Astronomy 401/Physics 903
Lecture 18
The Extragalactic Distance Scale

In order to study the structure of the universe, we need to be able to measure how far away things are. We also need to measure distances in order to determine the Hubble constant: $v = H_0 d$, so we need to measure both v (easy, for things that are far enough away so that peculiar velocities don't matter) and d (hard).

There are many methods of measuring distances, making up what's called the **extragalactic distance scale** or **cosmological distance ladder**. For objects within ~ 1 kpc we can measure **trigonometric parallaxes**, but beyond that we need other methods. There are many of these. Some are covered here, and see also Schneider sections 2.2 and 3.9.

1 Extragalactic distance indicators

Most astronomical distance indicators are what are called "standard candles." A standard candle is an object with a fixed luminosity, or with some other property we can measure that will tell us what its luminosity is. Recall the distance modulus, $m - M = 5 \log(d/10 \text{ pc})$; if we measure the apparent magnitude and know the absolute magnitude we can determine the distance.

Also used but less common are "standard rulers," objects with a fixed physical size; if we can measure the angular size and know the physical size, we can determine the distance.

1.1 Cepheid variables

Recall that Cepheids are variable stars whose period is directly related to their luminosity, discovered by Henrietta Swan Leavitt in the early 20th century. These stars pass through the **instability strip** on the HR diagram during late phases of stellar evolution, and they undergo radial pulsations with a period which depends on their luminosity. We also measure the color of these stars, to account for the width of the instability strip, so we have a **period-luminosity-color relation**,

$$M_V = -3.53 \log P_d - 2.13 + 2.13(B - V), \tag{1}$$

where M_v is the absolute V magnitude, P_d is the pulsation period in days, and $B - V$ is the color index. We can measure P_d, $B - V$ and apparent magnitude, and use the $P - L$ relation to calculate distance modulus. Very important: We need to know the extinction (light lost to dust) in order for this to work.

The most distant known Cepheids are ~ 40 Mpc away.

1.2 Expanding photosphere method

This method uses measurements of the photosphere of a supernova in two ways. If the supernova is close enough, we can measure the angular size of the photosphere $\theta(t)$, and determine the angular velocity of the expansion of the photosphere by comparing angular size measurements taken at different times, $\omega = \Delta\theta/\Delta t$. The transverse velocity of the expanding photosphere is $v_t = \omega d$, where d is the distance to the supernova. Assuming the expansion is spherically symmetric, the transverse velocity is equal to the radial velocity of the supernova ejecta v_{ej}, which we can measure from Doppler shifts of spectral lines. The distance to the supernova is therefore

$$d = \frac{v_{\text{ej}}}{\omega}. \tag{2}$$

Most supernovae are too far away for this to work, so we use another method. We assume that the expanding shell of hot gas radiates as a blackbody, so that the supernova's luminosity is given by the Stefan-Boltzmann law:

$$L = 4\pi R^2(t)\sigma T_e^4, \tag{3}$$

where $R(t)$ is the radius of the expanding photosphere and t is the age of the supernova. Assuming the radial velocity of the ejecta is nearly constant, $R(t) = v_{\rm ej}t$. With measurements of the temperature from the blackbody spectrum, the age, and the radial velocity, we can determine the luminosity and therefore the distance. Problems: expansion is neither spherical nor a perfect blackbody, and (as for all standard candles) we need to be able to correct for dust. Uncertainties are 10–25%.

1.3 Type Ia supernovae lightcurves

This is the most important extragalactic distance indicator, because it reaches to the largest distances. A Type Ia supernova is the explosion of a white dwarf star; the exact mechanism is still a topic of active research, but it may involve the merger of two white dwarfs, or a CO white dwarf that accretes material from a companion which pushes it over the Chandrasekhar limit and causes it to explode.

Whatever the cause, the useful fact for measuring distances is that the brightnesses and light curves (a plot of luminosity vs. time) of Type Ia SNe are very similar. They have average absolute magnitudes at maximum light of $\langle M_B \rangle \simeq \langle M_V \rangle \simeq -19.3 \pm 0.03$. Note: small scatter, and very bright; this is as bright as an entire galaxy.

What we actually measure is the brightness of the supernova at various points in time, and there is a well-defined inverse correlation between the maximum luminosity and the rate of decline of the light curve: brighter supernova take longer to decline. We can use this to determine the intrinsic peak luminosity.

Type Ia supernovae can be used to measure distances to > 1000 Mpc ($z \sim 0.25$) with an uncertainty of $\sim 5\%$, and these supernovae have now been detected to $z \sim 2$ (~ 5000 Mpc). We will return to this topic, since Type Ia supernovae are key to the measurement of dark energy and the acceleration of the expansion of the universe.

1.4 Globular cluster luminosity function

Another method is to look at some class of objects in a galaxy with a known brightness distribution. The luminosity function of globular clusters appears to be similar for most galaxies in which it has been measured, although we don't know if it's actually universal. The luminosity function peaks at a turnover magnitude $M_0 = -6.6 \pm 0.26$ (this is the average value from many different galaxies). So if we can measure the brightnesses of lots of globular clusters in a galaxy we can assume their luminosity function and absolute turnover magnitude to estimate the distance. This method can be used to ~ 50 Mpc.

Can do a similar analysis for the planetary nebulae in a galaxy, or the stars on the red giant branch in a color-magnitude diagram.

1.5 Tully-Fisher and D-σ relation

In order to reach even greater distances, we use the global properties of galaxies. We've already talked about the Tully-Fisher relation, $L \propto V^4$; this means that we can determine the luminosity of a spiral galaxy by measuring its rotational velocity, and therefore the distance.

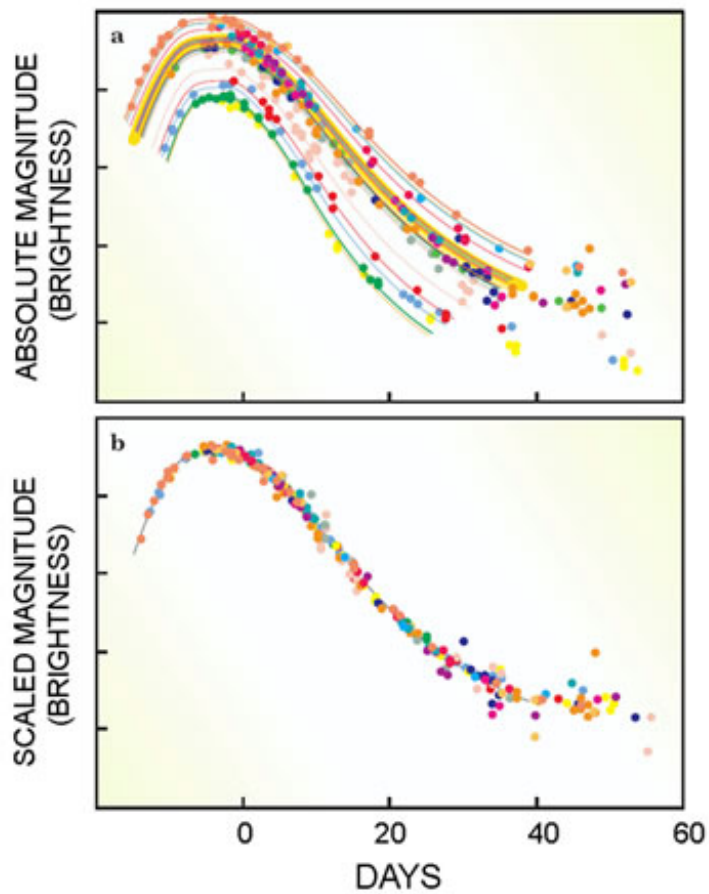

Figure 1: Top: Type Ia supernova light curves as observed. Bottom: The light curves after applying the time scale correction. The rate of decline depends on the luminosity (brighter supernovae decline more slowly), so by measuring the rate of decline we can determine the luminosity.

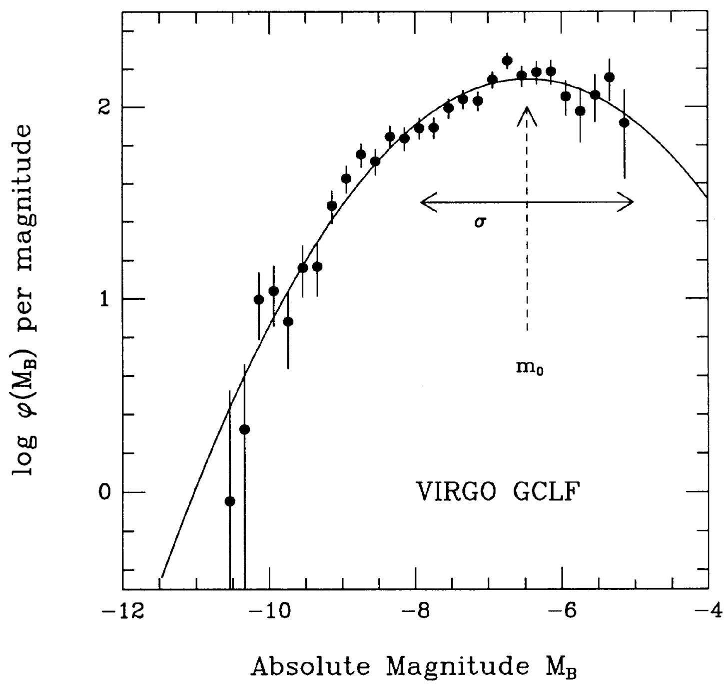

Figure 2: Globular cluster luminosity function for the globular clusters of four elliptical galaxies in the Virgo cluster.

The analogous relation for elliptical galaxies is the Faber-Jackson relation, $L \propto \sigma^4$, but as we've discussed this has a lot of scatter. Something called the $D - \sigma$ relation works better. This is another form of the fundamental plane, which relates radius, surface brightness and velocity dispersion. D is the angular diameter of a galaxy out to a surface brightness level of 20.75 B-mag arcsec^{-1}. Remember that surface brightness is independent of distance (for galaxies within about 500 Mpc, where cosmological effects aren't important), so D is inversely proportional to the distance to the galaxy. There is a strong correlation between σ and D, so by measuring the velocity dispersion and the angular diameter D we can determine the distance. This is a standard ruler, not a standard candle.

1.6 Summary

This has not been a comprehensive discussion; there are many different distance indicators, and we've only discussed a few of them here. The important point is that the different methods work best for different types of galaxies and to different distances, and have different uncertainties associated with them. We need to use as many different methods as possible to calibrate the various methods and understand their uncertainties.

Method	Uncertainty for single galaxy (mag)	Distance to Virgo Cluster (Mpc)	Range (Mpc)
Cepheids	0.16	15-25	40
Planetary nebula luminosity fuction	0.3	15.4 ± 1.1	50
Globular cluster luminosity function	0.4	18.8 ± 3.8	50
Tully-Fisher relation	0.4	15.8 ± 1.5	> 100
$D - \sigma$ relation	0.5	16.8 ± 2.4	> 100
Type Ia supernovae	0.10	19.4 ± 5.0	~ 5000