Activity 4: Parallax

Materials List:
- Ruler
- Calculator

Last time, we learned how to estimate the distance to an object when we already had a guess as to the object's size. But what if we don't have any clue about the object's size to begin with?

Consider the photograph on the right, which is one of the most famous photographs taken by the Hubble Space Telescope. It is a photograph of the **Crab Nebula**.

John Bevis is credited with discovering the Crab Nebula in England in 1731 through a telescope. The dramatic explosion (which looked like just a speck of light to naked eye observers on Earth) that created the nebula was actually seen (without instruments) and recorded by Chinese astronomers in 1054. The explosion lasted about two years, and therefore the bright speck looked like a "new star" and hence it was called a ***nova***, from the Latin for "new". We'll discuss exploding stars in greater depth in a later Activity.

If you, like John Bevis, had discovered the Crab Nebula through your telescope, you would see a cloudy patch in the sky but have no idea as to its distance or size. Let's take a look at a method that we can use to find the distance to an object of unknown size.

Aside:

> **Nebula** was a name introduced centuries ago that means "cloud" or "fog" and was given to any object in the night sky that looked "nebulous" (hazy and indistinct). Today, most nebulae have been studied in greater detail and identified as being galaxies or other interesting astronomical objects. The Crab Nebula pictured above is now known to be a **supernova remnant**, the ejected gas left after the explosion of a star.

Part 1: Parallax in the Classroom

STEP 1: Hold your arm out in front of you at arm's length and stick up your thumb (like a hitchhiker). Close only your left eye and take note of the "position" of your thumb relative to objects in the background (for instance, stationary objects on the far side of the room).

Having noted your thumb's relative position to the background, now close only your right eye (opening your left eye). ***Don't move your thumb or your head***. Now take note of your thumb's new apparent position relative to the background. What happened to your thumb's position relative to the background?

STEP 2: Why do you think this apparent motion happened? Did your thumb really move? If not, then why did it appear to move with respect to the background?

STEP 3: Now hold your thumb closer to your face, as close as you can while still being able to focus on it with one eye closed. Repeat the procedure in Step 1. What happened to the relative position of your thumb this time? Was there anything different about it this time, and if so, what was different?

STEP 4: In which case (thumb close to your face or thumb far from your face) did your thumb appear to move the *most*?

In which case (thumb close or thumb far) did your thumb appear to move the *least*?

The phenomenon you've just observed is called **parallax**.

SQ1: Use your observations to fill in the following blanks:

Parallax means…

Objects that are *farther* away appear to move __________________ with respect to
(more / less)
the background as compared to objects that are closer.

Objects that are *closer* appear to move _________________ with respect to the
(more / less)
background as compared to objects that are farther away.

Because things at different distances from us appear to move by differing amounts relative to the background, we can use this phenomenon of parallax to find the distance to an object (such as the distance from your eye to your thumb, in this example).

Could you reproduce this effect using one and only one eye and moving the location of your head (but not the location of your thumb!) between measurements? Why or why not?

The fact that we have *two eyes* is what allows us to see in three dimensions. Each eye has a slightly different perspective on our environment, and utilizing those two different images our brain constructs a three-dimensional model of what the eyes are seeing. This is how we know how far away things are, or in other words, it gives us *depth perception*.

Part 2: Parallax Angles and the Parsec[1]

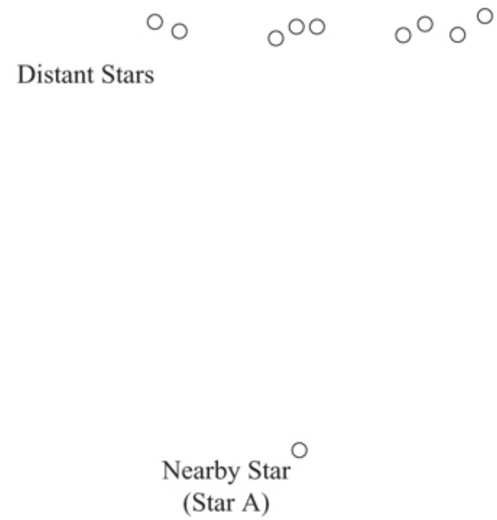
Consider the diagram below (next page) on the right. We see the Earth at two different times during its trip around the Sun, once in January and once in July. This is similar to looking at our thumb from two different angles by moving our head. Instead of our head changing locations, the Earth is changing locations as it orbits the Sun.

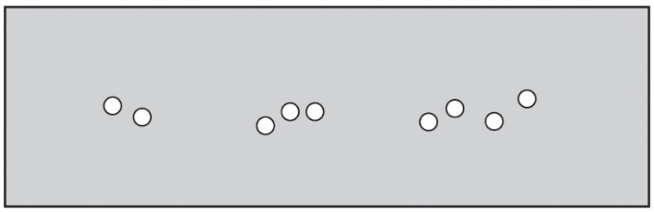
STEP 1: You are looking at the stars from Earth in January. Use a ruler to draw a straight line from Earth in January, through the Nearby Star (Star A), out to the Distant Stars. Which of the distant stars would appear closest to Star A in your night sky in January? Circle this distant star and label it "Jan".

STEP 2: Repeat Step 1 for July and circle and label the distant star "July".

[1] Much of this Part is directly from *Lecture-Tutorials for Introductory Astronomy* (3rd Edition) by Prather, et al.

STEP 3: In the box below, the same distant stars are shown as you would see them in the night sky. Draw a small X to indicate the position of Star A as seen in January and label it “Star A Jan”.



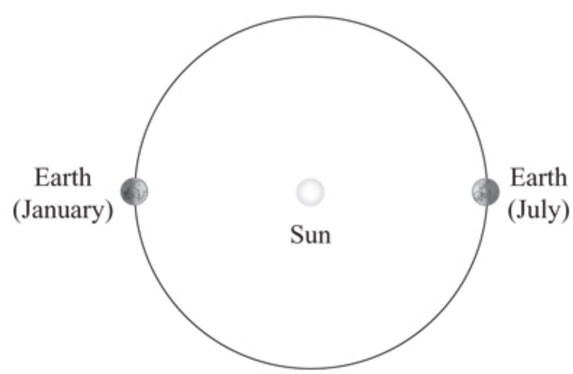


STEP 4: In the same box, draw another X to indicate the position of Star A as seen in July and label it “Star A July”.

SQ2: Describe how Star A would appear to move among the distant stars as Earth orbits the Sun counterclockwise from January of one year, through July, to January of the following year.

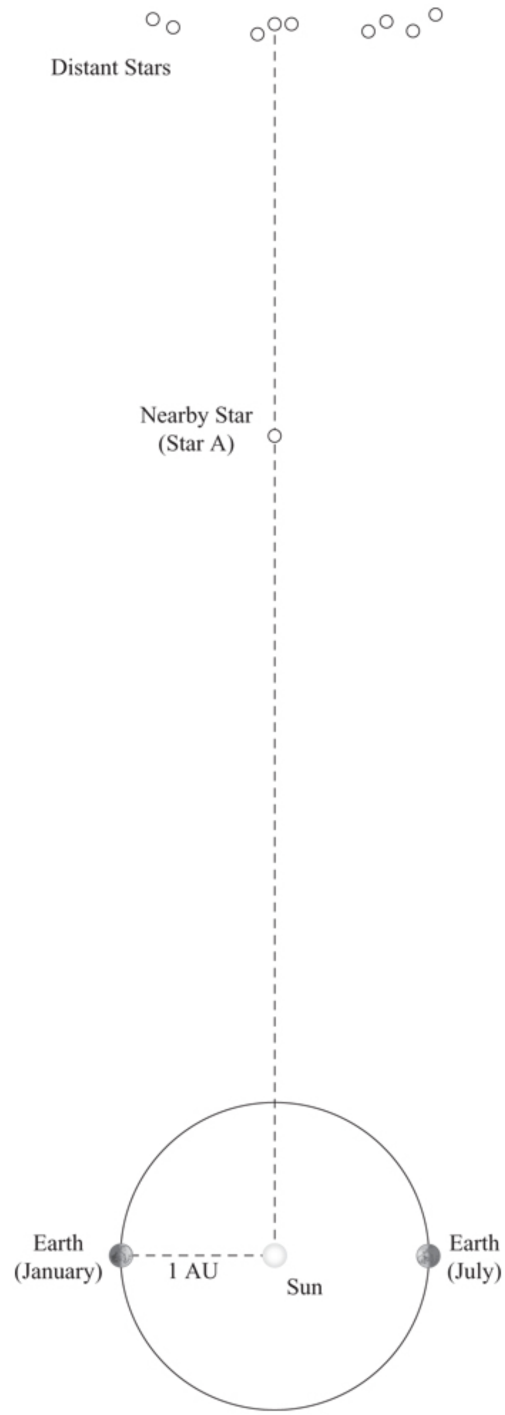
This apparent motion of nearby objects relative to distant objects is **parallax**, the same phenomenon you just observed with your thumb.

SQ3: Imagine two stars (call them C and D) that both exhibit parallax. If Star C appears to move back and forth by a greater amount than Star D, which star do you think is actually closer to you? Why do you think so?



STEP 6: Now we will use the next diagram below (next page) and on the right. Starting from Earth in January, draw a line through Star A to the top of the page.

There is now a narrow triangle created by: the line you drew, the vertical dotted line provided in the diagram, and the line connecting Earth and the Sun. The small angle, just below Star A, formed by the two longest sides of this triangle is called the **parallax angle** for Star A. Label this angle $\mathbf{p_A}$.



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STEP 7: Given that even the nearest stars are still very far away, would you expect parallax angles to typically be quite large or quite small?

Parallax angles are measured in arcseconds. To give you an idea of how small an arcsecond is: the thin edge of a credit card, when viewed from one football field away, covers an angle of about 1 arcsecond.

To describe distances to stars, astronomers use a unit of length called the *parsec*.

> A **parsec** is defined as the *distance* to a star that has a **par**allax angle of exactly 1 arc**sec**ond.
>
> The distance from Earth to a star 1 parsec away is about 3.26 light years.

Note: Since the distances to other stars are so great in comparison to the Earth-Sun distance, we can effectively say that the distance from the *Earth* to a distant star is very nearly the same as the distance from the *Sun* to that distant star.

STEP 8: If the parallax angle for Star A ($\mathbf{p_A}$) is 1 arcsecond, what is the distance from the Sun to Star A? Hint: Use the parsec as your unit of distance and that makes things extremely simple. Label this distance on the diagram.

STEP 9: Consider the following debate between two students regarding the relationship between parallax angle and the distance we measure to a star.

Student A: *If the distance to the star is more than 1 parsec, then the parallax angle must be more than 1 arcsecond. So a star that is many parsecs away will have a large parallax angle.*

Student B: *If we drew a diagram for a star that was much more than 1 parsec away from us, the triangle in the diagram would be taller and thinner than the one we just drew in Step 6. That should make the parallax angle smaller for a star farther away.*

Do you agree or disagree with either or both of the students? Explain your reasoning.

STEP 10: On your diagram on page 5, draw a second star along the dotted line farther from the Sun than Star A and label this faraway star "Star B". Repeat the process in which you draw another triangle for Star B and label that parallax angle $\mathbf{p_B}$.

Which star, the closer one (Star A) or the farther one (Star B) has the larger parallax angle?

Go back and look at your answers in Steps 7 and 9 and make sure they agree with your answer in Step 10.

Part 3: Parallax and the Distance to Stars [2]

Consider the starfield drawing shown in Figure 1 below. This represents a tiny patch of our night sky. In this drawing, we will imagine that the angle separating Stars A and B is just ½ of an arcsecond.

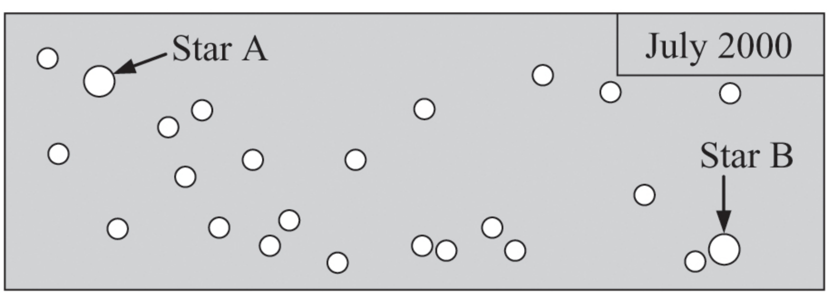

Figure 1

In Figure 2 (page 8), there are drawings of this starfield taken at different times during the year. One star in the field moves back and forth across the star field (it "***exhibits parallax***") with respect to the other, more distant stars.

[2] Much of this Part is directly from *Lecture-Tutorials for Introductory Astronomy* (3rd Edition) by Prather, et al.

STEP 1: Using Figure 2, determine which star exhibits parallax. This may take a little time and concentration but it's very doable. Circle that star on each picture in Figure 2.

STEP 2: In Figure 1 (previous page), draw a line that shows the range of motion for the star you saw exhibiting parallax in the drawings from Figure 2. Label the end points of this line with the months when the star appears at those end points.

STEP 3: Recall that Stars A and B have an angular separation of ½ an arcsecond in Figure 1. Compare that separation to the length of the line you drew in the same figure for the nearby star exhibiting parallax. Roughly what is the angular separation between the end points on the line you drew?

Important Note:

The **parallax angle** for a star is *one half* the angular separation between the end points of the star's observed motion.

The above statement can be proven with a little simple geometry. To see a demonstration of this, call your instructor over or watch this short video:

https://youtu.be/9tBOXqYk_1Q

What is the parallax angle for the star exhibiting parallax?

Parallax angle = ________________ arcseconds

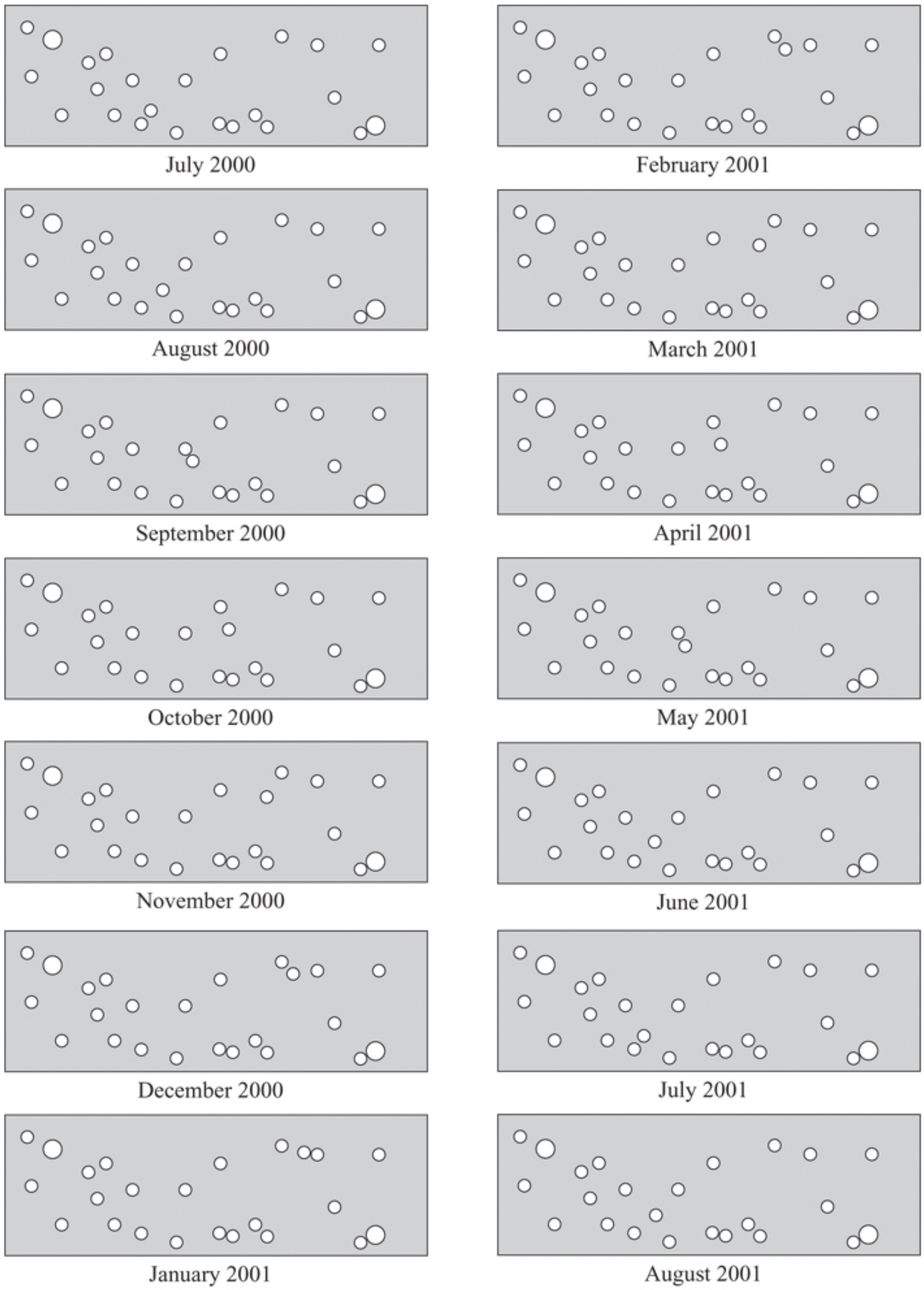
July 2000
February 2001
August 2000
March 2001
September 2000
April 2001
October 2000
May 2001
November 2000
June 2001
December 2000
July 2001
January 2001
August 2001

Figure 2

SQ4:

a) Recall that 1 parsec is defined as the *distance* to an object that has a *parallax angle* of 1 arcsecond.

For a star with a parallax angle of 2 arcseconds, would you expect the distance to the star to be 2 parsecs or ½ a parsec? Why? For guidance, look back at your answers to Step 9 (the student dialogue) and Step 10 in the previous Part.

b) For a star with a parallax angle of ½ an arcsecond, would you expect the distance to the star to be 2 parsecs or ½ a parsec? Why?

c) For a star with a parallax angle of ¼ of an arcsecond, what is its distance from us in parsecs?

d) What is the pattern here? What is the simple mathematical operation that takes you from parallax angle (in arcseconds) to distance (in parsecs)?

SQ5:

a) What is the distance from us to the nearby star exhibiting parallax in the drawings from Figure 2? (Look back at the parallax angle that you found for that star in Step 3 on page 7).

b) Convert this distance from parsecs into light years.

You've done it! You've found the distance to a (fictional) star just by watching it move back and forth in the sky over the course of a year (i.e., by watching it exhibit parallax).

Summary

Let's quickly review what we've learned about finding distances:

1) Given an object whose size is known (or can be estimated), we can find the distance to that object using the cotangent method. Give an example of when we did that previously in this course.

2) If we know nothing about the object's size, we can still estimate the distance to it using which technique? (Hint: Did you know the size of the star to which you found the distance in the SQ4?)

3) Given an object whose *distance* from us is known, we can estimate the *size* of the object using the cotangent method. We did that in the previous Activity with the Sun. Edmund Halley found the distance to the Sun using parallax, and then we used his result and the cotangent method to estimate the size of the Sun.

SQ6: Returning to Bevis and his discovery of the Crab Nebula, let's suppose that, like him, you've found a new object but you have no idea what its size is or what the distance to it is. What steps could you take to find both the size *and* the distance to the object? (Hint: would you have to find the size first and the distance second, or the other way around?)

Part 4: Stellar Distances and Beyond

It takes light about 8 minutes to traverse the distance from the Sun to the Earth. For this reason -- and analogous to how we use light years -- we can say the distance between Earth and the Sun is about 8 *light minutes*. A **light minute** is the distance light can travel in one minute.

STEP 1: How many AU are in 8 light minutes? Hint: no arithmetic required for this one!

SQ7: If the Sun were to suddenly change in some way (for instance, the appearance of a feature on its surface), how long would it be before we on Earth realized that the Sun had changed? Why?

STEP 2: In the previous Activity, we saw that Pluto is about 40 AU (on average) from the Sun. How far is Pluto from the Sun in *light minutes*? (Hint: Use what you already found regarding how many light minutes are in an AU.) Then, convert your answer into *light hours* using the fact that there are 60 light minutes in 1 light hour.

STEP 3: Eris is one of the farthest known objects in our solar system. Its current distance from the Sun is about 96 AU. Based on that, estimate the radius of our solar system in *light hours*. Since we know there are 8 light minutes in an AU, we can multiply that by 96 AU to get the distance in light minutes, and then divide by 60 to get the distance in light hours. This has been set up for you below.

$$\text{Solar System radius} = 96\ \text{AU} \times \frac{8\ \text{light minutes}}{1\ \text{AU}} \times \frac{1\ \text{light hour}}{60\ \text{light minutes}} =$$

> **Note:** It is difficult to define the radius of the solar system because it does not have a well-defined edge. Similarly, it is difficult to define the edge of Earth's atmosphere because it doesn't just abruptly end, but instead slowly fades away. The estimate above for the radius of the solar system will be sufficient for our purposes today, however.

STEP 4: The *nearest star* to Earth is called **Proxima Centauri** (part of the **Alpha Centauri** star system). The distance to Proxima Centauri is about 4.2 light years.

How many light hours are in a light year? *Hint:* How many hours are in a year? Fill in the missing numbers below and then multiply.

$$1\ \text{light year} = \frac{\quad\quad \text{days}}{1\ \text{year}} \times \frac{\quad\quad \text{hours}}{1\ \text{day}} = \quad\quad\quad \text{light hours}$$

If Proxima Centauri is 4.2 light years away, how far away is it in units of *light hours*? Again, fill in the missing number first.

$$4.2\ \text{light years} \times \frac{\quad\quad \text{light hours}}{1\ \text{light year}} =$$

SQ8: How far away is Proxima Centauri in units of solar system radii? Fill in the distance to Proxima Centauri in light hours (your answer from Step 4) and the number of light hours in a solar system radius (your answer from Step 3).

$$\text{distance to Proxima Centauri} = \qquad\qquad \text{light hours} \times \frac{1 \text{ solar system radius}}{\text{light hours}} =$$

STEP 5: Imagine we are repeating the previous Activity with the paper scale model of our solar system and we now want to include Proxima Centauri in our model at the appropriate distance. Recall our model only went out to Pluto, and Eris is more than twice as far. So we'll need double the length of paper to include Eris, which would equal 117 inches of paper. How much total paper would you need to get to Proxima Centauri? For fun, let's calculate this number in miles. First fill in your previous answer, then compute the amount of paper using the formula below.

$$\frac{117 \text{ inches}}{1 \text{ solar system radius}} \times \qquad\qquad \text{solar system radii to P Centuari} \times \frac{1 \text{ foot}}{12 \text{ inches}} \times \frac{1 \text{ mile}}{5280 \text{ feet}} =$$

That's a lot of paper. And remember, Proxima Centauri is our *nearest* neighbor!

STEP 6: **Polaris**, or the **North Star**, is perhaps the most famous object in the nighttime sky in the Northern Hemisphere. (It can't be seen at all in the Southern Hemisphere. We'll talk about that in much more detail in a couple of weeks.)

Using parallax, the distance to the North Star has been measured to be about 433 light years. Imagine you go outside and look at the North Star. What year was it on Earth when the light first started its journey from the North Star (a journey which culminated in being absorbed by your eye)? Was this before or after the signing of the Declaration of Independence?

Remember, we are looking at the North Star as it appeared *at the time the light left it*.

STEP 7: Another famous nighttime object is the **Orion constellation**. One of the stars within the Orion constellation is a blue-white supergiant star named **Rigel**. It is 863 light years from Earth, and yet it is visible with the naked eye because it is an incredibly bright star. Rigel is easily spotted when the Orion constellation is visible in the winter months. What year was it when the light first started its journey from Rigel to your eyes? Was this before or after the invention of the magnetic compass in 1182 AD?

STEP 8: Not only is Rigel impressively far away and impressively bright, it is also impressively large, as are other giant and supergiant stars such as Betelgeuse, Antares, and others. To get an idea of the size of these objects, open the following URL and watch the short video, which depicts a scale model of these various stars:

youtu.be/HEheh1BH34Q

Scale of the Milky Way

Our galaxy, the **Milky Way**, is a rotating disk of stars, gas, and dust that contains our solar system as well as *over 100 billion* other stars. On the next page is a picture of the Milky Way galaxy with the location of our Sun marked. The Milky Way is called a *spiral galaxy* (or sometimes a *barred spiral galaxy*) because of its spiral arms. The Andromeda galaxy is also a spiral galaxy.

The diameter of the Milky Way galaxy is about *150,000 light years.*

SQ9: Look at the picture below (next page). Is this image of the Milky Way a photograph taken by a camera or a drawing made by an artist? Why must your answer be true?


Norma
Scutum-Crux
Sagittarius
Sun
Orion
Perseus
Cygnus
10 000 ly
r powell