Lab 7 – The Cosmic Distance Ladder

Adapted from the University of Nebraska-Lincoln

ASTR 1020

Name:

Overview

In this activity, you will explore several runs of the cosmic distance ladder and become familiar with their technique, scientific use, and limitations.

Objectives

After completing this activity students will be able to:
- Describe the distance measurement methods of parallax, main sequence fitting, Cepheid variable stars, and supernovae
- Use each rung for distance calculations
- Explore the types of celestial objects each rung of the distance ladder is applicable to

Definitions

- **Parallax** – the apparent shift of an object's position relative to more distance background objects caused by a change in the observer's position
- **Apparent magnitude** – m; the apparent brightness of a celestial object as measured from Earth.

- **Parsec** – equal to 3.26 light-years; the distance an object must be to have a parallax angle of 1 arcsecond.
- **Absolute magnitude** – M; the brightness of a celestial object as measured from 10 parsecs.
- **Distance Modulus** – m-M; the difference between an objects apparent and absolute magnitudes.
- **Variable Star** – a star that varies in brightness with a recurring cycle of pulsations in brightness and size
- **RR Lyrae**– the dimmest type of variable star with the fastest pulsation periods of ~less than 1 day


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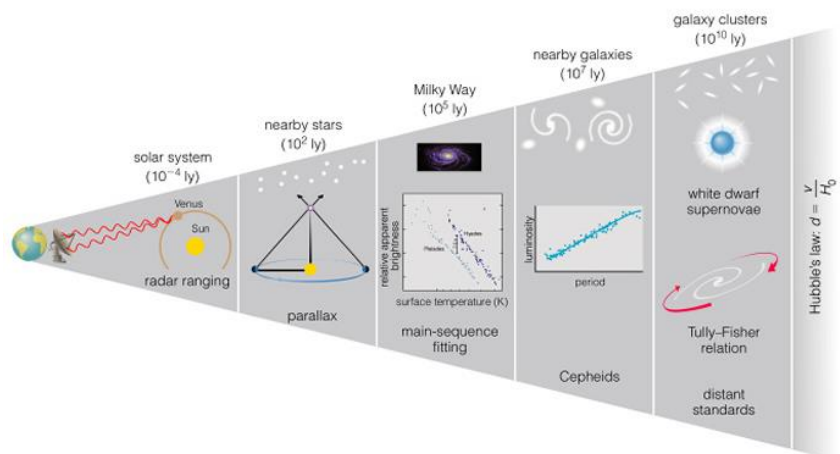
Part 1. Radar

Throughout this lab, you will be using simulators to answer questions about specific rungs of the distance ladder and calculate distances to celestial objects. Please visit this link:

https://astro.unl.edu/naap/distance/distance.html

Select 'Radar Ranging' next to 'Main Content.'

If the applet is not loading, please check that your Flash settings are set to "Allow." In Chrome, you can do this by clicking on the lock icon on your web browser's address bar.
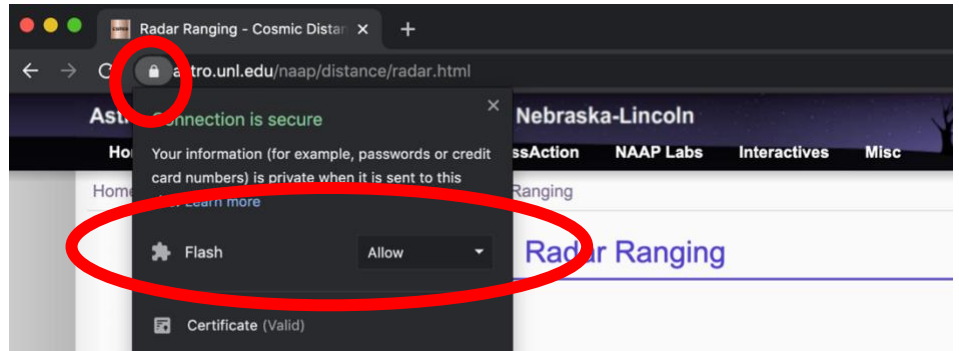
Note. Allowing Flash will vary depending on your web browser. If you are using a browser that is not Chrome, ask Google how you can allow Flash on your browser.

The simulator shows a simple example of radar ranging. By timing how long it takes this light echo to return and then dividing this time by 2 and multiplying by the speed of light, the distance to the planet can be determined. Radar ranging is a challenging technique to implement. The atmosphere poses difficulties and this is one reason that radio waves are used as the atmosphere is largely transparent to certain radio frequencies. The second difficulty is signal strength. The signal will start to spread out as soon as it is sent. The more distant the object, the more spread out the beam will be when it arrives and the more spread out the echo will be when it is received. The end result is a very weak signal. Strong signals must be broadcast and very sensitive detectors (i.e., extremely large, research-grade telescopes) are needed to detect the echo.

1. Over the last 10 years, a large number of ice balls have been found in the outer solar system out beyond Pluto. These objects are collectively known as the Kuiper Belt. An amateur astronomer wants to use the radar ranging technique to learn the rotation periods of Kuiper Belt Objects. Do you think that their plan would be successful? Explain why or why not.

Part 2. Parallax

Go back to the main page, then select 'Parallax Explorer' next to 'Main Content.' The simulator consists of a map providing a scaled overhead view of a lake and a road along the bottom edge where our observer represented by a red X may be located. The surveyor is equipped with a theodolite (a combination of a small telescope and a large protractor so that the angle of the telescope orientation can be precisely measured) mounted on a tripod that can be moved along the road to establish a baseline. An 'Observer's View' panel shows the appearance of the boat relative to trees on the far shore through the theodolite.

Configure the simulator to 'Preset A,' which allows us to see the location of the boat on the map. Drag the position of the observer around and note how the apparent position of the boat relative to background objects changes.

Triangulation

Position the observer to the far left of the road and click 'take measurement.' Now position the observer to the far right of the road and click 'take measurement' again. The distance between these two positions defines the baseline of our observations and the intersection of the two red lines of sight indicates the position of the boat. Lastly, click 'show ruler' and measure the distance from the baseline to the boat.

2. The scale of the map is 20 meters per ruler tick. Use this scale to calculate the distance from the baseline to the boat in meters and record your answer below.

Configure the simulator to 'Preset B.' The parallax explorer now assumes that you can make angular observations with a typical error of 3°. Due to this error, we will now describe an area where the boat must be located as the overlap of two cones as opposed to the intersection of two lines.

Conduct the triangulation process again. Due to the error in your measurements, the lines are now flat cones. The area of overlap between the cones is your best estimate as to where the boat is. You can't know where in that overlap area it is, but you know it's contained within that area.

3. a. What is your best estimate for the distance to the boat?

b. What is the maximum distance to the boat based on your best estimate?

c. What is the minimum distance to the boat based on your best estimate?

Configure the simulator to 'Preset C,' which limits the size of the baseline and has an error of 5°. **Repeat the triangulation process.**

4. a. What is your best estimate for the distance to the boat?

    b. In your own words, describe how accurately you can determine this distance and the factors are contributing to that accuracy.

Part 3. Distance Modulus

The distance modulus is shown in Equation 1:

$$m - M = 5\log(D) - 5 \qquad\qquad (Equation\ 1)$$

where D is the distance in parsecs, m is the apparent magnitude, and M is the absolute magnitude.

5. Fill in Table 1 with the missing values for four stars by solving Equation 1:

Table 1: Distance moduli data

Object	m	M	m-M	D (parsecs)
Star A	2.4			10
Star B		5		16
Star C	10			25
Star D	8.5	0.5		

Table 2: Typical distance moduli data for RR Lyrae stars

m-M	0	1	2	3	4	5	6	7	8	9	10	15	20	25
D (parsecs)	10	16	25	40	63	100	160	250	400	630	10^3	10^4	10^5	10^6

6. Using table 2, could one of the stars listed in the question 5 be an RR Lyrae star? Why or why not?

Part 4. Main Sequence Fitting

Main sequence fitting determines distances using HR Diagrams of clusters of stars. These stars are gravitationally bound, all located at the same distance, and formed at the same time from the same cloud of gas and dust. Main sequence fitting compares the location of the main sequence (where m is on the y axis) for the cluster stars to the location of the main sequence for nearby stars whose distances are measured from parallax (so these stars' M is on the y-axis). Any difference in position between the main sequences must be due to the distance of the cluster. The vertical position of the cluster main sequence is adjusted vertically so that it lines up with the main sequence of nearby stars. The amount of vertical adjustment gives the distance modulus.

Figure 1: Main sequence fitting example for the Pleiades star cluster
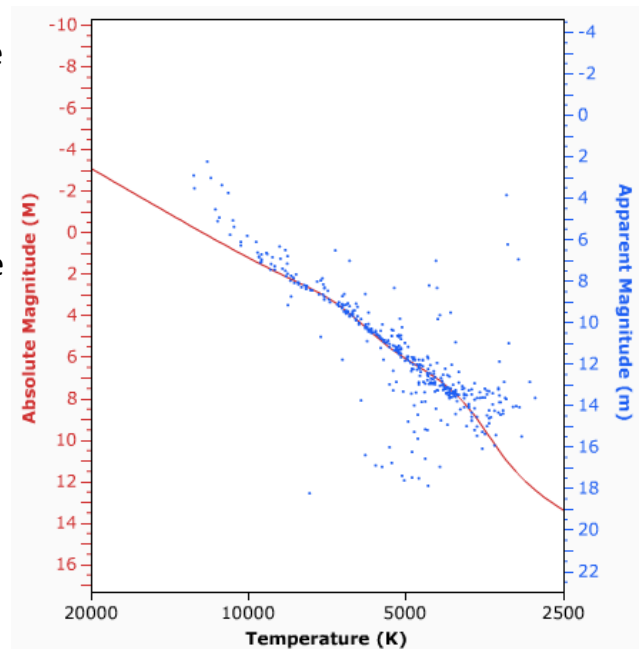
Go back to the main page, then select 'Cluster Fitting Explorer' next to 'Main Content.' The main sequence for nearby stars whose distances are known are plotted by absolute magnitude in red on the HR Diagram. In the 'Cluster Selection' panel, choose the 'Pleiades' cluster. The Pleiades data are then overplotted in apparent magnitude in blue. Note that the two y-axes are aligned, but the two main sequences don't overlap due to the distance of the Pleiades (since it is not 10 parsecs away).

If you move the cursor into the HR diagram, the cursor will change to a handle, and you can shift the *m* scale by clicking and dragging. Grab the Pleiades data and drag it until the two main sequences are best overlapped (example shown in figure 1).
We can now relate the two y-axes. Click on 'show horizontal bar' which will label the *M* (left) and *m* (right). Entering these into the 'Distance Modulus Calculator' will give you the distance to the cluster in parsecs.

7. Note that there are several stars that are above the main sequence in the upper left of the HR diagram. Why are these stars not on the main sequence?'

8. Also note that there are several stars below the main sequence, especially near temperatures of ~5000 K. Why are these stars not on the main sequence?

9. Select the 'Hyades' cluster in the 'Cluster Selection' panel and fill in the distance modulus data in table 3 below.

Table 3: Distance modulus for the Hyades star cluster

m	*M*	*D* (parsecs)

10. Select the 'M67' cluster in the 'Cluster Selection' panel and fill in the distance modulus data in table 4 below.

**Table 4: Distance modulus for the M67 star cluster**

m	*M*	*D* (parsecs)

Part 5. Supernovae

Astronomers recognize two main types of Supernovae explosions. Type I supernovae involve a white dwarf that is part of a binary system. A white dwarf is an earth-size ball of carbon and oxygen nuclei that is the collapsed core of a low mass star. If material flows rapidly from the binary companion star onto the white dwarf, a sudden burst of fusion is triggered and causes a Type I supernova. Type II supernovae involve very massive stars at the ends of their lives. These stars fuse progressively more massive nuclei in their cores – carbon, oxygen, magnesium, silicon – and finally a core of iron is formed. Fusion of elements heavier than iron no longer release energy to oppose the gravity of the star. So, the core is crushed to incredibly high temperatures and pressures by the weight of the overlying materials, and the all of the overlying layers "bounce" off of the core region. This Type II supernova is less energetic than the Type I and typically a massive object such as a neutron star or black hole is formed.

Because supernovae are such energetic events, astronomers can observe them at great distances. Type I supernovae are very uniform and easy to calibrate for standard candles since astronomers can calculate the amount of energy produced in the fusion that occurs before a Type I supernova. They are much more useful to astronomers as distance indicators than Type II Supernovae.

Figure 2: Example fit of supernovae data to a Type I profile
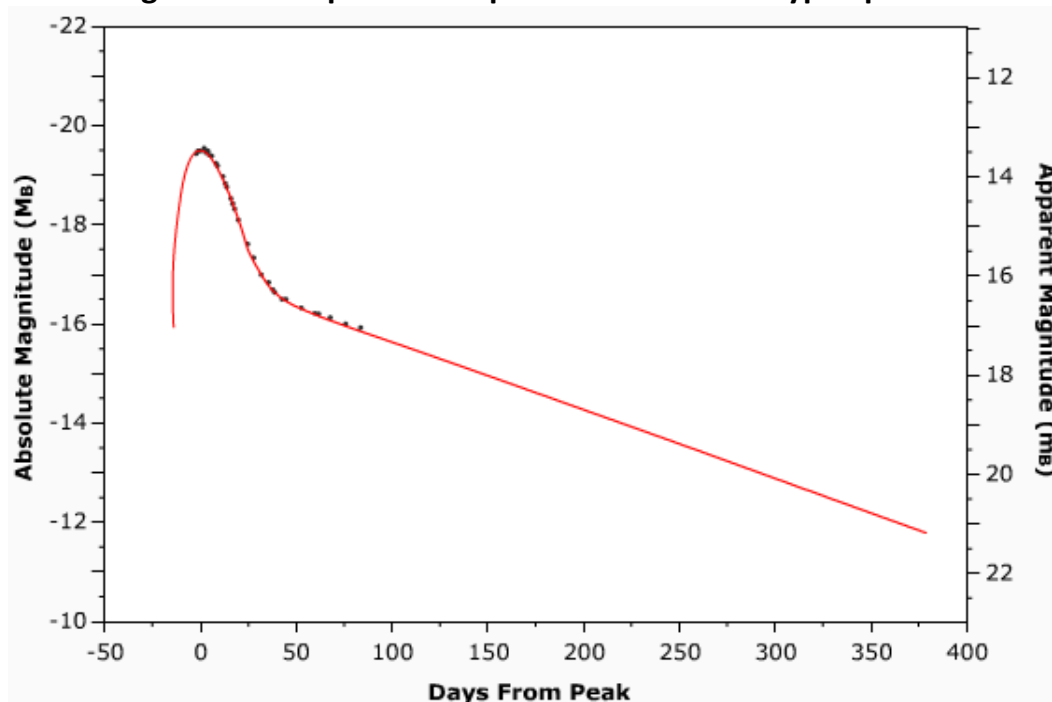
Go back to the main page, then select 'Supernovae Light Curve Explorer' next to 'Main Content.' The red line illustrates the expected profile for a Type I supernova in terms of its absolute magnitude. Data from various supernovae can be graphed in terms their apparent magnitude.

It is then possible to fit the data to the Type I profile with the appropriate shifts in time and magnitude, shown in figure 2, just like main sequence fitting. Once the data fit the profile, then the difference between *m* and *M* (labeled if 'show horizontal bar' is selected) again gives the distance modulus.

11. Select the '1994ae' supernova in the selection panel and fill in the distance modulus data in table 5 below.

Table 4: Distance modulus for the SN 1994ae

m	*M*	*D* (parsecs)

12. Select the '1987A' supernova in the selection panel. Explain why it is not possible to determine the distance to this supernova.

To complete this assignment for grading:

- Save this file: File -> Save As… -> Rename the file 'YourLastName – DistLadLab'
- Upload your file to 'Lab 7 – The Cosmic Distance Ladder' assignment in iCollege (click Add Attachments -> Upload -> upload renamed saved file -> Update).
- Complete the Reflection activity on iCollege
- Have a beverage of your choice in celebration!