we look at Andromeda which is at a distance of 2.5 million LY, we see it the way it was 2.5 million years ago, when the earliest humans started walking on the Earth.

As we look farther and farther at more distant galaxies, therefore, we are looking further and further back in time.

So, how far back do we go? Did the Universe always exist, or did it have a beginning?

A very simple observation tells us the answer: the night sky is dark!

The fact that the night sky is dark is called Olber's paradox. We started discussing it, and why the fact that the night sky is dark is paradoxical, but this topic will be written into the lecture notes for the next class, in order to preserve continuity.