Lab #19: Cepheids and the Distance Ladder

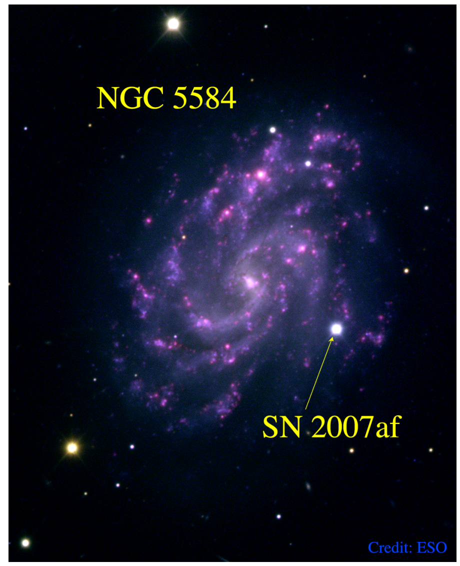
Cepheids are a type of pulsating variable stars, named after the prototype δ Cephei in the constellation Cepheus. They expand and contract, become brighter and dimmer with a period in the range of 3 to 100 days. Their brightness changes by a good half a magnitude.
They are large and bright as stars go, with an absolute brighness around M_V=-4^{mg}. That is four thousand times brighter than the Sun! They are visible from great distances. The Hubble Space Telescope can in fact resolve individual Cepheids in several external galaxies.
Henrietta Leavitt in 1908 noticed that they obey a period-luminosity relation. This is not hard to understand: a heavier Cepheid would oscillate more slowly, but it would also be brighter. Such a P-L relation, in turn, can be used to determine the distance of their host galaxies (as long as the galaxy is not too far away, so that we can discern the Cepheid separately): the time period can be measured, and the P-L relation tells the absolute magnitude of the star, then a comparison to its apparent magnitude tells the distance. This is the *only* way we know how to measure the distance of far-away galaxies. We have other ways to measure galaxies' distances, but all these other ways rely on a known distance of at least a dozen closeby galaxies. We need the Cepheid method for these closeby galaxies as the *first rung* of the distance ladder. If the Cepheid method has an error, all the rest of the rungs will be in error, and then all our knowledge of the size of the Universe will be wrong. This is why it is so important to get Cepheids' distances right.
It has turned out to be extremely difficult to set up correctly (i.e. *calibrate*) the P-L relation though. Early attempts were, no mistake, 250% off. The trouble is that, in order to correctly set up the P-L relation, we need to know the distance to at least a few Cepheids ahead of time. But they are large stars and large stars are very rare. Even the closest one is 900 light years away, far enough that even the Hipparchos satellite's famously precise parallax measurements could not determine the distance. (The only Cepheid closer than this is the well-known Polaris, but it is an *abnormal* one, with only a very small change, ~0.05^{mg}, in brightness.) Something radically new was needed.
A team of astronomers lead by Fritz Benedict (McDonald Observatory, Austin, TX) had the idea to use the fine guidance sensors (FGS) of the Hubble Space Telescope. These sensors were designed to keep the spacecraft properly oriented, but it turned out that they could also be used to determine the motion of bright stars with unheard-of precision. They used the FGS on 10 bright Cepheids, and measured their parallax. They published the results in 2007, out of which we quote here four stars:

Star	δ Cephei	ζ Geminorum	*l* Carinae	RT Aurigae
Parallax	3.66±0.15 mas	2.78±0.18 mas	2.01±0.20 mas	2.40±0.19 mas

The parallaxes are in *mas*, read milli-arc-seconds. They are tiny, meaning that the stars are very far away. (*1 mas = 0.001 arc sec*.)
In the first part of this laboratory you will be using a computer simulation of how these four stars look in the sky, and how fast they change their brightness. The simulations are truthful in that they show the variable stars brighten and dim as they do in fact. (All simulations start at February 15, 2007, $0^h00^m00^s$ Universal Time.) The simulated sky has the brightness of several

comparison stars indicated, so you can estimate the average brightness of each Cepheid. You will ‘observe’ each variable’s period and average brightness, and calibrate the P-L relation yourself.

In the second part of the laboratory you will apply your calibrated period-luminosity relation to determine the distance to two galaxies, NGC5584 and the Andromeda galaxy M31.



This same procedure was used in 2011 by a team lead by Adam Riess (Johns Hopkins University) and others to determine the distance to six galaxies, each a host to a Type-Ia supernova. (The picture shows one of these galaxies, NGC 5584, with the bright supernova SN 2007af.) Based on these distances, they could tell the maximum brightness of each exploding supernova, and found, with great precision (±2%) that they all have the (metallicity-corrected) absolute brightness of M_V=-19.3^{mg}. They could then use previous observations of 600 other supernovae in various galaxies with well-known redshifts to determine the distance of those galaxies. This gave them a chance to determine the Hubble constant with ±3% precision. As the age of the Universe is the reciprocal of the Hubble constant, this is how well we know now how old and how large the Universe is.

A few concepts and relations, to refresh your memory:

Parallax: the yearly orbit of Earth around the Sun is reflected in the stars. They move in tiny circles whose radius (in arc seconds) is called parallax. The reciprocal of the parallax equals the distance to the star, expressed in parsecs, $d[pc] = 1/\pi[as]$.

Parsec: *1 pc = 3.26 light years*, a unit of distance.

Absolute magnitude: how bright the star would look from a distance of 10 pc. The Sun’s absolute brightness is $M_V=+4.8^{mg}$. The absolute brightness range for stars is approximately from -12^{mg} (largest supergiants) to $+16^{mg}$ (tiniest red dwarfs). The index V refers to *visual* magnitude (yellow filter).

Distance modulus: The difference between apparent and absolute magnitude, $\Delta = m - M$. The farther the star is, the larger the distance modulus; $\Delta = 0$ at 10 pc. The distance modulus is related to the distance of the star as $\Delta = 5 \times \lg \frac{d}{10}$; *lg* means *10*-based logarithm. This is equivalent to (for your convenience) $d = 10^{1+\Delta/5}$. (*Units are parsecs for d and magnitudes for m, M, and Δ.*)

PROCEDURE AND LAB REPORT

Date:_______ Your name: ___________Partner's name: ___________ Section: ___/___

Maximum two students may work together as partners!

This laboratory needs a simulation running on the computer. For this reason, the report must be printed out and the paper copy must be used.

1. Listen to your instructor's introduction. You'll learn a few things that the lecture may not have covered, so pay close attention.

2. Start up the computer in Windows. If it is running Mac, you will have to restart it while holding down the OPTION key. Use the *Student* account to log in.

2. Read the introduction, then answer these questions:
(i) Imagine that the P-L relation of Cepheids is incorrectly calibrated and predicts that Cepheids are by 1.6 mg (i.e. four times) brighter than what they really are. How would this affect our knowledge of the distance to external galaxies? ____
____
(ii) The longer the period of a Cepheid is the _________ it is.
(iii) Why has it been very diffcult to establish the correct calibration of the Cepheid P-L relation? ____

3. Start up the simulation (click *Desktop→AstroLabs→Cepheids*). The '*WELCOME*' page appears; as you work with the various stars, you'll always return to this page. Click '*Introduction*'.

The 'Introduction' page shows the constellation of Cepheus as you see it with the naked eye in a dark location in the summer. Identify δ Cephei (the letter is small Greek delta). Start the animation. Observe how it gets brighter and dimmer periodically. Notice that the magnitude is a smaller number when the star is brighter. Go back to the "*Welcome*" screen.

4. Click Delta Cephei and start the animation. Observe how the stars brightens and dims. The graph is called the light curve, brightness (magnitudes) vs. time in days. Note the characteristic light curve of classical Cepheids: they brighten quickly, and return to minimum much slower.

Record the time and brightness of each the maximum and the minimum of the variable. Write 'max' or 'min' in the first row as appropriate.

δ Cep	___	___	___	___	___	___	___	___	___	___
time										
mg										

Subtract the time of the first maximum from the second to get a rough estimate of the period. Your result is _____ *days*. Now, you will get a more precise number if you do the subtraction over five periods, and divide the total time by five. The more accurate result is _____ *days*. Record also the average brightness of the star; this will be the average between the maximum and the minimum brightness. Your result is _____ *mg*.
Insert these values in the **table in Part 6** and go back to the "*Welcome*" screen.

5. Click ζ Gem, ***l*** **Car, RT Aur** and repeat the exercise above, filling in the tables of minima and maxima. (Here, ζ is the Greek letter small zeta. Note the use of the three-letter abbreviations of the constellation names.)

The magnitudes of the stars in minima and maxima will have to be estimated. This is how it is done in real life as well. Pause the animation when the star is in maximum (minimum). Find a comparison star that is just brighter than the variable, and another one that is just dimmer. Subtract and tell how many tenths of magnitude the difference is between the two comparison stars. Based on this, imagine in your mind how much of a difference a tenth of a magnitude would look. Then, tell how many tenths the star is brighter than the dimmer of the two comparison stars (or brighter than the dimmer one). Subtract (or add) to figure out the brightness of the variable star.

You'll need some practice to do this. In fact, for two hundred years, amateur astronomers all over the world have used this way of estimating the brighness of variable stars and provided great service to professional astronomy.

Use common sense to check that the number you got for the brightness makes sense. Keep in mind that a larger number means a dimmer star!

ζ Gem	___	___	___	___	___	___	___	___	___	___
time										
mg										
l Car	___	___	___	___	___	___	___	___	___	___
time										
mg										
RT Aur	___	___	___	___	___	___	___	___	___	___
time										
mg										

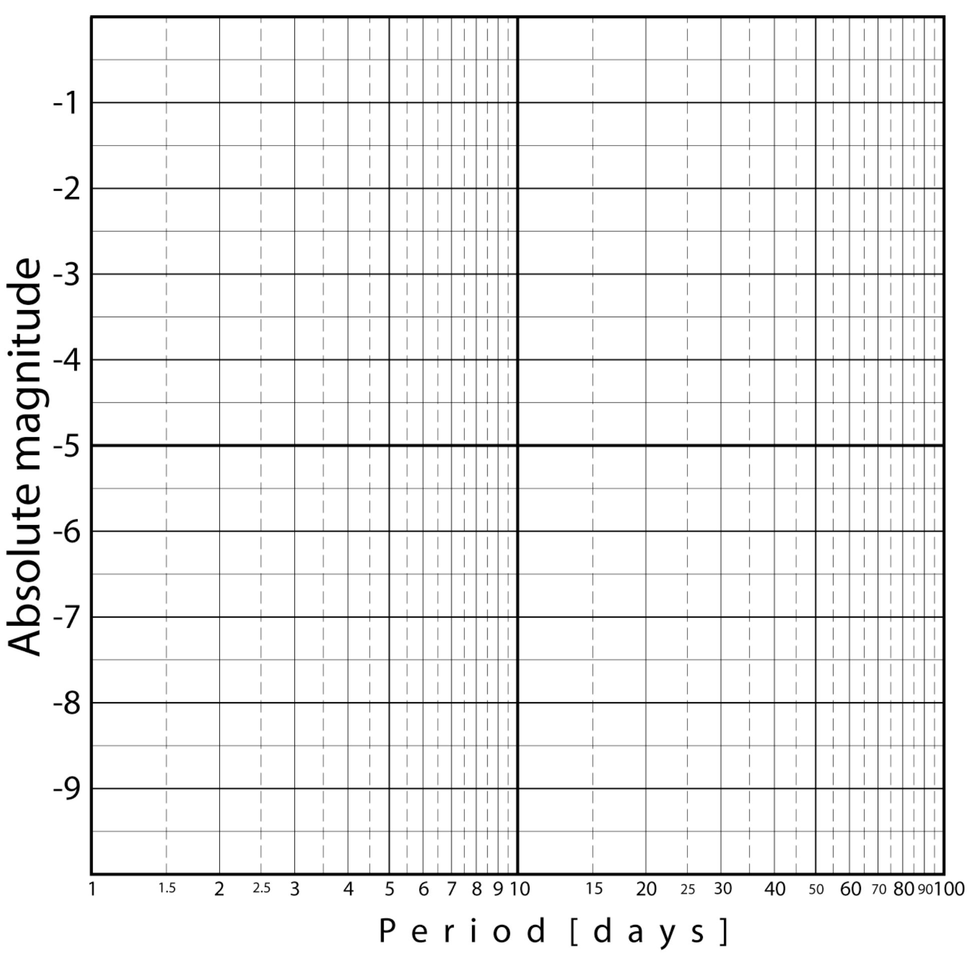
6. Do the necessary calculations in order to determine each star's absolute magnitude. Use what you learned from the introduction, and fill in the table below. Don't forget to convert *mas* to *as*, recall *1 as = 1000 mas*.

The line before the last contains measured values of the extinction of light due to interstellar dust between us and the star, based on the strength of the absorption lines of interstellar matter in the spectrum of the star. You must correct the absolute magnitude for this extinction.

Star	δ Cephei	ζ Geminorum	*l* Carinae	RT Aurigae
Parallax (π)	*3.66±0.15 mas*	*2.78±0.18 mas*	*2.01±0.20 mas*	*2.40±0.19 mas*
Period (P)	*days*	*days*	*days*	*days*
Apparent brightness (m)	*mg*	*mg*	*mg*	*mg*
Distance (d)	*pc*	*pc*	*pc*	*pc*
Distance modulus (Δ)	*mg*	*mg*	*mg*	*mg*
Absolute brightness (M)	*mg*	*mg*	*mg*	*mg*
Dust extinction	*0.23 mg*	*0.06 mg*	*0.52 mg*	*0.20 mg*
Corrected M	*mg*	*mg*	*mg*	*mg*

7. Plot in the absolute magnitude of each of the four stars vs. its period. The uneven graph paper you use for this is called a *logarithmic* graph paper. The scale on the x-axis is *logarithmic*, which automatically turns your plot into a plot of M_V vs. *lg P*, and since Henrietta Lewitt's discovery we know that this logarithmic plot should put the stars on a straight line.*

THE PERIOD-LUMINOSITY RELATION



Draw the four points in the graph, and mark each with the name of the star.

Using a ruler, draw a straight line across the points, as close to each as possible.

Extra credit:
Read off, from your line,

(i) the *P = 10 days* intercept, *a* = ____ *mg*,

(ii) the slope of the curve, *b* = ___ *mg*.

The P-L relation is
$M_V = a + b \times (\lg P - 1)$.

* Lewitt used observations of many Cepheids I the Large Magellanic Cloud (LMC), a satellite galaxy of our Galaxy. These Cepheids are all at the same distance, so she could conclude that the P-L relation was a straight line, but no knowing the distance to the LMC she could not tell where to draw the line in the graph.

Now understand what you have done. You have measured each of the four star's period, and determined their absolute magnitude, then you have established a relationship between them. (We call it Period-Luminosity relation, although in fact it is period-magnitude relationship. But absolute magnitude and luminosity are essentially the same thing.)

This relationship can now be used for other Cepheid variables, including those in external galaxies. Their period is relatively easy to measure, and you can use your graph to read off their absolute magnitudes. Relating this to their observable apparent magnitudes, you can tell the distance to these galaxies! This we will do with two galaxies now.

8. Use the animation of M31-V1. The Andromeda Galaxy is the #31 object in the Messier Catalogue, i.e. M31, and this variable is the brightest truly extragalactic Cepheid of all (except those in the Magellanic Clouds). Notice that, even if a Cepheid is much brighter than an average star in the galaxy (the average is about $+5^{mg}$, a Cepheid is -3^{mg}, absolute), it is still quite hard to make out an individual Cepheid in the Andromeda Galaxy, even in the Hubble Space Telescope image you are using.
Determine the period of this Cepheid using the animation, and insert your answer in the table below. You'll notice that it is a long-period Cepheid. Why do you think it is so? Explain: ____________ ____.
The measurement of the maximum and minimum brightness of the star is more difficult than it was for galactic Cepheids, due to *crowding* – the bright background of the large number of unresolved stars. This is one of the hard observational problems in astronomy. We suggest to pause the animation where the star is middle brightness (halfway between maximum and minimum), and use the comparison stars then. Enter your estimate in the table.

Star	V1 – M31	V1 - NGC 5584	V2 - NGC 5584	V3 - NGC 5584
Period (P)	*days*	*days*	*days*	*days*
Apparent brightness (m)	*mg*	*mg*	*mg*	*mg*
Absolute brightness (M)	*mg*	*mg*	*mg*	*mg*
Distance modulus (Δ)	*mg*	*mg*	*mg*	*mg*
Δ averaged		*mg*		
Distance (d)	*pc*	*pc*		
Distance (d)	*light years*	*light years*		

Now, you can use your calibrated P-L relation (the plot above) to read off the absolute magnitude of V1-M31. Put this star on the plot, and indicate its name there. Enter your answer in the table now, then fill out the rest of the column. Based on your result, you can tell, is M 31 part of our Galaxy (which is ~ *100,000 light years* across), or is it outside the Galaxy? ____

9. Use the animation of the Cepheids V1, V2, V3 in NGC 5584. This is one of the closest Type-1a supernova host galaxies (SN 2007af). Your measurement of the distance to NGC 5584 can be used to calibrate the Type-Ia supernova method of distance determinations.
Repeat the exercise as in Part 8. This time, you need to average the three results for the distance modulus. They are supposed to be equal, but the uncertainty in the brightness estimates introduces an error which will be lowered by the averaging. (*Watch out:* if the three values for Δ are very different, say they differ by more than a half a magnitude, than you must have made a *mistake*. That is *not* a statistical *error* and it cannot be corrected by averaging. It such a case you must find the error and correct it before proceeding.)
Is the galaxy NGC 5584 closer or farther than the Andromeda Galaxy? __________________ .

10. Observe the eruption of *SN 2007 af* in NGC 5584. This was a Type-Ia supernova discovered on March 1, 2007 by Ko-ichi Itagaki. According to your observation, it attained its maximum brightness on ____________ . It would be too difficult to tell its maximum brightness from the animation, because of crowding around both the supernova and around possible comparison stars. It was much easier to tell the maximum brightness using a small telescope in which the galaxy does not look bright. The maximum brightness turned out 13.0^{mg}, observed by many astronomers all around the world. Using this data, what was the absolute magnitude of SN 2007 af at maximum light? ______________ . (Show your calculation in the bottom of this page.)

This value, and a few other similar determinations of Type-Ia supernova absolute brightnesses, serve to *calibrate* the next rung of the *cosmic distance ladder*. Now, any Type-Ia supernova in any galaxy, with its maximum brightness observed, would allow you to tell that galaxy's distance.