MEASURING DISTANCES TO GALAXIES

The key to discovering **Hubble's Law**, and thus the expansion of the universe, was to be able to measure two numbers:

- The distance to another galaxy
- The "velocity of recession" of the galaxy, that is, the speed at which it is moving away from us.

When Hubble first did this in the 1930's, he found that distance and velocity were nicely correlated – one increased with the other. The more distant the galaxy, the faster it was moving away. He had discovered the expansion of the universe. In equation form,

$$\text{velocity} = \text{constant} \times \text{distance}$$

where the "constant" in the equation is now called Hubble's constant.

But how are these measurements done in the first place?

First of all, measuring the velocity of recession is fairly easy. The motion of the galaxy towards or away from us shows up as a ***Doppler shift*** in its spectrum: if the galaxy is moving away, the whole spectrum (including the spectrum lines of the elements like hydrogen, iron, and so forth) are all shifted to the red side (toward longer wavelength). The amount of shift in wavelength is proportional to the speed.

The second part – and the harder part – is to measure the distance. How do you do this for a galaxy far outside our own Milky Way? Using parallax (which we do for stars within about 100 parsecs of the Sun) is out of the question: galaxies are *millions* of parsecs away, which is much too far to show any measurable parallax shift.

The answer is to use the fact that *galaxies are made of stars*. And, we know quite a lot about stars because we ourselves are living in the midst of a galaxy, surrounded by stars of all types which we can study in great detail. So what we do, in short, is this:

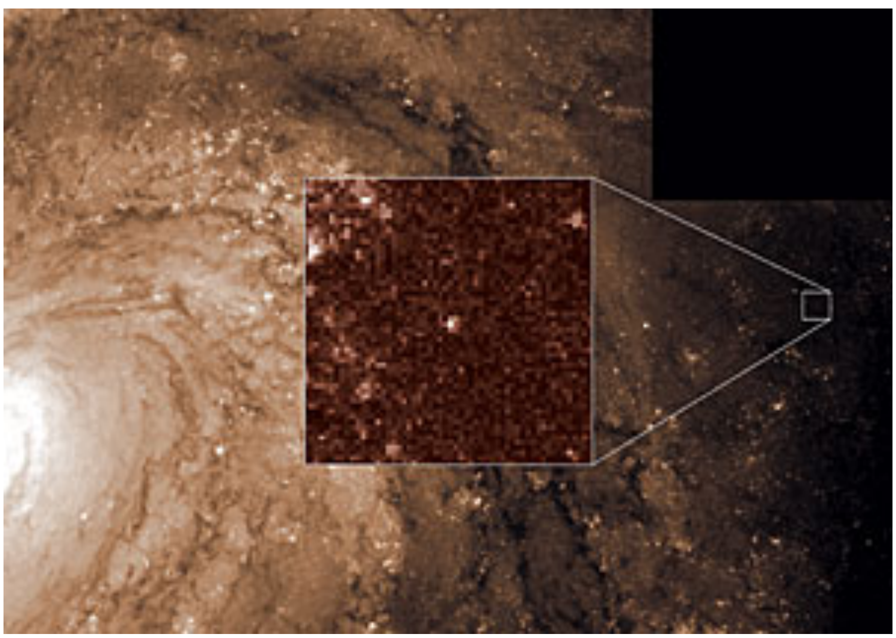
- pick a galaxy that looks like it might be fairly "close" (in intergalactic terms!)
- inspect it very carefully to find *recognizable types of stars whose properties we already know*
- measure how faint these particular stars appear to be (the farther away they are, the fainter they look to us)
- finally, compare their true luminosity (which we know beforehand) with how faint they look in that galaxy, to decide how far away they must be. Problem solved!

But wait: galaxies are made up of *billions* of stars. How can you ever find just a few with some particular characteristics that you want?

Probably the best way to explain this is by illustrating the method with one example. We will describe one type of very useful star called the ***Cepheid.***

Cepheid stars have a lot of very rare, interesting, and (for our purposes) extremely useful properties. First, they are very luminous: they are giant and supergiant stars, which stand out in any random collection of stars. Second, they are variable in their light output: they get *brighter and dimmer* in a regular cycle, somewhat like a light bulb attached to a dimmer switch that is constantly being turned up and down. *[Footnote: what is in fact happening to the star to cause it to vary is that its outer layers are actually pulsating: they are moving outward and inward like a balloon being inflated and then deflated. As* *the size of the star changes, its light output goes up and down too. These stars are in a certain stage of their evolution where they are temporarily trapped in this semi-unstable cycling phenomenon. If you are interested to read more about the Cepheid phenomenon, you can find lots of tutorials on the Web – see one listed below.]*

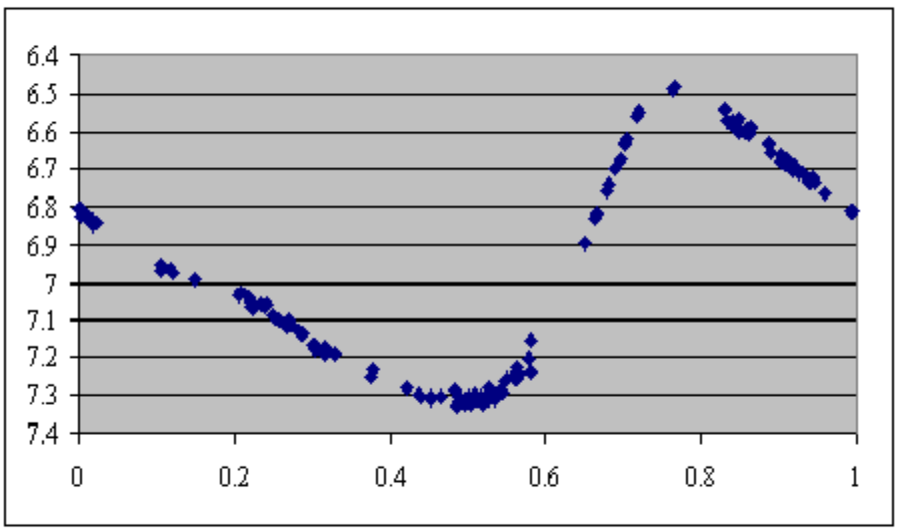
Most stars are quite steady in their light output (including, thankfully for us, our own Sun. Life on Earth depends on having a good steady energy output from the Sun). Variable stars are quite rare, but this is part of what makes them useful: they call attention to themselves. All you have to do is watch a group of stars for a while, and the few that are variables will be easy to spot. (A rough but useful analogy is to think of a large crowd of people all standing very quietly, except for one noisy guy who is jumping up and down waving his arms. Which person is easiest to pick out from a distance?)



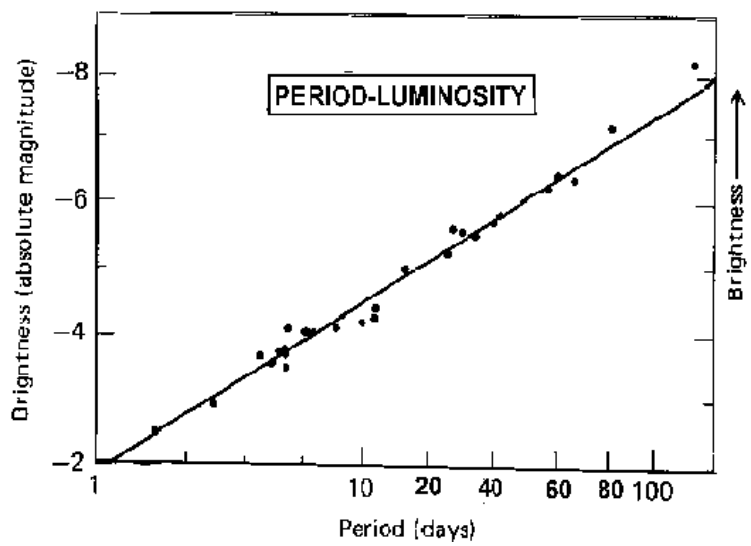
The image above shows one Cepheid variable that is located in a distant galaxy: it's at the center of the little inset box to the right, and the zoomed square at center shows an expanded version. By taking a long series of photographs of this galaxy, it is possible to spot the few bright stars (Cepheids) that "change" with time.

OK, so we can find variable stars in other galaxies. How does this help find the distance?

The next stage is to find the period of variability: that is, the cycle time, or the amount of time it takes for the up-and-down light output of the star to repeat. The graph below shows a sample "light curve" (brightness versus time) for one Cepheid variable. Each blue dot represents one measurement, and the whole graph shows one complete cycle of the variable star. (Never mind about the details of the numbers on the scale. In effect, this particular star is about twice as bright at the top end of the cycle as it is at the bottom end, and it takes several days to go through its whole cycle.)



The final link in the chain that we need is that the period of the variable depends on the star's average luminosity. That is, brighter Cepheids take longer to go through their cycle. *[Physically, the reason for that is that the more luminous Cepheids are bigger stars, and it just takes longer for their outer layers to go through the cycle of pulsation. Analogy: think of a playground swing. Shorter swings go back and forth quickly; longer swings take more time.]* By measuring nearby Cepheids in our own Milky Way galaxy, we can find the correlation between their periods and their luminosities, which looks something like the following graph:



This so-called ***period-luminosity relation*** is the solution we have been looking for! The logic is now very simple:

- Find some Cepheids in a nearby galaxy, by watching it carefully.
- Measure the periods of the Cepheids (they will be in the range of a few days to a few weeks, as you see from the graph).
- From the period of each one, you can now predict their true luminosity, from the Period-Luminosity relation that you already know from our Milky Way.
- Now compare the true luminosity of each one with its measured brightness, and thus deduce how far away it must be to appear that faint.

In practice, Cepheid-calibrated distances have been measured for dozens of galaxies, far enough away to show Hubble's Law and to give a pretty accurate value of Hubble's constant and the rate of expansion of the universe.

In this writeup, we have concentrated on one particular method of measuring distances to galaxies (the Cepheids). However, there are other methods as well. As was indicated above, most of them rely on finding *recognizable types of stars* in the target galaxy whose properties are already well known. As well as Cepheids, the types of objects that have been used include

- RR Lyrae stars (another type of variable star)
- Planetary nebulae
- Globular star clusters
- Supernovae

In practice, astronomers use all these methods and, if any of them disagree with any of the others, constantly try to track down the reasons for it and improve the methodology. This whole subject has a very long history (starting with Hubble's first work in the mid-1930's) and it is only in the last 5 years or so that there has been general agreement that we know the value of Hubble's constant to better than about 10% accuracy.