Just How Far is That Star? Or …

… If we know how much light diminishes over distance, and we know how bright the star really is, can we answer the question?

Suggested Grade Level(s): 9-12
Estimated class time: two or three class periods

Summary

In this investigation students will use "point-source" light, light meters, and graphing software to quantify the reduction in light over distance. Through careful measurement of light received at several distances, students will discover the best fit of the data is the inverse square rule. Using this rule, students will then calculate the distance between the light source and the light meter at random placements. Finally, students will extend this principle to model the manner in which distances to Cepheid variable stars are measured; the distance between the Cepheid (here the light source) and the Earth (the light meter) can be determined by comparing the output of the source to the amount of light received. An historic scientific breakthrough occurred when the period-luminosity relationship of Cepheids was quantified throughout the early 1900s. This breakthrough allowed astronomers to gain a more correct understanding of the dimensions of our galaxy and the Universe beyond.

Objectives

Students will:
- Discover how light diminishes over distance and describe this mathematically.
- Calculate the distance to objects of known luminosity using this relationship.

National Science Standards

- NS.9-12.1 SCIENCE AS INQUIRY
  As a result of activities in grades 9-12, all students should develop
  - o Abilities necessary to do scientific inquiry
  - o Understandings about scientific inquiry
- NS.9-12.4 EARTH AND SPACE SCIENCE
  As a result of their activities in grades 9-12, all students should develop an understanding of
  - o Origin and evolution of the earth system
  - o Origin and evolution of the universe
- NS.9-12.5 SCIENCE AND TECHNOLOGY
  As a result of activities in grades 9-12, all students should develop
  - o Understandings about science and technology

- NS.9-12.7 HISTORY AND NATURE OF SCIENCE
  As a result of activities in grades 9-12, all students should develop understanding of
    - ○ Science as a human endeavor
    - ○ Nature of scientific knowledge
    - ○ Historical perspectives

Knowledge Prerequisite

- It is helpful if students are familiar with Microsoft Excel® graphing software, but not absolutely necessary. A pre-lab activity to review this might be beneficial.
- Students should know topics from, or be currently taking, Algebra II.

Teacher Background Notes

The discovery nature of this investigation is best served if students complete it before reading/learning about the behavior of light, or the difficulty of measuring the vast distances to objects in space.

Throughout the lab students are directed to measure distances between the light and the meter in centimeters. However, they are asked to record these values as meters on the data tables. The reason for this is that lux values are customarily given in lumens/m^2 and this eliminates confusion later on.

Precision and accuracy of results are highly dependent upon the light source consistently producing light at its rated output. Fresh batteries, and matching battery and light voltage are imperative to achieve this.

Excel® graphing software is not necessary. Any graphing software capable of providing an equation, which shows the relationship between variables, will suffice.

There are three separate activities (procedures I, II, III) for students to engage in. Procedures I and II are preceded by a teacher-directed "Engagement." Part III is preceded by an "Explanation" given by the teacher.

Equipment (per lab group)

- 1 cardboard box painted flat black on all inside surfaces. The box should be at least 50 cm deep, and it should be long and wide enough for students to reach in to arrange equipment inside (the two smaller boxes with light source and light meter. See "Exploration" for details). An opening of 40 cm × 40 cm is recommended.

- 2 small boxes, approximately 6 cm × 6 cm × 10 cm. The boxes should be painted flat black on all exterior surfaces. Place rocks, or some other material inside the boxes to add weight to reduce the likelihood of the boxes moving around after they are positioned.

- 1 light source. A 7.5 V flashlight bulb works well. A lamp base and battery pack can usually be obtained at a retail electronics store. Because flashlight bulbs have small filaments, they approximate light from a point source.

- 1 light meter capable of reading 0-600 lumens. The sensing device must be attached to the readout by a cable so that it can be enclosed in the box while students observe the readout outside the box. The cable should be at least 80 cm long.

- about 20 cm painter's (blue) masking tape

- 1 meter stick

Procedure:

I. Engagement

Invite students to join in a mental experiment. They are to imagine being in a very large, but completely dark room. All surfaces in the room are completely non-reflective so nothing is revealed about the dimensions of the room. The students are not permitted to move at all.

Suddenly the darkness is interrupted by a point of blinding bright light.

Ask the students if they would be able to tell whether:
- the light source is actually not bright at all, but simply very close, OR
- the light source is actually very bright, but far away

Allow one minute of discussion and then ensure students understand they really would not be able to judge this if there was no reflected light.

Ask students what additional information they would need to know to answer the question. Accept relevant answers and guide discussion (if necessary) to ensure they understand they would need to know how bright the light really is (i.e. a 50 W bulb or a 500 W bulb), AND how light diminishes over distance.

Ask students to recall the last time they looked up at the stars on a dark night and relate that experience to the mental experiment. How can they tell if the stars are not bright but

simply close, OR truly bright but far away? Allow discussion to develop the analogy. Ensure students comprehend the lack of depth perception from an Earth-bound view.

Finally, have students predict how much they believe light diminishes over distance. This hypothesis should be written out; they should make some attempt to quantify this (i.e. if the distance from the light source is doubled, the light is reduced by half, etc.).

II. Exploration

In this part of the activity, students could be permitted to design their own experiment to test their hypothesis, OR they may follow the procedure that follows.

<u>Procedure I</u>
1. Create a data table.

Distance from Light Source (m)	Light Received (lux)
0.05	
0.10	
0.15	
0.20	
0.25	

2. Use about 10 cm of the blue tape to secure the light source to the top of one small box. Align the light source with the edge of the box.

3.   Use the remaining 10 cm of tape to attach the sensor of the light meter to the top of the other small box. Have the edge of the sensor aligned with the edge of the box.

4. Adjust the height of the boxes (if needed) so the sensor is always at the same level as the filament of the bulb.

5. Place the box with the light source at the back of the larger "black" box. Check to be sure the larger box is well sealed and that no light leaks in.

6. Measure forward 5 cm from where the light source rests, and position the small box with the light sensor.   Check to be sure the distance between the light and the light sensor is 5 cm.   Also adjust the position of the boxes so the light is directly opposite the light sensor.

7. With the light *off*, carefully close the open end of the box, being careful not to pull on the cable to the sensor. If there are any gaps where light could filter in, cover these.

8. Monitor the read-out on the light sensor. If the sensor is detecting light, check again for gaps and cover these. If the sensor is still sensing light after all noticeable gaps are covered, then this value should be deducted from *all* subsequent readings.

9. Turn on the light and close the box, again being careful to not pull on the cable to the sensor, and ensuring all gaps are covered.

10. Wait for the read-out on the light sensor to stabilize and record the value.

11. Repeat steps 6, 9 and 10 for distances of 10, 15, 20, and 25 cm.

12. Graph the data and determine the mathematical relationship between distance and the reduction in light.

    To accomplish this, the graphing function in Microsoft Excel® may be used. Students should select a *scatter-plot*. Distance should be set as the X value and Light Received as Y. When the graph is created, students should add a *Trend-Line* using the *Power* function. In this same menu, they should select Options and *display equation on chart*. If students have reproducible results, the equation should very nearly represent an inverse square relationship.

13. Print the graph with the equation and submit with the lab write-up.

Procedure II
1. Create a second data table as follows:

Light Received (lux)	Calculated Distance (m)	Actual Distance (m)	% Error

2. One member of each lab group should place the light sensor in the box at a random distance between 5 and 25 cm from the light source.

3. Close the box as described in step 9, Procedure I.

4. Allow the sensor to stabilize and record Light Received (lux).

5. The equation generated in Procedure I may be rearranged to solve for Distance (x).

$$y = Nx^a \text{ re-arranges to } x = (y/N)^a \text{ or } x = (y/N)^{\frac{1}{a}}$$

6. Using the value recorded in step 4, calculate the value for x (Distance). Record this value on the data table.

7. Open the box and measure the actual distance between the light source and the sensor. Record this value on the data table, and then calculate % error. (calculated distance-actual distance/actual distance) × 100)

8. Repeat steps 2 – 7 for two other random placements.

III. Explanation

Tell students that a method to determine actual brightness of some stars was produced by the work of astronomers in the early to middle part of the 20th century. The stars used for this purpose are older stars that have become unstable and swell and contract within a period of time spanning days or weeks. These Cepheid variable stars are more luminous if they have long periods and less luminous if they have short periods. Over several decades the precise luminosity was determined based on the period of the Cepheids. Astronomers were then able to combine that knowledge with the understanding of how light diminishes over distance (Inverse Square Law) to determine the distance to Cepheids. In Procedure I and II of this investigation, the students came very close to discovering this inverse square relationship.

If we consider light leaving a point source (the flashlight bulb, or a distant star) we recognize that light uniformly "spreads out" and becomes less concentrated as it moves farther from the source. If we know how much light is actually being emitted by a source, and we measure how much light is received at some distance from the source, we can then calculate how far away the light source must be. The actual relationship is

$$d = \sqrt{\frac{P}{4\pi E}}$$

where d is the distance from the source (meters)
P is the output of the light-source (lumens)
E is the light received (lumens/m^2 or lux)

Comparing the Inverse Square Law to the equation generated in Procedure I provides a good opportunity to discuss reasons why the relationship generated from experimental conditions differs from the actual relationship (i.e. reflection within the box, etc.).

IV. Elaboration

Students will now attempt to determine the distance between the light source and the sensor in the same way astronomers determine the distance between Earth and Cepheid variable stars.

To do Procedure III, you will need to determine the output of the light source you have selected. This is usually listed on the package the bulbs come in. You might need to convert the unit you are given into lumens. There are several simple on-line calculators available for making this conversion. Provide students with this value. Using this value, they should again be able to determine the distance between the light source and the sensor.

<u>Procedure III</u>

1. Create a third data table as follows:

Light Received (lux)	Calculated Distance (m)	Actual Distance (m)	% Error

2. One member of the group should place the sensor in the box at a random distance from the light source. Again the sensor and the light should be directly opposite each other. Turn the light on and close the box. Allow the read-out to stabilize and record the value.

3. Calculate the distance between the light and the sensor. Record the calculated distance.

4. Carefully open the box and measure the distance between the light and the sensor. Record the measured distance.

5. Calculate the percent error between your calculated distance (cd) and the actual distance (ad). ((cd-ad/ad) × 100)

6. Repeat steps 2,3,4,5 for two additional random distances.

V. Evaluation

Students should respond to the following questions in complete and thoughtful sentences.

1. To determine the distance to a star (or any point source of light), what must be known?

2. Explain how light diminishes over distance.

3. Examine your % error calculations. Using meaningful detail, explain what you could do differently to reduce error in this experiment.

4. Which method of determining distance between the light source and the light sensor had less error? WHY do you think this is so?

4. Revisit your original hypothesis regarding how light diminishes over distance. Do the results of this investigation support or contradict your prediction? EXPLAIN your answer with supporting details.

Student Handout

Just How Far is That Star? Or …
… If we know how much light diminishes over distance, and we know how bright the star really is, can we answer the question?

Learning Objectives

- Discover how light diminishes over distance and describe this mathematically.
- Calculate the distance to objects of known luminosity using this relationship.

Equipment (per lab group)

- 1 cardboard box painted flat black on all inside surfaces. The box should be at least 50 cm deep, and it should be long and wide enough to reach into to arrange equipment inside. An opening of 40 cm X 40 cm is recommended.

- 2 small boxes, approximately 6 cm X 6 cm X 10 cm. The boxes should be painted flat black on all exterior surfaces. Place rocks, or some other material inside the boxes to add weight to reduce the likelihood of the boxes moving around after they are positioned.

- 1 light source. A 7.5 V flashlight bulb works well. A lamp base and battery pack can usually be obtained at a retail electronics store. Because flashlight bulbs have small filaments, they approximate light from a point source.

- 1 light meter capable of reading 0 – 600 lumens. The sensing device must be attached to the readout by a cable so that it can be enclosed in the box while students observe the readout outside the box. The cable should be at least 80 cm long.

- about 20 cm painter's (blue) masking tape

- 1 meter stick

ENGAGEMENT

On the form that follows, write a prediction about how much light diminishes over distance. This hypothesis should be written out; you must make some attempt to quantify this (i.e. if the distance from the light source is doubled, the light is reduced by half, etc.).

EXPLORATION

Procedure I

1. Use about 10 cm of the blue tape to secure the light source to the top of one small box. Align the light source with the edge of the box.

2.   Use the remaining 10 cm of tape to attach the sensor of the light meter to the top of the other small box. Have the edge of the sensor aligned with the edge of the box.

3. Adjust the height of the boxes (if needed) so the sensor is always at the same level as the filament of the bulb.

4. Place the box with the light source at the back of the larger "black" box. Check to be sure the larger box is well sealed and that no light leaks in.

5. Measure forward 5 cm from where the light source rests, and position the small box with the light sensor.   Check to be sure the distance between the light and the light sensor is 5 cm.   Also adjust the position of the boxes so the light is directly opposite the light sensor.

6. With the light _off_, carefully close the open end of the box being careful not to pull on the cable to the sensor. If there are any gaps where light could filter in, cover these.

7. Monitor the read-out on the light sensor. If the sensor is detecting light, check again for gaps and cover these. If the sensor is still sensing light after all noticeable gaps are covered, then this value should be deducted from _all_ subsequent readings.

8. Turn on the light and close the box, again being careful to not pull on the cable to the sensor, and ensuring all gaps are covered.

9. Wait for the read-out on the light sensor to stabilize and record the value on the form that follows.

10. Repeat steps 6, 9 and 10 for distances of 10, 15, 20, and 25 cm.

11. Graph the data and determine the mathematical relationship between distance and the reduction in light.

To accomplish this, the graphing function in Microsoft Excel® may be used.

Select a *scatter-plot*. Distance should be set as the X value and
Light Received as Y. When the graph is finished, select the Chart tool and add a
Trend-Line using the *Power* function. In this same menu, select Options and
display equation on chart.

12. Print your graph with the equation and submit with the lab write-up.

Procedure II

1. One member of each lab group should place the light sensor in the box at a
   random distance between 5 and 25 cm from the light source.

1. Close the box as described in step 9, Part I.

2. Allow the sensor to stabilize and record Light Received (lux).

3. The equation generated in Part I may be rearranged to solve for Distance (x).

$$y = Nx^a \quad \text{re-arranges to} \quad x = (y/N)^a \text{ or } x = (y/N)^{\frac{1}{a}}$$

4. Using the value recorded in step 3, calculate the value for x (Distance). Record
   this value on the data table.

5. Open the box and measure the actual distance between the light source and the
   sensor. Record this value on the data table, and then calculate % error.
   ((calculated distance-actual distance/actual distance) × 100).

6. Repeat steps 2-7 for two other random placements.

ELABORATION

Procedure III

1. One member of the group should place the sensor in the box at a random distance
   from the light source. Again the sensor and the light should be directly opposite
   each other. Turn the light on and close the box. Allow the read-out to stabilize
   and record the value.

2. Calculate the distance between the light and the sensor using the formula

$$d = \sqrt{\frac{P}{4\pi E}}$$

where d is the distance from the source (meters)
P is the output of the light-source (lumens)
E is the light received (lumens/m^2 or lux)

3. Record the calculated distance.

4. Carefully open the box and measure the distance between the light and the sensor. Record the measured distance.

5. Calculate the percent error between your calculated distance (cd) and the actual distance (ad). ((cd-ad/ad) X 100)

6. Repeat steps 2,3,4,5 for two additional random distances.

EVALUATION

Respond to the following questions in complete and thoughtful sentences.

1. To determine the distance to a star (or any point source of light), what must be known?

2. Explain how light diminishes over distance.

3. Examine your % error calculations. Using meaningful detail, explain what you could do differently to reduce error in this experiment.

4. Which method of determining distance between the light source and the light sensor had less error? WHY do you think this is so?

5. Revisit your original hypothesis regarding how light diminishes over distance. Do the results of this investigation support or contradict your prediction? EXPLAIN your answer with supporting details.

JUST HOW FAR IS THAT STAR?   Name _____

ENGAGEMENT

In the space below, write a hypothesis that predicts how light diminishes over distance. Do your best to quantify your prediction.

EXPLORATION

Part I.

Distance from Light Source (m)	Light Received (lux)
0.05	
0.10	
0.15	
0.20	
0.25	

Based on your results, write the equation that represents the relationship between distance and light received in the space below.

Part II.

Light Received (lux)	Calculated Distance (m)	Actual Distance (m)	% Error

ELABORATION

Part III.

Light Received (lux)	Calculated Distance (m)	Actual Distance (m)	% Error

EVALUATION

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