ASTR368
The Large-Scale Structure of the Universe

The Distance Ladder

The cosmic distance ladder (also known as the extragalactic distance scale) is the way astronomers measure the distance of objects in space. No one method works for all objects and distances, so astronomers use a number of methods. The methods that work best on the most distant sources depend on accurate distances to the nearby sources. Therefore, the errors compound. Each rung of the ladder provides information that can be used to determine the distances at the next higher rung.

Direct measures

We can only measure distances directly in two ways:
1) radar. We can bounce radar signals off the interior planets, and from that information and geometry determine the distance to the Sun.
Range: few AU

2) parallax. Why do we need the distance to the Sun? Because the parallax depends on knowing this distance. Do you all know about parallax?
Using parallax we can determine the distance to stars within a few kpc.

$$d = 1/p \tag{1}$$

where d is the distance in pc and p is the parallax in arcseconds. As the distance increases, the angle decreases until eventually it is unmeasurable. Recently we have parallax measurements using VLBI of even more distant sources. But parallax measurements are really only useful within our Galaxy. How could we extend parallax?
Range: few kpc

Standard candles

To extend the distance ladder we can use standard candles, or objects of known luminosity. This is the main way for getting large-scale distances. We can then measure the brightness and use

$$F = \frac{L}{4\pi d^2} \tag{2}$$

or

$$d = \left(\frac{L}{4\pi F}\right)^{0.5} \tag{3}$$

In stupid magnitudes,

$$m - M = 5\log d - 5 \tag{4}$$

so

$$d = 10^{0.4(m-M+5)} \tag{5}$$

So we need some standard candles. How do we determine a standard candle:

- need to determine the luminosity or absolute magnitude of a class of objects
- need to confirm at all luminosities are the same, or at least calibratable through some other observation
- need to make sure this class is actually a class. This is actually a big problem, because different classes of objects can have similar properties.

What standard candles do we have:

Cepheids

Henrietta Swan Levitt noticed that the most luminous cepheids had the longest periods, which gave rise to the Cepheid Period-Luminosity relation:

$$M_V = -3.53 \log P_d - 2.13 + 2.13(B - V)\,, \tag{6}$$

with P_d in days. So we can measure the period of a standard candle and determine it's luminosity. There are actually many different types of variable stars that can be mistaken for Cepheids. This has led to numerous problems over the years, as those other types have different, or no, period-luminosity relations.
Range: 30 Mpc

Tully-Fisher/ Faber-Jackson

We talked about these before, but using these relations we can convert between measured velocities and the luminosity of the galaxies.
Range: > 100 Mpc

Type 1a supernovae

Type 1a supernova are caused by white dwarfs exploding when the accrete to be more than the Chandesekhar mass of 1.4 Msun. Since they all have the same mass, they have similar properties and can be used as standard candles (with some calibration)
Range: > 1000 Mpc

There has been some controversy lately about whether Type 1a SN are actually standard candles. Part of the problem comes from distinguishing Type 1a SN at great distances.

Expansion

Assume we have an expanding region of gas that emits emission lines. We can measure the line shift from the near side to the edge. This gives us an expansion velocity $v_{\rm ej}$. We can also measure the angular size of the region theta. If we can then see the expansion $\omega = d\theta/dt$, then the transverse velocity $v_\theta = \omega d = v_{\rm ej}$. Therefore,

$$d = \frac{v_{\rm ej}}{\omega} \tag{7}$$

Can work for SN for example out to 10s of Mpc.
Works for Novae for a slightly smaller range of 20Mpc.

Luminosity distributions

Many luminosity distributions follow a common shape. Examples are for H II regions, planetary nebulae, globular clusters. The idea is that if you can sample the distribution in apparent magnitude, you can then shift it up by an amount corresponding to the distance to get absolute magnitude. Works for -HII regions -PN -globulars -main sequence fitting -red giant stars - galaxies in clusters

A similar method uses the brightest N objects to do the same.

Range: ~ 50 Mpc (much less for MS fitting)

Large-Scale Structure

Before we go much further, we have to review the concept of "redshift." Redshift refers to the shift in wavelength due to the recession of galaxies. A few galaxies are blueshifted, meaning they have a velocity toward us (notably Andromeda), but the vast, vast majority are redshifted, meaning they have a velocity away from the Sun.

The Universe is expanding, and quickly. In the early 1900s, V.M. Slipher was measuring the redshift of galaxies. These galaxies were not known to be external to the Milky Way, so it was especially surprising when he found that all of them, with the exception of Andromeda, were redshifted. How does this work?

$$\frac{(\lambda_o - \lambda_e)}{\lambda_e} = \frac{\Delta\lambda}{\lambda} = v/c = z \tag{8}$$

or

$$\frac{\nu_e - \nu_o}{\nu_o} = \frac{\Delta\nu}{\nu} = \frac{v}{c} = z \tag{9}$$

where the "o" subscripts refer to the observed and "e" to emitted and z is the redshift ($z = v/c$). Here we see wavelength or frequency shifts related to the recessional velocity. If the wavelength is decreasing or the frequency is increasing, the velocity is positive. Note the difference in the order of subtraction. The numerators are a matter of convention for optical astronomy. These are the non-relativistic formulae, for when $v \ll c$.

In the relativistic limit,

$$\frac{\lambda_o}{\lambda_e} = \left(\frac{1+\beta}{1-\beta}\right)^{0.5} - 1 \tag{10}$$

or

$$z = \left(\frac{1+\beta}{1-\beta}\right)^{0.5} - 1 \tag{11}$$

or

$$\frac{v}{c} = \left(\frac{(z+1)^2 - 1}{(z+1)^2 + 1}\right) \tag{12}$$

where $\beta = v/c$.

Note that to actually measure redshift we need multiple identifiable spectral lines.

In 1925, Hubble discovered Cepheids in Andromeda, and established that it was external to the Milky Way. Identifying Cepheids in other galaxies, and combining with Slipher's velocities, he found that the redshift was correlated with the distance:

$$v = H_0 d\,, \tag{13}$$

where H_0 is the Hubble constant. This is Hubble's Law. Since v is in $\mathrm{km\,s^{-1}}$ and d in Mpc, H_0 is in $(\mathrm{km\,s^{-1}})/\,\mathrm{kpc}$. We can therefore reduce it to units of 1/s.

Hubble understood that he had found evidence for the expansion of the universe. This was the birth of modern cosmology.

What does Hubble's Law mean? As long as we are not in a special place in the Universe (more on that later), the expansion must happen everywhere at once. Imagine the Universe as the United States. If it doubled in size in one second, from our vantage point locations 1000 km away would be 2000 km away, and moving away at 1000 $\mathrm{km\,s^{-1}}$. Locations 2000 km away would now be 4000 km away and moving away at 2000 $\mathrm{km\,s^{-1}}$. We therefore see the expected relationship between v and d. This expansion does not affect gravitationally bound systems like galaxies themselves, the Solar System, galaxy clusters, etc.

One of the real powers of using Hubble's law is that we have another way of determining distances. In the non-relativistic case,

$$d = \frac{cz}{H_0} \tag{14}$$

This should only be used for $z < 0.13$. Or for higher redshifts,

$$d \simeq v/H_0 = \frac{c}{H_0}\frac{(z+1)^2 - 1}{(z+1)^2 + 1} \tag{15}$$

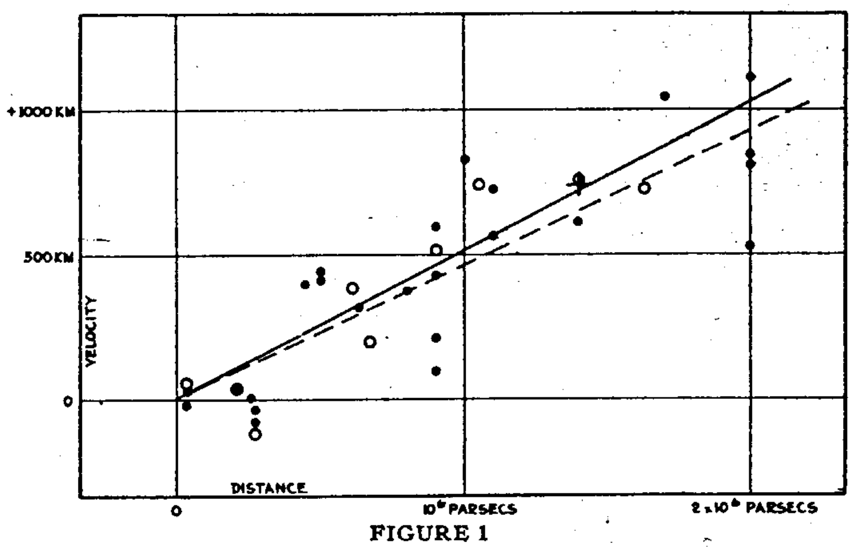

Figure 1: Hubble's original figure.

The value of H_0

H_0 is simply the slope of the v vs d line. Why could that be? As we saw above, it's tough to measure d. So we can parameterize our ignorance:

$$H_0 = 100h\,(\mathrm{km\,s^{-1}})/\mathrm{Mpc} \tag{16}$$

Value of H_0

The Hubble constant is near 70 $\mathrm{km\,s^{-1}}$/Mpc, although different experiments find different values. The Planck satellite found H_0 is 67.3 ± 1.2 $\mathrm{km\,s^{-1}}$/Mpc.

Structures

Galaxies love to cluster together into larger structures. Hubble's Law has allowed astronomers to map the distribution of galaxies in three dimensions. Here are some very rough numbers, but keep in mind that there are large deviations from these.

Name	Number	Diameter (Mpc)	Vel. Disp. ($\mathrm{km\,s^{-1}}$)	Mass ($M_\odot$)	M/L ($M_\odot/L_\odot$)
Group	< 50	$1.4h^{-1}$	150	$10^{13}\,h^{-1}$	$250h$
Poor cluster	50-100s	few h^{-1}	500	$10^{14}h^{-1}$	$300h$
Rich cluster	100s-1000s	$5\,h^{-1}$	1000	$10^{15}h^{-1}$	$400h$

Why are all these values in terms of h^{-1}? Why is M/L dependent on h?

Regular clusters have their mass centrally condensed, while irregular clusters do not.

The richer the cluster or group, the more elliptical galaxies it gas cD galaxies are at the centers.

Where is all the mass? We can use the Virial theorem to get

$$M \simeq \frac{5\sigma_r^2 R}{G} \tag{17}$$

If $\sigma_r = 1000$ km s^{-1} and $R = 1$Mpc, we get $3 \times 10^{15}\ M_\odot$. But the luminosity is $5 \times 10^{12}\ L_\odot$ for Coma, so the M/L ratio is 660. That is a crazy amount of dark matter!

Local Examples

The Local Group is our home group of galaxies. It has about 35 members within 1Mpc of the Milky Way.

Three spirals most prominent: us, Andromeda, and Triangulum.

13 irregulars, including LMC and SMC

rest are dwarf irregulars and dwarf spheroidals

distribution of galaxies clustered around us and Andromeda

Andromeda and us re on collision course

Virgo Cluster

-Classified as a rich, irregular cluster

-Covers a $10^\circ \times 10^\circ$ region of sky (moon and Sun are $\sim 0.5^\circ$ diameter)

-Center is 16.5 ± 0.1 Mpc away in the constellation of Virgo.

-250 large, 2,000 smaller galaxies

- 3 Mpc across

- mass $\sim\ 10^{15}\ M_\odot$

Coma Cluster

-Rich, irregulars

-angular diameter 4°, physical 6 Mpc (book also uses 3 Mpc)

-90 Mpc away

-10,000 galaxies

- mass $\sim 10^{15}\ M_\odot$

The mass of clusters

Most of the baryonic mass in clusters is in the form of hot, X-ray gas. In fact, this is most of the baryonic mass in the universe. This gas is accelerated by the extreme potential, and cools via Bremsstrahlung.

Bremsstrahlung is a two-body process between electrons and protons. The emissivity therefore depends on n^2. As the density of this hot gas increases, it emits more readily and cools faster.

Superclusters

Clusters of clusters are called superclusters. They are up to 100Mpc across. We are in the local supercluster. In between superclusters are voids with few galaxies. Superclusters are flattened structures seen in redshift survey maps.

Cluster timescales

https://www.astro.virginia.edu/class/whittle/astr553/Topic13/Lecture_13.html

Bound clusters are "virialized" (done merging, and stable) in time periods of a few crossing times

$$t_{\rm cross} = \frac{R}{\sigma} \simeq \text{few } 10^9 \text{ years} \quad (18)$$

If relaxed, galaxy-galaxy interactions are important and massive objects sink to the center. This is why we have cD galaxies at the center of rich clusters.

Note that this is similar to the free fall time. $t_{\rm ff} \simeq 1/(G\rho)^{0.5}$ so

$$\frac{r}{v} \simeq \frac{1}{G\rho}^{0.5} \quad (19)$$

$$\frac{Gr^2m}{r^3} = v^2 \quad (20)$$

$$\frac{Gm}{r} = v^2 \quad (21)$$

"Violent relaxation" is merger time-scale between two clusters, other such "violent" acts. This timescale is 2-5 crossing times. Assumes many interactions simultaneously. Still few 10^9 to 10^{10} years.

Two-body relaxation:

$$t_{\rm relax} \simeq 2\frac{t_{\rm cross}N}{\ln(N)} \quad (22)$$

This is the approximate time it takes for individual particle-particle interactions to cause significant deviations from orbits if matter is uniformly distributed.

For individual galaxies we get $t_{\rm relax} = 10^{11} - 10^{12}\,$yr while for subgroups (3-30 galaxies) this becomes $10^9 - 10^{11}\,$yr. So relaxation is generally not significant for most galaxies However, for subgroups or galaxies near the center, some relaxation is expected Don't forget, this kind of relaxation leads to equipartition (in energy), so massive galaxies will settle Although massive galaxies are often found in cluster cores, it is unclear if this is due to relaxation or merging.]

Collision time-scale for interactions

$$t_{\rm coll} = \frac{1}{n\sigma v}\,, \quad (23)$$

where n is the density, σ the cross section, v the velocity. mfp $= 1/(n\sigma)$

How important are these timescales?
Supercluster: $t_{\rm cross}$ t_H. Galaxies cannot have migrated from low to high density regions. Thus, isolated galaxies born isolated.
Loose Groups: $t_{\rm cross} \simeq t_{\rm relax} < t_H$. Probably still infalling. Collisions rare because density so low.
Compact Groups: $t \ll t_H$ so must collapse. Must be recently formed, or replenished with new members, or share a DM halo with nearby sources.
Clusters: $t_{\rm cross} < t_H$. Clusters really should be virialized. But, in Virgo, E's virealized, spirals not yet.
Cluster cores: $t_{\rm relax} \ll t_H$. Virialized, relaxed, mass segregation (cD galaxies are center)