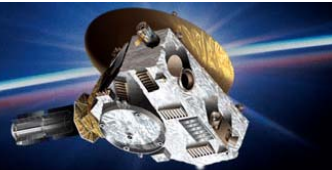


# NEW HORIZONS

To Pluto and Beyond

<http://pluto.jhuapl.edu>



## Stellar Illumination

**Overview:** Students explore how a stellar occultation occurs, how planetary atmospheres can be discovered, and how planetary diameters can be determined using actual light curves from stellar occultation events.

**Target Grade Level: 9-12**

**Estimated Duration: 1 40-minute session**

**Learning Goals: Students will be able to...**

- understand how stellar occultations occur.
- create light curves from a demonstration of various stellar occultation events.
- interpret light curves from various actual stellar occultation events to determine if a planet or body has an atmosphere.
- calculate the diameter of planets or moons using actual stellar occultation light curves.

**Standards Addressed:**

**Benchmarks (AAAS, 1993)**

The Nature of Science, 1B: Scientific Inquiry

The Physical Setting, 4A: The Universe

**National Science Education Standards (NRC, 1996)**

Unifying Concepts and Processes: Evidence, models, and explanation

Science as Inquiry: Understandings about scientific inquiry

**Principles and Standards for School Mathematics (NCTM, 2000)**

Representation Standard

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## Background:

Pluto, Charon and other Kuiper Belt Objects (KBOs; many small bodies in orbit around the Sun beyond the orbit of Neptune to about 50 AU) are so far away that many Earth-based instruments and techniques are not able to probe the atmospheres or determine accurate sizes of these distant bodies. For example, Figure 1 is an example of the best images we can obtain of Pluto and Charon using Earth-based telescopes in the visible range of the spectrum.

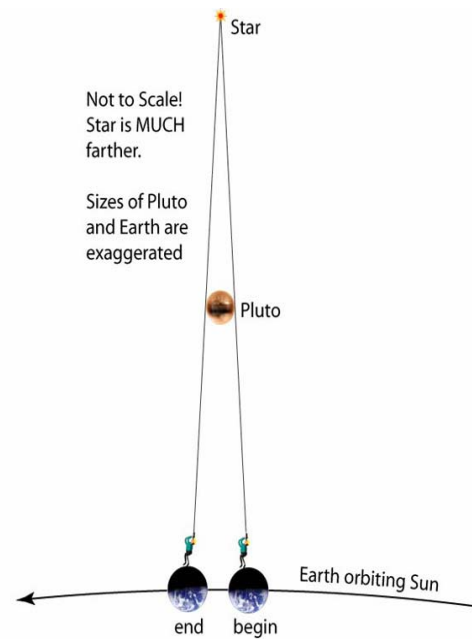


**Figure 1.** Pluto and Charon captured by the 2.6 meter Nordic Optical Telescope, La Palma, the Canary Islands. (Image courtesy: Nordic Optical Telescope Scientific Association).

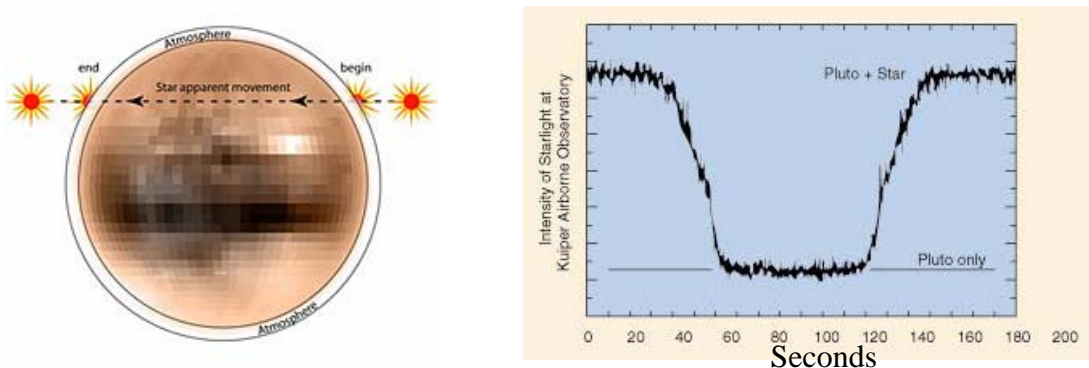
However, stellar occultation is **one** Earth-based observing method that enables us to learn about the atmospheres and diameters of distant bodies, with a spatial resolution of a few kilometers. A stellar occultation occurs when a nearby solar system body passes in front of a distant background star. The intensity of the starlight is recorded as time goes by, beginning before and stopping after the occultation. These data are displayed as a light curve, which is a graph of intensity versus time. From light curves, scientists can determine the density profile of an atmosphere, and the width of the planet or body along the apparent path of the star. (The star isn't actually moving, but it appears to move along a path as indicated in Figure 3).

When the occultation is observed from Earth, the combined orbital motions of Earth and the solar system body contribute to the rate of the stellar occultation. Figure 2, right, illustrates the geometry of a stellar occultation from a bird's eye perspective. While it is not indicated in the Figure, Pluto is also moving during the occultation, albeit at a much slower orbital velocity than our own.

Based on this geometry, it appears to the Earth-based observer that the star passes from right to left behind the occulting planet. If the occulting planet or solar system body has an atmosphere, the intensity of light from the star dims as its light is absorbed and refracted by the atmosphere. After the star is behind the planet, only the light reflected by the planet (from the Sun) is recorded in the light curve. See what this looks like in Figure 3, below.

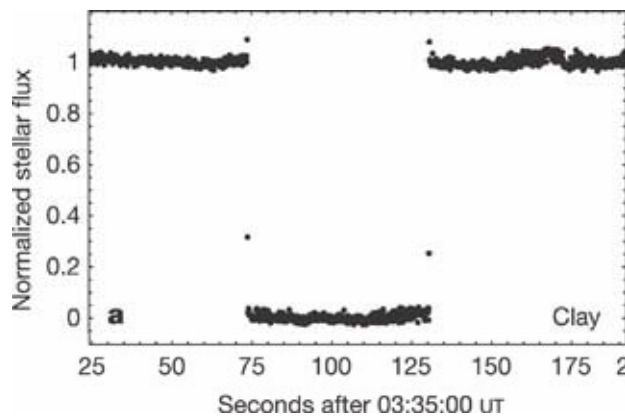


**Figure 2.** A bird's eye view of the geometry of a stellar occultation. Notice that in reality the star is much farther away from Pluto and Earth and the sizes of Pluto and Earth are exaggerated. (Image courtesy: JHU/APL)



**Figure 3. Left:** Pluto and what the apparent motion of the star looked like during the occultation on June 9, 1988. **Right:** The light curve from that occultation. Notice how the light from the star dims over about 30 seconds, which indicates that Pluto has an atmosphere. Also, the slope of the line appears to change as the star is almost behind or just emerging from behind Pluto indicating some structure in Pluto’s atmosphere, perhaps due to a temperature change, a haze layer or maybe both. (Images courtesy: JHU/APL).

Contrast the light curve from Pluto in Figure 3, with a light curve from Charon in Figure 4. Pluto has an atmosphere, whereas Charon does not.



**Figure 4.** The light curve from a stellar occultation by Charon on July 11, 2005. This data was collected using a 6.5 meter telescope (Clay) at Las Campanas Observatory, La Serena, Chile. (Image courtesy: Las Campanas Observatory).

The diameter of a planet or body can also be determined using light curve data, even though the apparent path of a star, known as the chord, does not necessarily pass through the widest part of a planet. Essentially one uses Earth’s orbital velocity relative to the occulting body and the duration of the occultation (not including the atmosphere) to calculate the distance traveled during that time. In the **Stellar Illumination group activity (With Answers)** one such calculation is done for you. In this example, we assume the chord passes through the widest part of Charon. The math would be more

complicated if chords that did not pass through the widest part were used to calculate the diameter of the body.

Stellar occultations have certainly helped us learn about the atmospheres and diameters of Pluto and Charon. With more and more bodies being discovered in the Kuiper Belt, stellar occultations will likely continue to be a useful tool for probing distant atmospheres and determining KBO sizes...that is, until the New Horizons spacecraft flies in for a much closer encounter in 2015!

## Materials:

- LED light (small light available as a key chain in most hardware stores; preferably one that can be switched on and off)
- translucent paper (vellum, tracing paper, etc.) (4 sheets)
- white opaque paper (construction paper, cardboard, etc.) (4 sheets)
- paint stirrers (or fashion handles out of a few layers of cardboard) (4)
- glue or tape
- Stellar Occultation student data sheet (1 per student)
- Geometry of a Stellar Occultation teacher sheet (create transparency/project)
- Apparent Stellar Motion teacher sheet (create transparency/project)
- Stellar Illumination group activity sheet (1 per student)
- Answers to Stellar Occultation student data sheet (for teacher use)
- Answers to Stellar Illumination group activity sheet (for teacher use)



## Procedure:

### *Generally speaking...*

**What the teacher will do:** The teacher will distribute the Stellar Occultation student data sheets and allow time for students to answer the questions independently. Then the teacher will demonstrate stellar occultations using a small LED light and simplified models of planets with different atmospheres. The teacher will divide the class into groups and distribute the Stellar Illumination group activity sheet. Finally he/she will walk around the room answering questions as necessary.

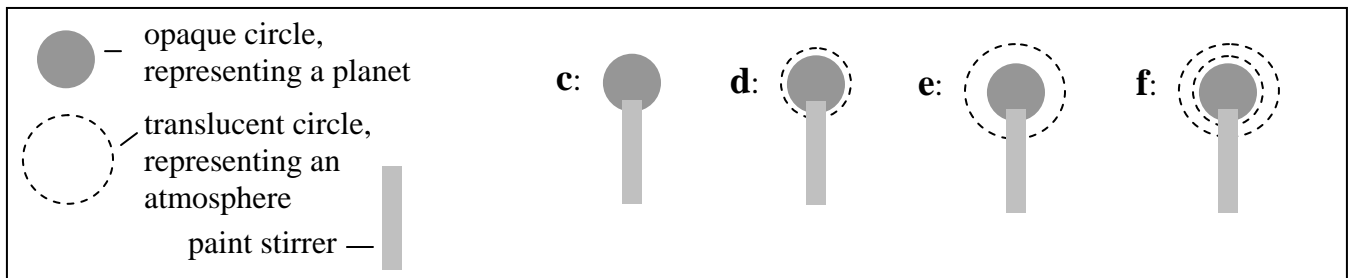
**What the students will do:** The students will describe what a stellar occultation might look like, without having seen one or explored the topic. Then they will observe the teacher's stellar occultation demonstration and draw simple light curves to represent what they are seeing. They will be assigned to groups to complete the Stellar Illumination group activity sheet.

### Advance Preparation

1. Gather materials and make copies as indicated in the **Materials** section.
2. Create a transparency of the **Geometry of a Stellar Occultation** and the **Apparent Stellar Motion** teacher sheets if you use an overhead projector. If you can project your computer screen, save these sheets to your computer in a convenient location. Otherwise, make copies and use them to help you draw larger versions on the board.
3. Assemble the planets with or without atmospheres for the Stellar Occultation demonstration using the translucent paper, opaque paper, paint stirrers/cardboard, and glue or tape as follows:
  - a. From the opaque paper, cut out 4 circles with a diameter of about  $4\frac{1}{2}$  inches.
  - b. From the translucent paper, cut out 2 circles with 6 inch diameters and 2 circles with  $8\frac{1}{2}$  inch diameters.

- c. Planet with no atmosphere: using tape or glue, attach one of the opaque circles to a paint stirrer like a lollipop (see “c.” in Figure 1 below).
- d. Planet with a small atmosphere: using tape or glue, attach one of the opaque circles to one of the 6-inch diameter translucent circles so that the opaque circle is centered within the translucent circle (see “d.” in Figure 1 below). Then attach a paint stirrer to the opaque (smaller) circle like a lollipop.
- e. Planet with a deep atmosphere: using tape or glue, attach one of the opaque circles to one of the 8½-inch diameter translucent circles as above, and attach a paint stirrer as above.
- f. Planet with a layered atmosphere: using tape or glue, attach one of the opaque circles to one of the 6-inch diameter translucent circles so that the opaque circle is centered within the translucent circle. Then attach these to one of the 8½-inch diameter translucent circles as above, and attach a paint stirrer as above.

Figure 1.



### In-class Procedure

1. Begin by handing out Part 1 of the **Stellar Occultation** student data sheet (2 pages) and ask them to complete Part 1 independently. Do not explain stellar occultations or provide background material, since the goal of this part of the activity is for students to think through the abstract concept and commit to how it might look before they have observed or discussed the phenomenon. Give students enough time to complete the activity—between 5 and 10 minutes.
2. While they are working on the student data sheet, write the fundamental question being addressed on the board: “How do we know if a planet or a moon has an atmosphere?”
3. After students have completed Part 1 of the **Stellar Occultation** student data sheet, provide some brief background information on stellar occultations, including a projection or drawing of the diagram that illustrates the **Geometry of a Stellar Occultation** provided (For example, Fig. 2). You may also want to project or draw the **Apparent Stellar Motion** image provided (For example, Fig. 3).

Figure 2:

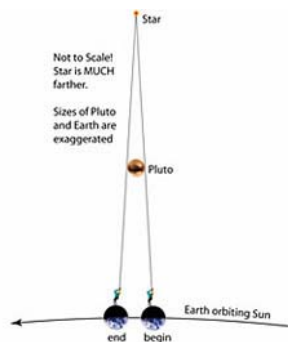
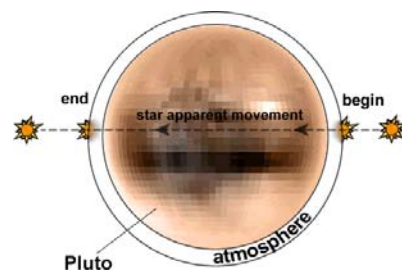


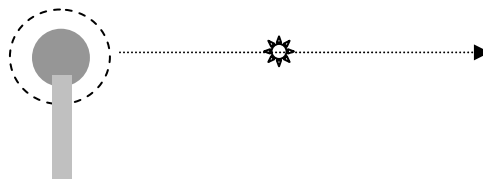
Figure 3:



4. Distribute Part 2 of the **Stellar Occultation** student data sheet that begins on the third page of that hand-out. Ask students to observe your demonstration. They should be able to see the simulated occultation from their desks and you standing at the front of the classroom. Ask them to complete Part 2 of the **Stellar Occultation** student data sheet as you demonstrate the different types of atmospheres (note: students will draw a light curve of what they observe). Count out loud using ‘one one thousand, two one thousand, etc.’ For each planet/atmosphere (Figure 1, above, c through f) you should turn on the LED and hold it facing the students, but aim it well above their heads. Hold the planet by the paint stirrer with the translucent piece facing them (the opaque circle and the attached part of the paint stirrer facing you) and slowly move it toward the LED horizontally (see diagram below), in front of the LED, and continue until the planet/atmosphere is several inches past the LED.

Figure 4.

Hold onto the paint stirrer with one hand and move it along the path of the arrow (toward the LED, in front of the LED, and then past it)



NOTE:

- Establish before beginning the demonstration that the LED by itself is a “10” on their **Stellar Occultation** student data sheet brightness scale. Then they can fill in the light curves as you demonstrate different occultation events.
- To help students create clear and uniform light curves, try to time your demonstration for each planet as follows (you may want to practice):
  - Time = 0, just beginning and planet is far from star
  - Time = 5 sec., atmosphere is in front of star, if it has one, and if not star is not yet behind planet
  - Time = 10, star is behind planet and cannot be seen
  - Time = 15, star is behind the atmosphere on the far side of the planet, if it has one, and is not behind the planet
  - Time = 20, star is away from planet and un-obscured
  - To adhere to this time series, it might be helpful for you to count out loud to the class as you proceed.
- The LED represents a star, the translucent paper represents an atmosphere, and the opaque circle represents a planet or a moon. Notice how the planet moves, not the star (LED). You may want to point out that it is actually mostly the movement of Earth along its orbit that causes the planet to appear to move in front of the very distant star. Also note, planets closer to the Sun orbit faster than Earth, and planets farther from the Sun than Earth have slower or longer orbits.
- Make sure you pass the planet/opaque circle in front of the LED and not just the atmosphere for at least your first pass.

- Then you can demonstrate what happens when just the atmosphere passes in front of the star by holding your planet down lower if desired.
  - You may wish to demonstrate each occultation several times so that students can watch the first time, then record the light curve the second time and fill in any gaps in their data or ask questions the third time.
5. Explain to students that the light curves from stellar occultations are one way to reveal information about the absence or presence of an atmosphere, and—if one exists—the structure of an atmosphere. In addition, they can be used to determine the diameter of a planet or solar system body.
  6. Divide the class into groups of three or four students. Distribute the **Stellar Illumination** group activity sheet. Walk around the room and answer questions as necessary. NOTE: you may want to talk to the students about “noise” in the data from the stellar occultations in this activity. The light curves are not smooth, but rather have small, jagged deviations from the main trend of the curve. According to the American Heritage Dictionary, in science, *noise* is “disturbance, especially a random and persistent disturbance, that obscures or reduces the clarity of a signal.” In this application, that means that the small deviations from the main trend of the light curve can be ignored.



## Extensions and Adaptations:

- To adapt this activity for middle school grades, omit the final diameter calculations on the **Stellar Illumination** group activity sheet.
- For students with vision impairment:
  - Demonstrate a stellar occultation using sound intensity instead of light intensity. Download this free tone generator: <http://www.nch.com.au/tonegen/index.html> (click on ‘download’. You can purchase this software for more options, but you can download just one tone for free). Limit the sound output from your computer to just one speaker by disconnecting any additional speakers. Position the blind or visually impaired student near the speaker of the computer. Start the tone by clicking “Play”. Move a pillow (or other sound-absorbing material) slowly in front of the computer speaker, cover the speaker, then move the pillow away slowly in a similar motion to that of the mock-planet and the light source. Experiment with different sound-dampening materials to try to create changes in the tone similar to the planets with larger atmospheres, smaller atmospheres, no atmosphere, etc. in the Stellar Occultation demonstration.
  - Print one of the “brightness versus time” graphs from the Stellar Occultation student data sheet using a swell form machine. Ask students to graph the relative tone (rather than brightness) with time using push pins on the graph paper. You will need to read out time for them every few seconds. Then they can connect the points along the graph using string or yarn by looping it around each of the push pins to create a “sound curve” (rather than light curve).
  - Print the actual light curves from Pluto, Charon, and Uranus from the Stellar Illumination group activity using a swell form machine so they can interpret the light curves and answer questions about the atmospheres of these bodies.

## References:

Some images attributed to JHU/APL or the Johns Hopkins University Applied Physics Laboratory were taken from the New Horizons website: <http://pluto.jhuapl.edu/>

Elliot, J.L., A. Ates, B.A. Babcock, A.S. Bosh, M.W. Buie, K.B. Clancy, E.W. Dunham, S.S. Eikenberry, D.T. Hall, S.D. Kern, S.K. Leggett, S.E. Levine, D.S. Moon, C.B. Olkin, K.J. Osip, J.M. Pasachoff, B.E. Penprase, M.J. Person, S. Qu, J.T. Rayner, L.C. Roberts, Jr, C.V. Salyk, S.P. Souza, R.C. Stone, B.W. Taylor, D.J. Tholen, J.E. Thomas-Osip, D.R. Ticehurst, and L.H. Wasserman. The recent expansion of Pluto’s atmosphere. *Nature* **424**, 165-168 (2003)

French, R.G., T.J. Jones, and A.R. Hyland. The 1 May 1982 Stellar Occultation by Uranus and the Rings: Observations from Mount Stromlo Observatory. *Icarus* **69**, 499-505 (1987)

Gulbis, A. A.S., J.L. Elliot, M.J. Person, E.R. Adams, B.A. Babcock, M. Emilio, J.W. Gangestad, S.D. Kern, E.A. Kramer, D.J. Osip, J.M. Pasachoff, S.P. Souza, and T. Tuvikene. Charon's radius and atmospheric constraints from observations of a stellar occultation. *Nature* **439**, 48-51 (2006)

Stern, A., and J. Mitton. 1989. *Pluto and Charon: Ice Worlds on the Ragged Edge of the Solar System*. John Wiley & Sons, Inc.: New York

## **Standards Addressed:**

### **National Science Education Standards (NRC, 1996)**

#### **Content Standards: 9-12**

##### **Unifying Concepts and Processes, CONTENT STANDARD:**

- Evidence, models, and explanation

##### **Science as Inquiry, CONTENT STANDARD A:**

- Understandings about scientific inquiry

### **Benchmarks (AAAS, 1993)**

#### **Chapter 1. The Nature of Science**

##### **1B: Scientific Inquiry**

Grades 9 through 12

- Sometimes, scientists can control conditions in order to obtain evidence. When that is not possible for practical or ethical reasons, they try to observe as wide a range of natural occurrences as possible to be able to discern patterns.

#### **Chapter 4. The Physical Setting**

##### **4A: The Universe**

Grades 9 through 12

- Increasingly sophisticated technology is used to learn about the universe. Visual, radio, and x-ray telescopes collect information from across the entire spectrum of electromagnetic waves; computers handle an avalanche of data and increasingly complicated computations to interpret them; space probes send back data and materials from the remote parts of the solar system; and accelerators give subatomic particles energies that simulate conditions in the stars and in the early history of the universe before stars formed.

### **Principles and Standards for School Mathematics (NCTM, 2000)**

#### **Representation**

Grades K through 12

- Use representations to model and interpret physical, social, and mathematical phenomena



# Stellar Occultation!




Name: \_\_\_\_\_






Part 1: To be completed independently.

Let's assume a planet is going to pass in front of a distant star, and you are going to observe this event using a series of pictures from a very sensitive telescope.

In your telescope, this is what the star looks like: \*

And this is what the planet looks like: 

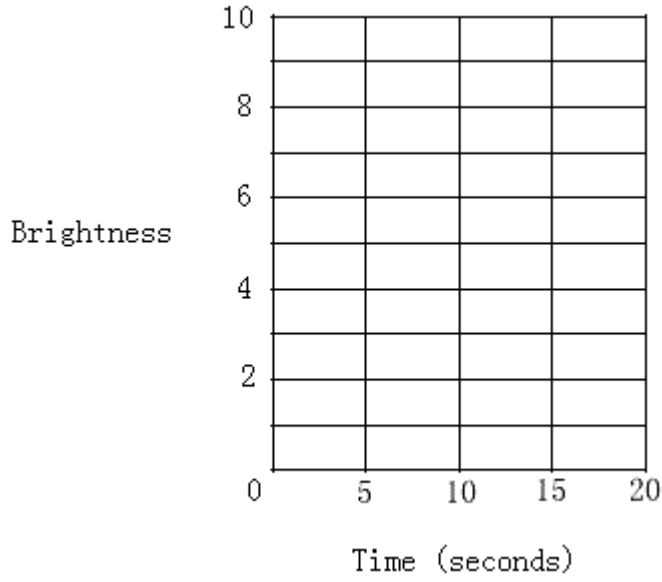
Describe how you think the star and the planet will look during this event under different scenarios using the table below:

|  |  * |  * |  | *  | *  |
|--|---|---|---|---|---|
| time (seconds)   | 0   | 5   | 10  | 15  | 20  |
| First, what would it look like if the planet has NO atmosphere...            |   |   |   |   |   |
| Now describe what you think you might see if the planet has an atmosphere... |   |   |   |   |   |

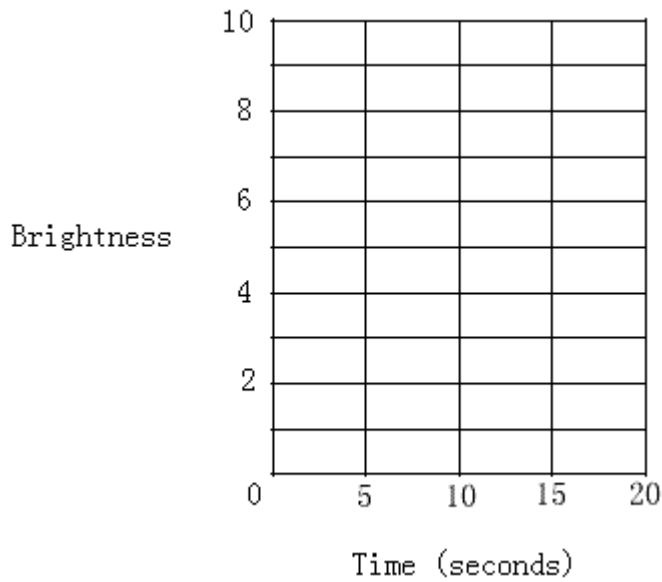
Your sensitive telescope is also equipped with a device that measures the brightness of the objects you are viewing. Assume the only two objects you are viewing are the star and the planet. You happen to know the brightness of the star by itself is 10.

Complete the graphs for the brightness of the star versus time below, but this time thinking just about the brightness that your telescope would record when each picture is captured (that is at time = 0, at time = 5, at time = 10, etc. Refer to the table above for reference).

Graph 1: For the planet with NO atmosphere:



Graph 2: For the planet with an atmosphere:



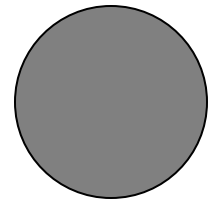
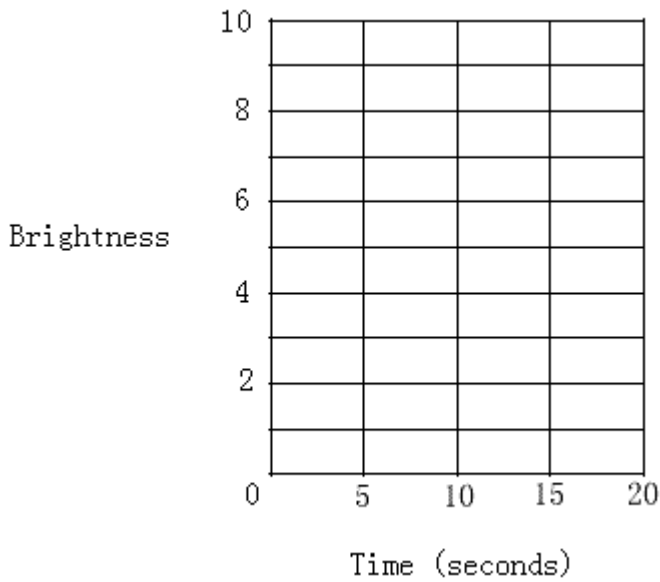
How are Graphs 1 and 2 similar? How are they different?

**Part 2: To be completed along with the Stellar Occultation demonstration.**

During this demonstration, you are to observe stellar occultations for different planets and record the brightness of the star versus time in the graphs below. Again assume the star has a brightness of 10. Also, draw a picture of the planet (and its atmosphere) next to the graph for later (the first one is done for you).

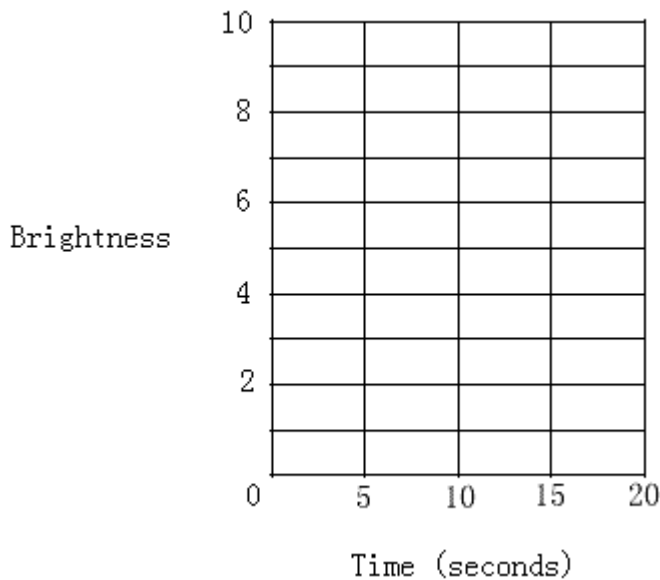
Planet 1:

Picture:



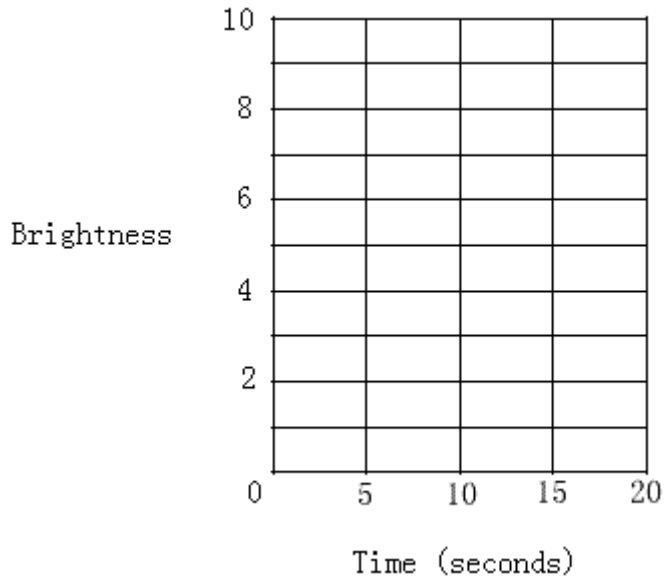
Planet 2:

Picture:



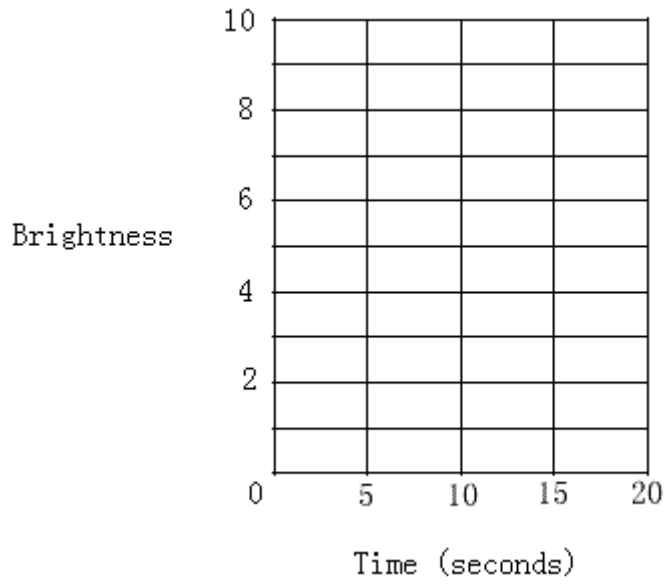
Planet 3:

Picture:



Planet 4:

Picture:

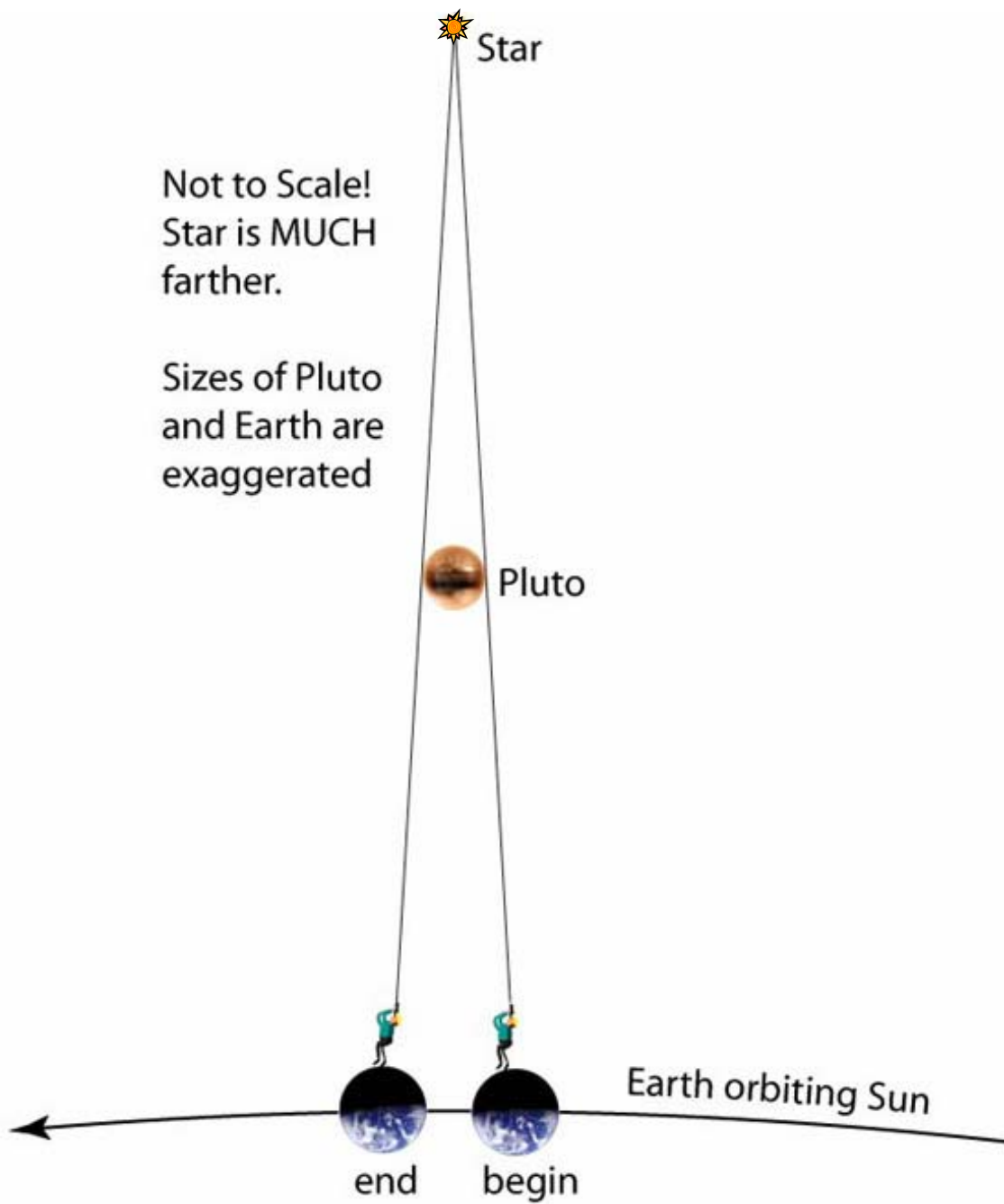


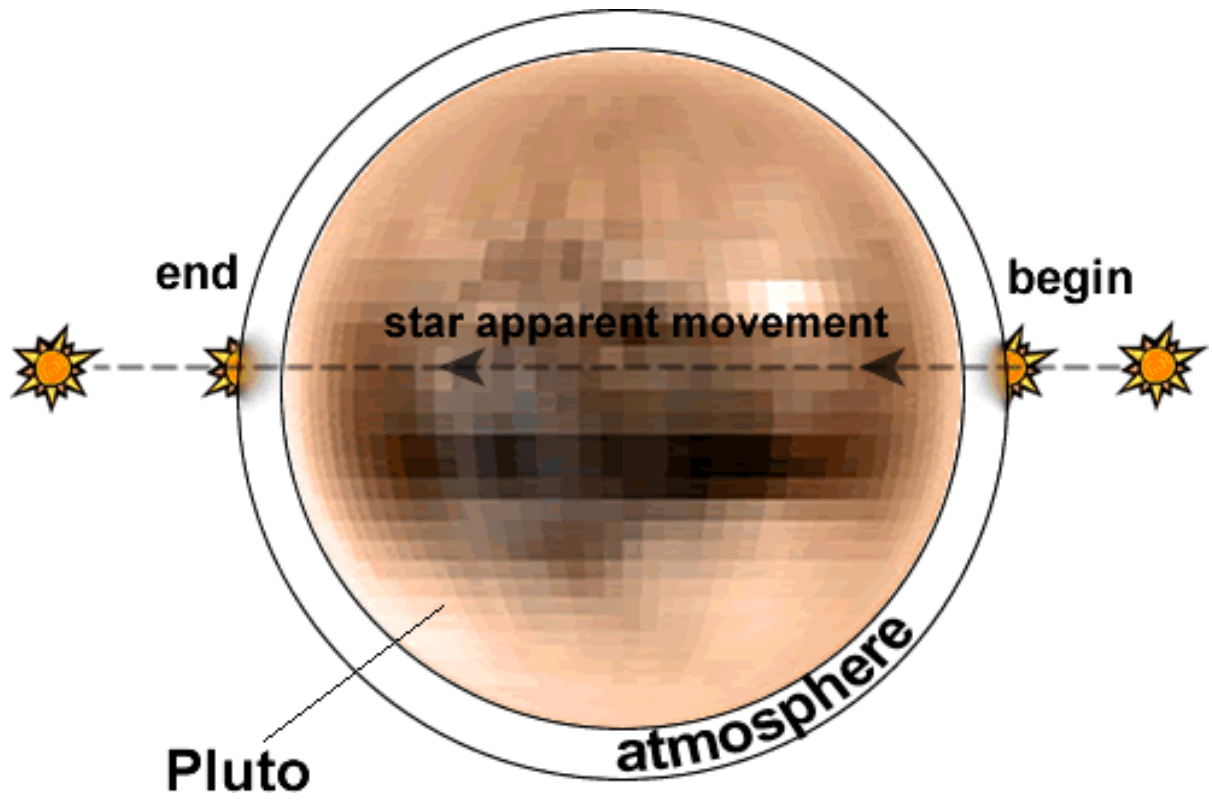
Now go back to your graphs and, looking at the picture you drew of the planet and its atmosphere (if it had one), fill in the points between times 0 and 5 seconds, between times 5 and 10, etc. Try to accurately re-create a continuous “light curve”. Answer the following questions about the light curves.

How can you tell from a light curve if a planet has an atmosphere or not?

What features of an atmosphere can you distinguish from a light curve?

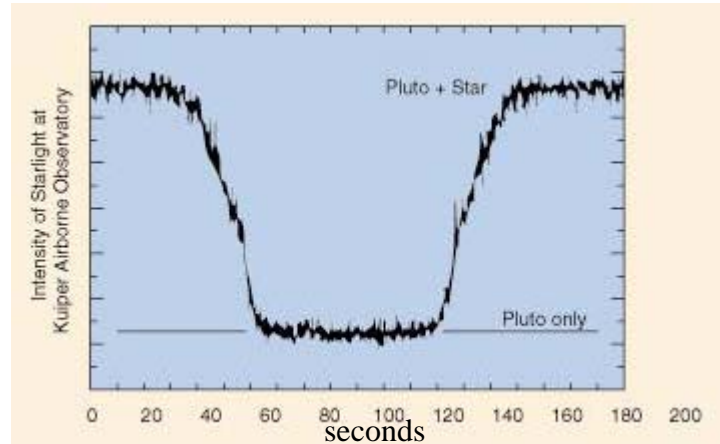




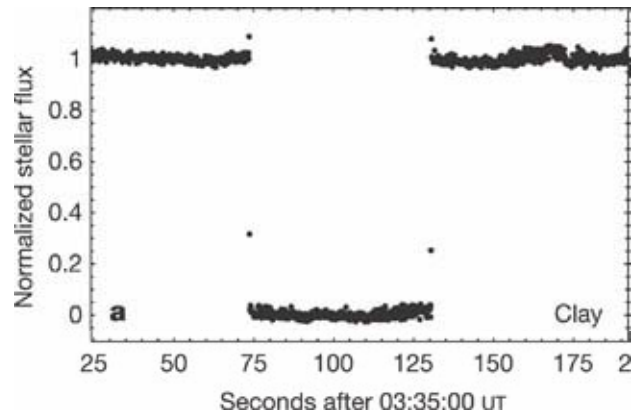


## Stellar Illumination Group Activity

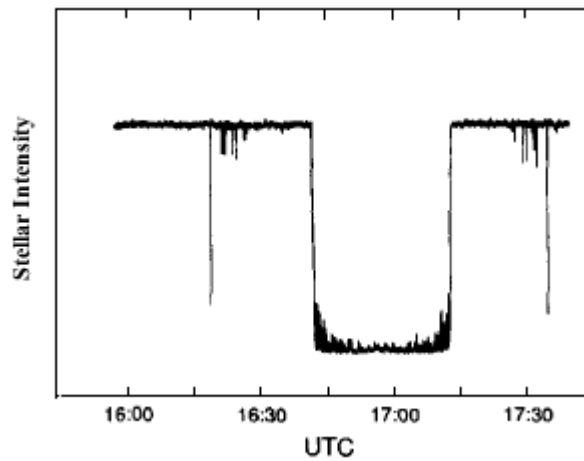
You have observed demonstrations of stellar occultations involving planets with different atmospheres. During these demonstrations you recorded your observations in the form of simple *light curves*. Below are several actual light curves from stellar occultations by various planets or solar system bodies. Interpret these light curves in the questions below.



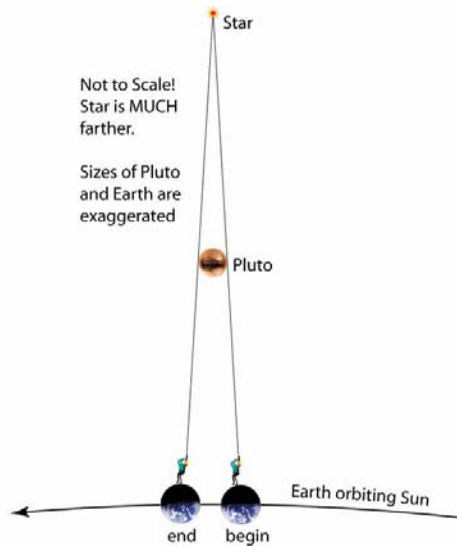
1. Above is a light curve of a stellar occultation by Pluto. Do you think Pluto has an atmosphere based on this data? Why or why not?



2. On the previous page is a light curve from a stellar occultation by Pluto's moon, Charon. Do you think Charon has an atmosphere based on this data? Why or why not?



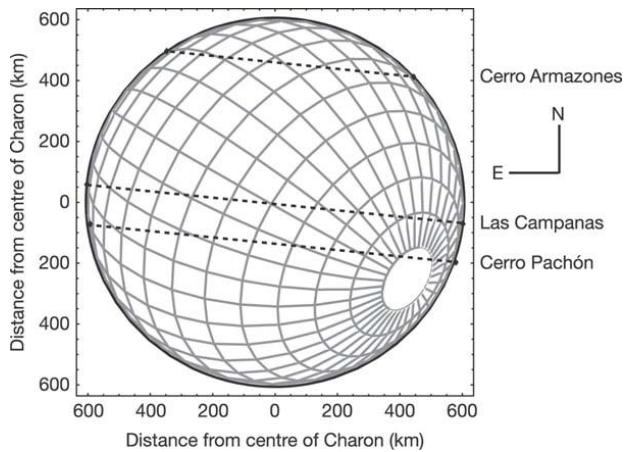
3. Above is a light curve from a stellar occultation by Uranus.
- Do you think Uranus has an atmosphere based on these data? Why or why not?
  - What do you suppose caused the features in the light curve on either side of the planet?



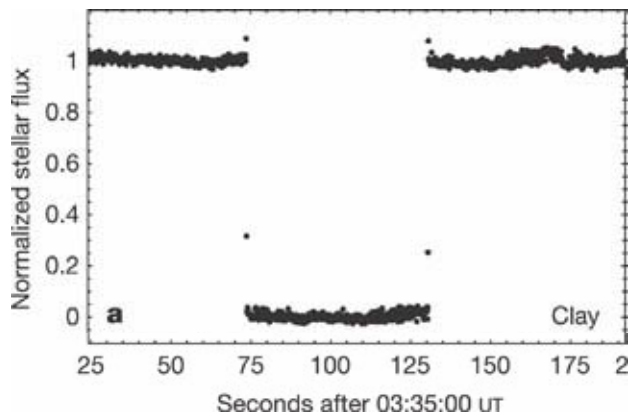
4. The demonstrations of stellar occultations you observed in class were helpful to illustrate how these events occur, but they distorted some of the important science in the process. Using the diagram above to help you, describe two ways in which the in-class demonstrations differ from actual stellar occultations.
- -

Stellar occultation events can reveal the presence, absence, and sometimes structure of an atmosphere. They can also be used to calculate the diameter of the occulting body (the planet, moon, or asteroid) if the star appears to pass behind the widest part of the planet or body.

5. Calculate Charon's diameter. This information may be useful:
- Earth's mean orbital velocity = 29.78 km/s
  - Pluto's mean orbital velocity = 4.74 km/s
  - Assume Charon is stationary with respect to Pluto during the occultation
  - Assume the apparent path of the star passes through the center or widest part of Charon



**Figure 1.** Dashed lines overlaid on a diagram of Charon indicate the apparent path of the star during the stellar occultation from different observatories on Earth. In this activity, we are using data from the 6.5-m Clay telescope at Las Campanas Observatory, La Serena, Chile.



**Figure 2.** Light curve from before, during, and after the stellar occultation of the star 'C313.2' by Charon on July 11, 2005. This data is from the 6.5-m Clay telescope at Las Campanas Observatory, La Serena, Chile.

Show your calculations here:

## Stellar Occultation! (With answers for the Teacher)

Part 1: To be completed independently.

Let's assume a planet is going to pass in front of a distant star, and you are going to observe this event using a series of pictures from a very sensitive telescope.






In your telescope, this is what the star looks like:



And this is what the planet looks like:



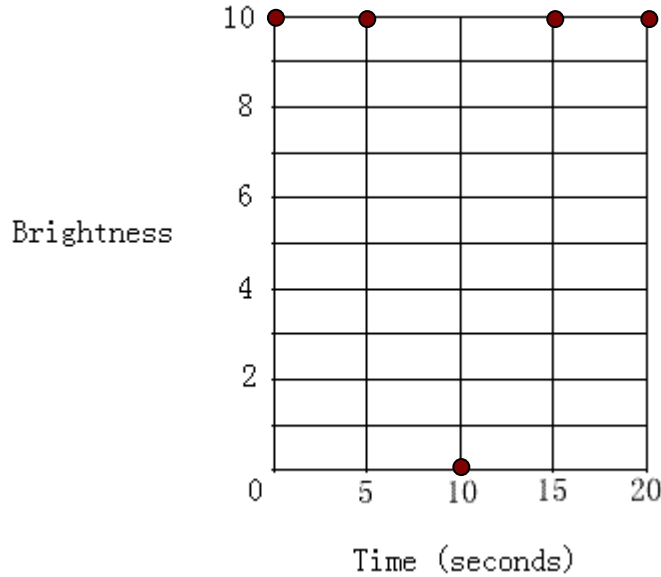
Describe how you think the star and the planet will look during this event under different scenarios using the table below:

|  |  * |  * |  | *  | *  |
|--|---|---|---|---|---|
| time (seconds)   | 0   | 5   | 10  | 15  | 20  |
| First, what would it look like if the planet has NO atmosphere...            | (you would see a planet with a star near it)  | (you would see a planet with a star right next to it)                               | (you would see just a planet, no star)  | (you would see a planet with a star right next to it)                                 | (you would see a planet with a star near it)  |
| Now describe what you think you might see if the planet has an atmosphere... | (you would see a planet with a star near it)  | (you would see a planet, and the star would be dim due to the planet's atmosphere)  | (you would see just a planet, no star)  | (you would see a planet, and the star would be dim due to the planet's atmosphere)    | (you would see a planet with a star near it)  |

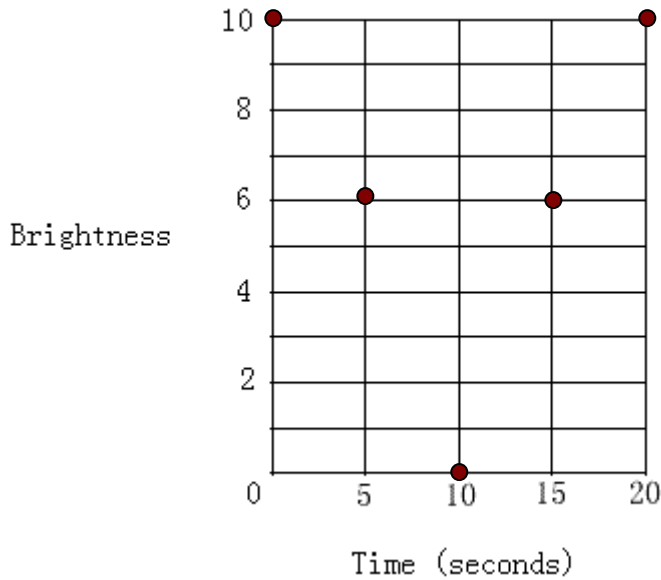
Your sensitive telescope is also equipped with a device that measures the brightness of the objects you are viewing. Assume the only two objects you are viewing are the star and the planet. You happen to know the brightness of the star by itself is 10.

Complete the graphs for the brightness of the star versus time below, but this time thinking just about the brightness that your telescope would record when each picture is captured (that is at time = 0, at time = 5, at time = 10, etc. Refer to the table above for reference).

Graph 1: For the planet with NO atmosphere:



Graph 2: For the planet with an atmosphere:



Note: the 5 sec and 15 sec data points can be anything less than 10 and greater than 0—student answers will vary within this range.

How are Graphs 1 and 2 similar? How are they different?

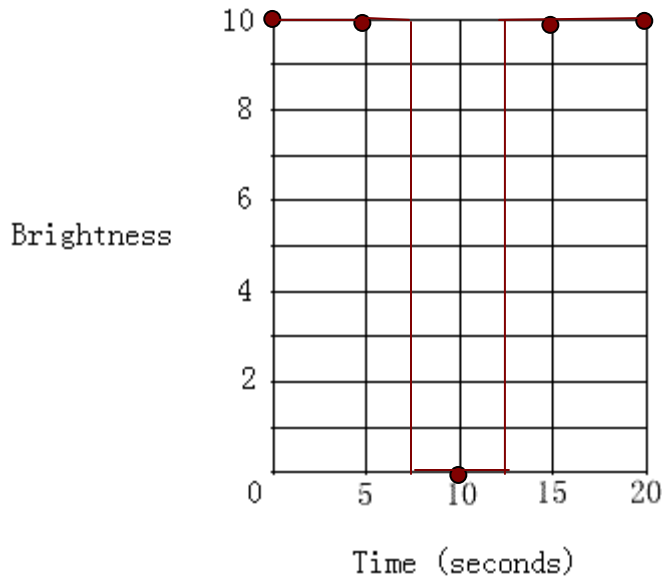
(The 0 sec, 10 sec, and 20 sec points are the same for both graphs. However, with no atmosphere all of the brightness from the star is visible, so in Graph 1 the 5 sec and 15 sec points are the brightness from the star (10). In Graph 2 the 5 sec and 15 sec points are the dimmed brightness of the star, since the planets atmosphere causes the star to appear less bright.)



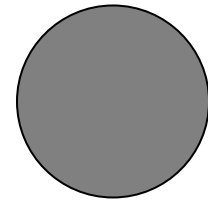
**Part 2: To be completed along with the Stellar Occultation demonstration.**

During this demonstration, you are to observe stellar occultations for different planets and record the brightness of the star versus time in the graphs below. Again assume the star has a brightness of 10. Also, draw a picture of the planet (and its atmosphere) next to the graph for later (the first one is done for you).

Planet 1:

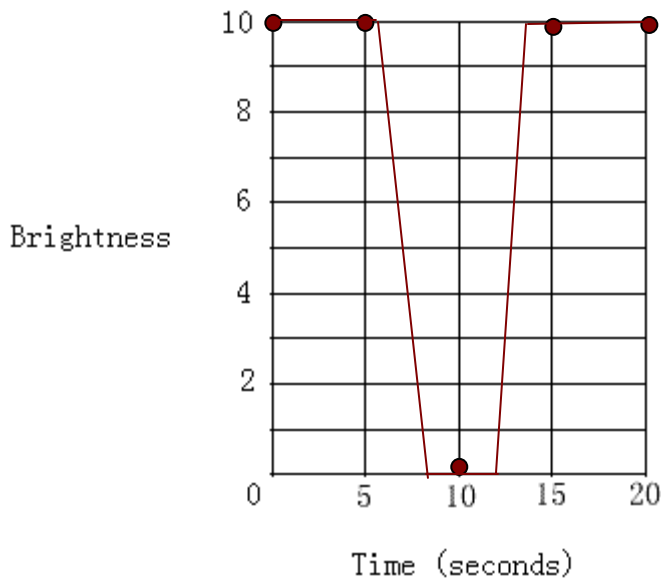


Picture:

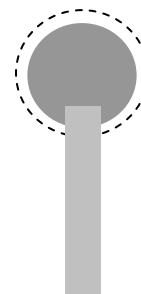


Note: these graphs will vary somewhat based on your demonstration

Planet 2:

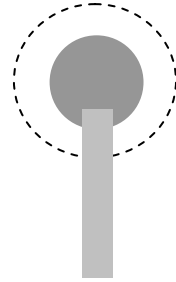
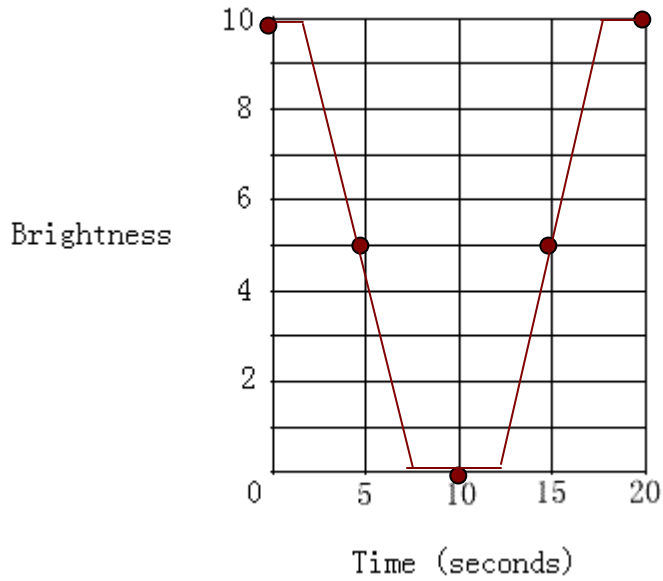


Picture:



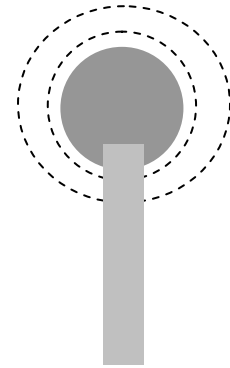
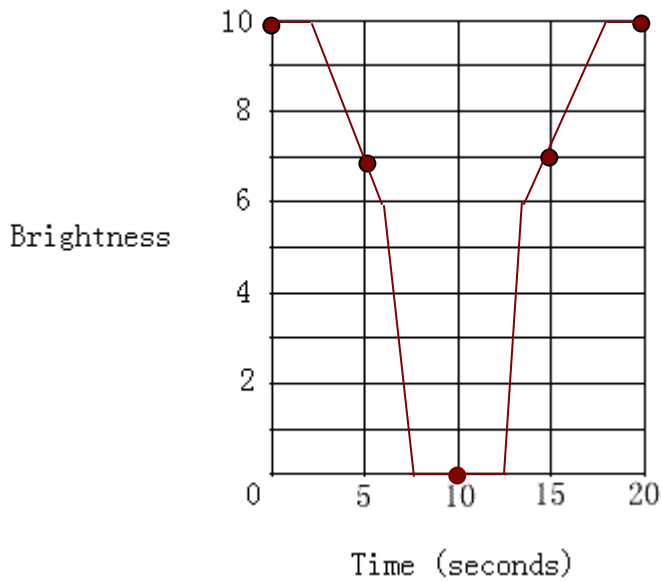
Planet 3:

Picture:



Planet 4:

Picture:



Now go back to your graphs and, looking at the picture you drew of the planet and its atmosphere (if it had one), fill in the points between times 0 and 5 seconds, between times 5 and 10, etc. Try to accurately re-create a continuous “light curve”. Answer the following questions about the light curves.

How can you tell from a light curve if a planet has an atmosphere or not?

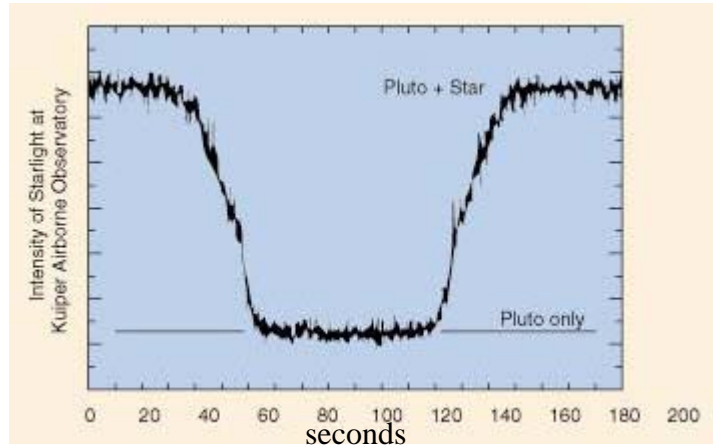
(If a planet has no atmosphere, the light curve goes from the full brightness of the star (10) to 'no' brightness of the star (0) basically instantaneously, whereas if there is an atmosphere the brightness from the star slowly dims, creating a gentler slope in the curve.)

What features of an atmosphere can you distinguish from a light curve?

(You can distinguish if there are multiple layers in the atmosphere, and also the thickness of the atmosphere.)

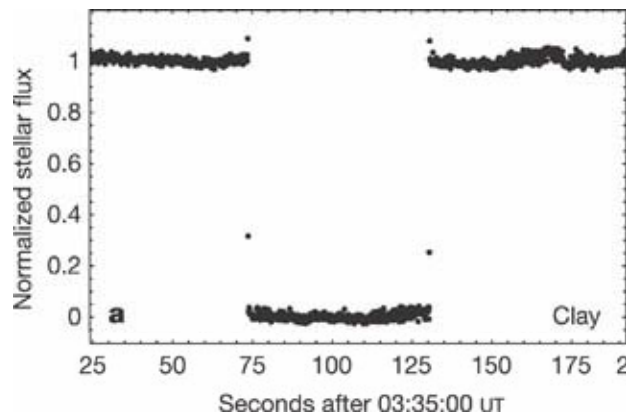
## Stellar Illumination Group Activity (WITH ANSWERS)

You have observed demonstrations of stellar occultations involving planets with different atmospheres. During these demonstrations you recorded your observations in the form of simple *light curves*. Below are several actual light curves from stellar occultations by various planets or solar system bodies. Interpret these light curves in the questions below.



6. Above is a light curve of a stellar occultation by Pluto. Do you think Pluto has an atmosphere based on this data? Why or why not?

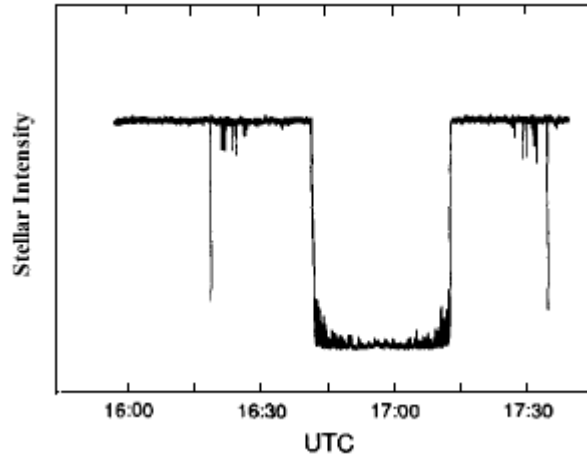
(Yes, because there is a somewhat gradual slope in the line from the “Pluto + Star” intensity to the “Pluto only” intensity. If there were no atmosphere, this line would be vertical. The intensity of starlight gradually dims as the star appear to near and exit from behind Pluto, rather than a very abrupt change in intensity.)



7. Above is a light curve from a stellar occultation by Pluto’s moon, Charon. Do you think Charon has an atmosphere based on this data? Why or why not?

(No, or there might be a very, very small atmosphere (indicated by the one data point between the “Star + Charon” intensity and the “Charon only” intensity). But basically

that looks like a vertical line, indicating no atmosphere. The intensity dramatically drops to just that of Charon as the star appears to near and exit from behind Charon.)

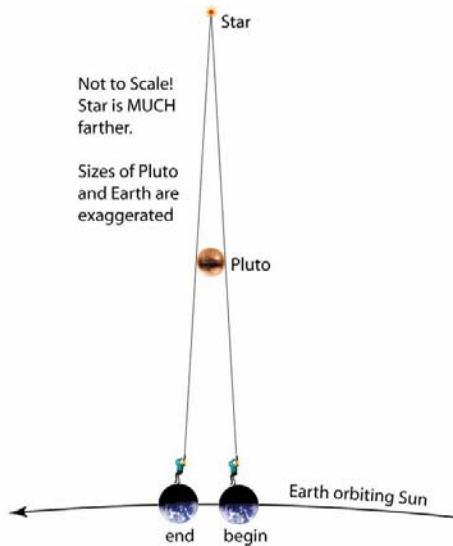


8. Above is a light curve from a stellar occultation by Uranus.
  - a. Do you think Uranus has an atmosphere based on this data? Why or why not?

(yes it does have an atmosphere, but it is difficult to discern in this light curve, so you might want to accept either answer if justified.)

- b. What do you suppose caused the features in the light curve on either side of the planet?

(Rings! This is how rings were discovered on Uranus—interpreting light curves from a stellar occultation!)

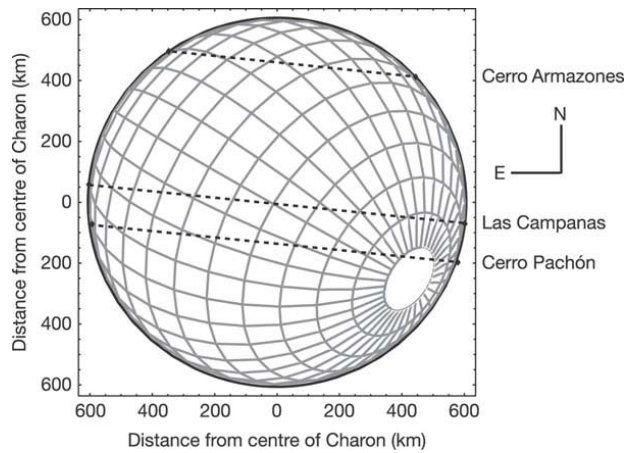


9. The demonstrations of stellar occultations you observed in class were helpful to illustrate how these events occur, but they distorted some of the important science in the process. Using the diagram above to help you, describe two ways in which the in-class demonstrations differ from actual stellar occultations.
- (In the demonstration the planet moved, which is true, but the planet's movement is small in comparison with our (Earth's) movement. In the demonstration the observer remained stationary, whereas in an occultation Earth's movement is primarily responsible for what we observe.)
  - (In the demonstration the light source (i.e. the star) was very close to the back of the planet, whereas in reality the star is very, very far from the occulting planet and from Earth).

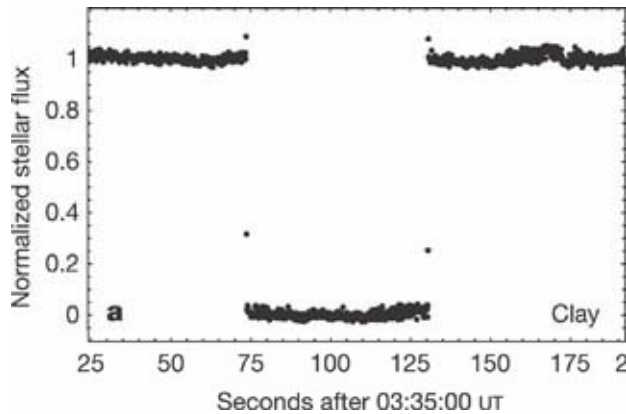
Stellar occultation events can reveal the presence, absence, and sometimes structure of an atmosphere. They can also be used to calculate the diameter of the occulting body (the planet, moon, or asteroid) if the star appears to pass behind the widest part of the planet or body.

10. Calculate Charon's diameter. This information may be useful:
- Earth's mean orbital velocity = 29.78 km/s
  - Pluto's mean orbital velocity = 4.74 km/s
  - Assume Charon is stationary with respect to Pluto during the occultation

- Assume the apparent path of the star passes through the center or widest part of Charon



**Figure 1.** Dashed lines overlaid on a diagram of Charon indicate the apparent path of the star during the stellar occultation from different observatories on Earth. In this activity, we are using data from the 6.5-m Clay telescope at Las Campanas Observatory, La Serena, Chile.



**Figure 2.** Light curve from before, during, and after the stellar occultation of the star ‘C313.2’ by Charon on July 11, 2005. This data is from the 6.5-m Clay telescope at Las Campanas Observatory, La Serena, Chile.

Show your calculations here:

(The general equation used is:  $\text{velocity} = (\text{change in distance}/\text{change in time})$ )

The velocity used here is the relative velocity, which accounts for Earth’s orbital velocity as well as the orbital velocity of the Pluto/Charon system. Note, we are not concerned with the rate Charon orbits Pluto, but the rate at which they orbit the Sun. And for the duration of the occultation (about 50 sec) we can assume Charon is stationary with respect to Pluto (i.e. we ignore Charon’s orbital velocity about Pluto, which is quite small anyway at 0.23 km/s).

The relative velocity is simply Earth’s velocity – Pluto’s velocity, or:

$$\text{Velocity}_{\text{rel}} = 29.78 \text{ km/s} - 4.74 \text{ km/s} = 25.04 \text{ km/s}$$

Note: we subtract Pluto's velocity from Earth's because Pluto is orbiting slower or has a smaller orbital velocity than Earth's.

Now we just need to plug our  $velocity_{rel}$  and the time of the occultation into our general velocity equation to solve for the distance or diameter of Charon!

$$\text{Distance} = (\text{velocity}_{rel}) * (\text{time})$$

$$\text{Distance} = (25.04 \text{ km/s}) * (50 \text{ s}) = 1252 \text{ km}$$

Therefore, the diameter of Charon is about 1252 km. (Since the currently accepted value of the diameter is 1212 km, we are pretty close!)