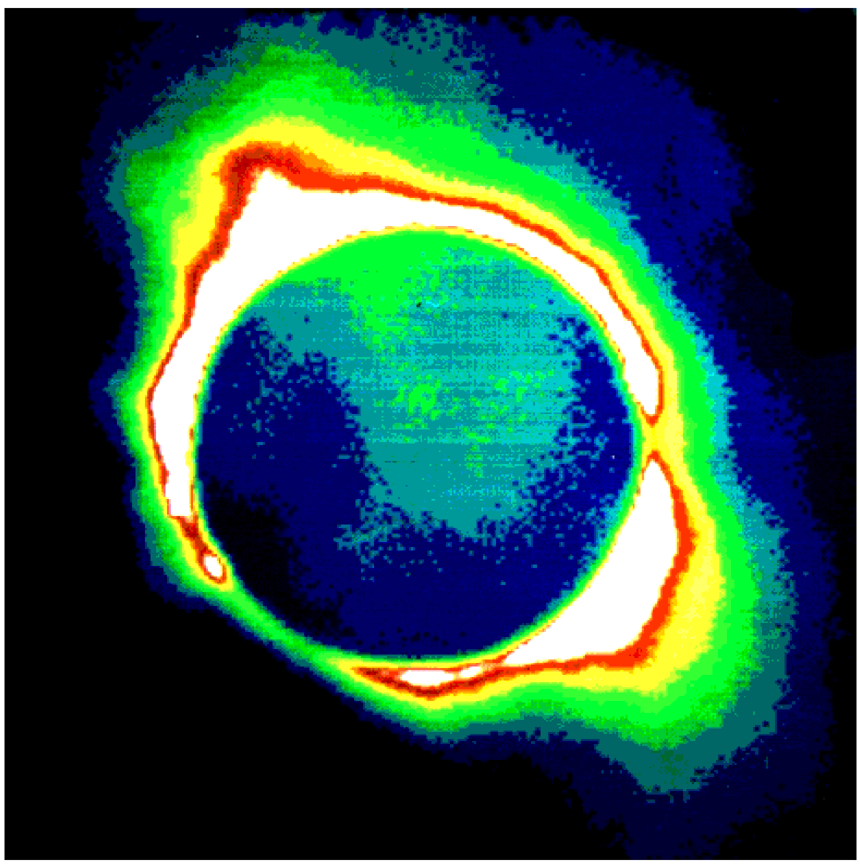
HANDS-ON UNIVERSE

HIGH SCHOOL SCIENCE AND MATH
IN THE CONTEXT OF ASTRONOMY
INVESTIGATIONS

Measuring Distance



by Lawrence Hall of Science
University of California, Berkeley
Lawrence Berkeley National Laboratory
and TERC of Cambridge, Massachusetts

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HOU provides a visual and analytic way of exploring the universe.

Use HOU images from professional telescopes, along with HOU image processing software, to pursue investigations of astronomical objects, phenomena, and concepts. Opportunities available to HOU students can lead to accessing professional-grade telescopes via the World-Wide Web for observations as part of research projects such as searching for supernovae and asteroids.

- HOU has been developed and operated by staff at Lawrence Berkeley National Laboratory and Space Science Laboratories at the University of California at Berkeley, Californa, with generous support from the National Science Foundation (grant # ESI-9252915) and the US Department of Energy. The HOU curriculum was developed by TERC with contributions from the Berkeley staff and teachers. The educational center for HOU currently resides at Lawrence Hall of Science, University of California, Berkeley.

- The Berkeley staff responsible for the development of the HOU system includes:
  Carl Pennypacker, Elizabeth Arsem, Kinshuk Govil, John Refling, Gerard Monsen, Jeff Friedman, Dick Treffers, Julia Lee, and Mimi Kwan (with past contributions from Silvia Gabi, Bruce Grossan, Michael Richmond, and Rori Abernathy).

- The curriculum development team includes:
  Tim Barclay and Jodi Asbell-Clarke from TERC
  (with contributions from Hughes Pack, Northfield-Mount Hermon School; Phil Dauber, Alameda High School; Rich Lohman, Albany High School; Tim Spuck, Oil City High School; Vivian Hoette, Adler Planetarium; Alan Gould, Lawrence Hall of Science; Geri Monsen, and Carl Pennypacker).

- Lawrence Hall of Science HOU staff includes:
  Carl Pennypacker, Alan Gould, Miho Rahm Lulu Lin, and Amelia Marshall.

Measuring Distance

Table of Contents

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Constant Sheet

Planetary Data:

Planet	Mass (kg)	Ave Radius (m)	Ave Orbital Radius(m)
Mercury	3.32×10^{23}	2.44×10^{6}	5.79×10^{10}
Venus	4.87×10^{24}	6.08×10^{6}	1.08×10^{11}
Earth	5.97×10^{24}	6.36×10^{6}	1.49×10^{11}
(Moon)	7.35×10^{22}	1.74×10^{6}	
Mars	6.42×10^{23}	3.40×10^{6}	2.28×10^{11}
Jupiter	1.90×10^{27}	6.80×10^{7}	7.78×10^{11}
Saturn	5.69×10^{26}	5.70×10^{7}	1.43×10^{12}
Uranus	8.69×10^{25}	2.51×10^{7}	2.87×10^{12}
Neptune	1.03×10^{26}	2.44×10^{6}	4.50×10^{12}
Pluto	1.30×10^{22}	1.50×10^{6}	5.90×10^{12}

Physical and Astronomical Constants:

Gravitational Constant = G = 6.673×10^{-11} N-m^2/kg^2
Speed of Light in a vacuum = c = 2.9979×10^{8} m/s
Earth-Sun Distance = Astronomical Unit = AU = 1.496×10^{11} m
Earth-Moon Distance = 3.844×10^{8} m
Parsec = pc = 206265 AU = 3.26 ly = 3.09×10^{16} m
Light year = ly = 9.5×10^{15} m
Mass of the Sun = 1.989×10^{30} kg
Luminosity of the Sun = 3.83×10^{26} W
Radius of the Sun = 6.96×10^{8} m

Brightness Conversion Table
Magnitudes to Brightness (W/m^2)

Mag.	I	R	V	B	U	Bolometric
5.0	2.40×10^{-11}	1.65×10^{-11}	3.61×10^{-11}	9.24×10^{-11}	1.83×10^{-11}	2.40×10^{-10}
5.1	2.19×10^{-11}	1.51×10^{-11}	3.29×10^{-11}	8.43×10^{-11}	1.67×10^{-11}	2.19×10^{-10}
5.2	2.00×10^{-11}	1.37×10^{-11}	3.01×10^{-11}	7.69×10^{-11}	1.52×10^{-11}	2.00×10^{-10}
5.3	1.82×10^{-11}	1.25×10^{-11}	2.74×10^{-11}	7.02×10^{-11}	1.39×10^{-11}	1.82×10^{-10}
5.4	1.66×10^{-11}	1.14×10^{-11}	2.50×10^{-11}	6.40×10^{-11}	1.27×10^{-11}	1.66×10^{-10}
5.5	1.52×10^{-11}	1.04×10^{-11}	2.28×10^{-11}	5.84×10^{-11}	1.16×10^{-11}	1.52×10^{-10}
5.6	1.38×10^{-11}	9.52×10^{-12}	2.08×10^{-11}	5.33×10^{-11}	1.06×10^{-11}	1.38×10^{-10}
5.7	1.26×10^{-11}	8.69×10^{-12}	1.90×10^{-11}	4.86×10^{-11}	9.63×10^{-12}	1.26×10^{-10}
5.8	1.15×10^{-11}	7.92×10^{-12}	1.73×10^{-11}	4.44×10^{-11}	8.79×10^{-12}	1.15×10^{-10}
5.9	1.05×10^{-11}	7.23×10^{-12}	1.58×10^{-11}	4.05×10^{-11}	8.02×10^{-12}	1.05×10^{-10}
6.0	9.57×10^{-12}	6.60×10^{-12}	1.44×10^{-11}	3.69×10^{-11}	7.32×10^{-12}	9.57×10^{-11}
6.1	8.76×10^{-12}	6.02×10^{-12}	1.32×10^{-11}	3.37×10^{-11}	6.68×10^{-12}	8.76×10^{-11}
6.2	7.99×10^{-12}	5.49×10^{-12}	1.20×10^{-11}	3.07×10^{-11}	6.09×10^{-12}	7.99×10^{-11}
6.3	7.29×10^{-12}	5.01×10^{-12}	1.10×10^{-11}	2.80×10^{-11}	5.56×10^{-12}	7.29×10^{-11}
6.4	6.65×10^{-12}	4.57×10^{-12}	1.00×10^{-11}	2.56×10^{-11}	5.07×10^{-12}	6.65×10^{-11}
6.5	6.07×10^{-12}	4.17×10^{-12}	9.13×10^{-12}	2.33×10^{-11}	4.63×10^{-12}	6.07×10^{-11}
6.6	5.54×10^{-12}	3.81×10^{-12}	8.33×10^{-12}	2.13×10^{-11}	4.22×10^{-12}	5.54×10^{-11}
6.7	5.05×10^{-12}	3.47×10^{-12}	7.60×10^{-12}	1.94×10^{-11}	3.85×10^{-12}	5.05×10^{-11}
6.8	4.61×10^{-12}	3.17×10^{-12}	6.93×10^{-12}	1.77×10^{-11}	3.51×10^{-12}	4.61×10^{-11}
6.9	4.21×10^{-12}	2.89×10^{-12}	6.33×10^{-12}	1.61×10^{-11}	3.21×10^{-12}	4.21×10^{-11}
7.0	3.84×10^{-12}	2.64×10^{-12}	5.77×10^{-12}	1.47×10^{-11}	2.93×10^{-12}	3.84×10^{-11}
7.1	3.50×10^{-12}	2.41×10^{-12}	5.27×10^{-12}	1.34×10^{-11}	2.67×10^{-12}	3.50×10^{-11}
7.2	3.20×10^{-12}	2.20×10^{-12}	4.80×10^{-12}	1.23×10^{-11}	2.44×10^{-12}	3.20×10^{-11}
7.3	2.91×10^{-12}	2.00×10^{-12}	4.38×10^{-12}	1.12×10^{-11}	2.23×10^{-12}	2.91×10^{-11}
7.4	2.66×10^{-12}	1.83×10^{-12}	4.00×10^{-12}	1.02×10^{-11}	2.03×10^{-12}	2.66×10^{-11}
7.5	2.43×10^{-12}	1.67×10^{-12}	3.65×10^{-12}	9.29×10^{-12}	1.85×10^{-12}	2.43×10^{-11}
7.6	2.21×10^{-12}	1.52×10^{-12}	3.33×10^{-12}	8.48×10^{-12}	1.69×10^{-12}	2.21×10^{-11}
7.7	2.02×10^{-12}	1.39×10^{-12}	3.04×10^{-12}	7.38×10^{-12}	1.54×10^{-12}	2.02×10^{-11}
7.8	1.84×10^{-12}	1.27×10^{-12}	2.77×10^{-12}	7.06×10^{-12}	1.41×10^{-12}	1.84×10^{-11}
7.9	1.68×10^{-12}	1.16×10^{-12}	2.53×10^{-12}	6.44×10^{-12}	1.28×10^{-12}	1.68×10^{-11}

Brightness Conversion Table
Magnitudes to Brightness (W/m^2)

Mag.	I	R	V	B	U	Bolometric
8.0	1.51×10^{-12}	1.04×10^{-12}	2.28×10^{-12}	5.83×10^{-12}	1.16×10^{-12}	1.51×10^{-11}
8.1	1.38×10^{-12}	9.49×10^{-13}	2.08×10^{-12}	5.32×10^{-12}	1.06×10^{-12}	1.38×10^{-11}
8.2	1.26×10^{-12}	9.66×10^{-13}	1.90×10^{-12}	4.85×10^{-12}	9.66×10^{-13}	1.26×10^{-11}
8.3	1.15×10^{-12}	7.90×10^{-13}	1.73×10^{-12}	4.43×10^{-12}	8.81×10^{-13}	1.15×10^{-11}
8.4	1.05×10^{-12}	7.21×10^{-13}	1.58×10^{-12}	4.04×10^{-12}	8.04×10^{-13}	1.05×10^{-11}
8.5	9.55×10^{-13}	6.58×10^{-13}	1.44×10^{-12}	3.69×10^{-12}	7.34×10^{-13}	9.55×10^{-12}
8.6	8.71×10^{-13}	6.00×10^{-13}	1.32×10^{-12}	3.36×10^{-12}	6.69×10^{-13}	8.71×10^{-12}
8.7	7.95×10^{-13}	5.47×10^{-13}	1.20×10^{-12}	3.07×10^{-12}	6.11×10^{-13}	7.95×10^{-12}
8.8	7.25×10^{-13}	5.00×10^{-13}	1.10×10^{-12}	2.80×10^{-12}	5.57×10^{-13}	7.25×10^{-12}
8.9	6.62×10^{-13}	4.46×10^{-13}	9.99×10^{-13}	2.55×10^{-12}	5.08×10^{-13}	6.62×10^{-12}
9.0	6.04×10^{-13}	4.16×10^{-13}	9.12×10^{-13}	2.33×10^{-12}	4.64×10^{-13}	6.04×10^{-12}
9.1	5.51×10^{-13}	3.79×10^{-13}	8.32×10^{-13}	2.12×10^{-12}	4.23×10^{-13}	5.51×10^{-12}
9.2	5.03×10^{-13}	3.46×10^{-13}	7.59×10^{-13}	1.94×10^{-12}	3.86×10^{-13}	5.03×10^{-12}
9.3	4.59×10^{-13}	3.16×10^{-13}	6.93×10^{-13}	1.77×10^{-12}	3.52×10^{-13}	4.59×10^{-12}
9.4	4.18×10^{-13}	2.88×10^{-13}	6.32×10^{-13}	1.61×10^{-12}	3.21×10^{-13}	4.18×10^{-12}
9.5	3.82×10^{-13}	2.63×10^{-13}	5.77×10^{-13}	1.47×10^{-12}	2.93×10^{-13}	3.82×10^{-12}
9.6	3.48×10^{-13}	2.40×10^{-13}	5.26×10^{-13}	1.34×10^{-12}	2.68×10^{-13}	3.48×10^{-12}
9.7	3.18×10^{-13}	2.19×10^{-13}	4.80×10^{-13}	1.22×10^{-12}	2.44×10^{-13}	3.18×10^{-12}
9.8	2.90×10^{-13}	2.00×10^{-13}	4.38×10^{-13}	1.12×10^{-12}	2.23×10^{-13}	2.90×10^{-12}
9.9	2.65×10^{-13}	1.82×10^{-13}	4.00×10^{-13}	1.02×10^{-12}	2.03×10^{-13}	2.65×10^{-12}
10.0	2.41×10^{-13}	1.66×10^{-13}	3.65×10^{-13}	9.30×10^{-13}	1.85×10^{-13}	2.41×10^{-12}

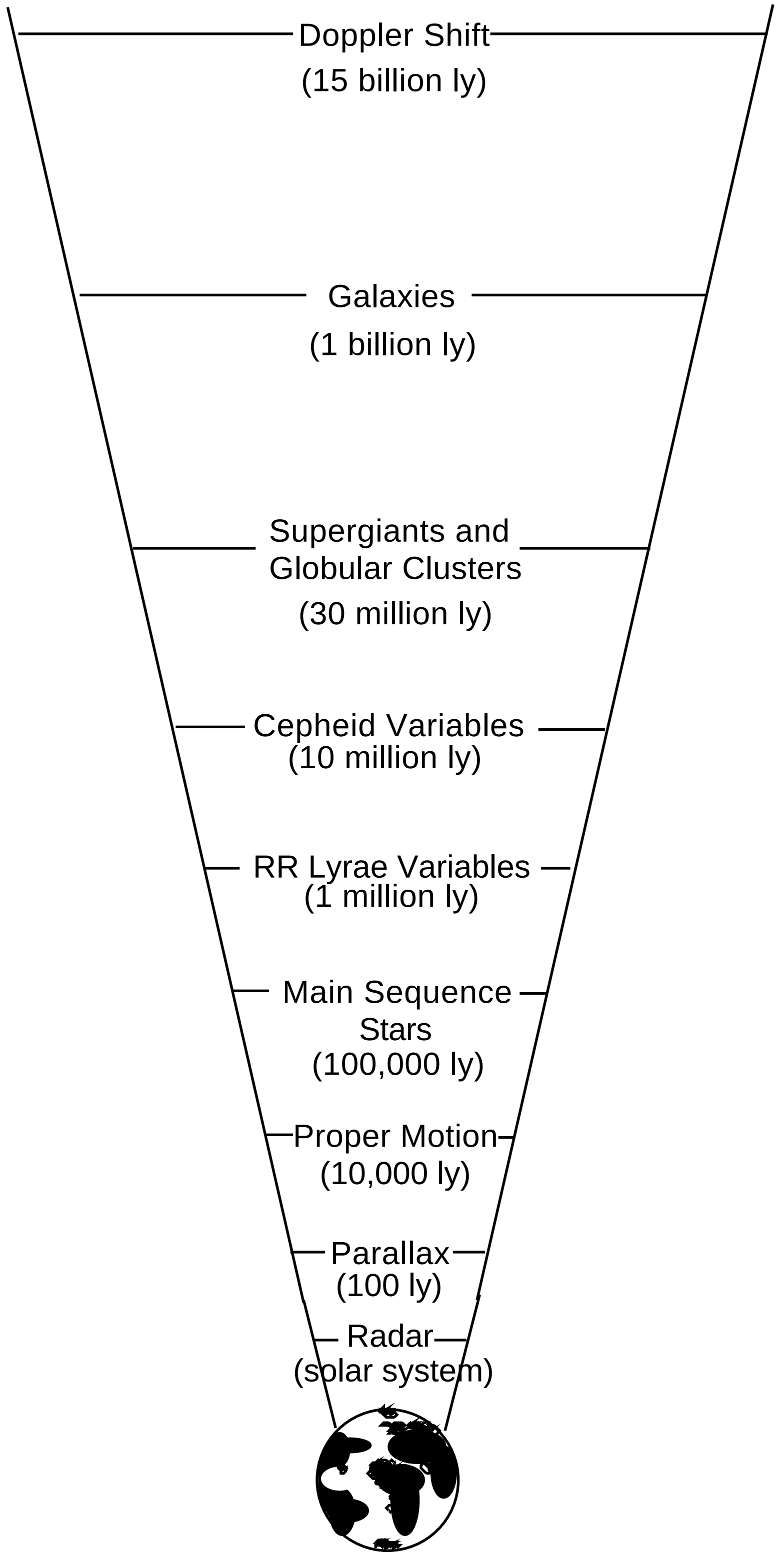
HANDS-ON UNIVERSE™
DISCUSSION SHEET

THE COSMOLOGICAL DISTANCE LADDER

There are various distance measurement techniques used in astronomy. They each lend themselves to observations for a particular range of distances using particular kinds of equipment. Astronomers use these techniques to build a distance ladder for the scale of the universe. Within the HOU curriculum you can learn how to determine the distance to Cepheid Variable stars which are used as the primary indicators in estimating the size and age of our universe.

Distance measurements for objects within our solar system and even to nearby stars are considered to be very accurate. As one proceeds up to higher rungs of the ladder, meaning to farther distances, the methods used to measure distance become less reliable. Less is known about objects farther away so it becomes harder to be certain which are usable as standard candles. Also, the distances measured on each rung of the ladder are confirmed by measurement techniques using the lower rung. If a mistake is made on any rung, that error is propagated all the way up the ladder.

For the Distance Ladder figure shown on the next page, the first two rungs are the only ones that are independent measurements that do not rely on the accuracy of other measurements or estimates. The rest of the rungs use assumptions about various objects as standard candles. Notice that Type Ia supernovae are not found on this distance ladder. That is because they may be standard candles that do not depend on measurement of closer objects. Astronomers, including the developers of HOU, are trying to understand these special supernovae well enough to be able to use Type Ia supernova as standard candles. When this goal is achieved, we will be able to observe supernovae and infer their distance as independent measurements based on their apparent brightness.



The Distance Ladder

HANDS-ON UNIVERSE™
SUPPLEMENTARY ACTIVITY 18
TECHNIQUES FOR MEASURING DISTANCE

Distance is one of the most elusive parameters for astronomers because, in general, it can not be measured directly. The apparent brightness of a star can be measured using photometry tools and in some cases the luminosity can be inferred by other techniques. When these two parameters are both known, the following equation can be used to calculate the distance.

$$\textbf{Apparent Brightness} = \frac{\textbf{Luminosity}}{4\pi \mathbf{d}^2}$$

where d = the distance to the object.

When a class of objects is known to have a certain luminosity, they can be used as standard candles. Examples include Cepheid Variable stars and certain types of supernovae.

An Activity to Demonstrate Standard Candles:

One group of students is going to challenge the rest of the class to determine the brightness of several flashlights relative to each other. Three or four students stand at one end of a long, dark hallway with lights of various brightness. The rest of the class is the audience at the other end of the hall. The students with the lights stand at varying distances from the audience (but not so close that they can be clearly seen) and switch their lights on. Try different combinations (dimmer lights close, brighter ones farther away) to trick the audience into misjudging which lights are brightest. Lights may be held higher or lower off the ground to create the illusion of being closer or farther away. Repeat the activity with lights having the same brightness.

1. How can you make the dimmer light appear brightest to the audience?
2. Can the audience be sure which light is closest when observing lights of various brightness?
3. Can the audience be sure which light is closest when observing lights of the same brightness?

Standard candles can be used to infer the distance to some objects and those are used to help in finding distances to further objects. When a standard candle, such as a Cepheid Variable star, is in a nearby galaxy the distance to that galaxy can be determined. If it can then be assumed that all galaxies of the same type all have the same brightness, the ratio of apparent brightness of a distant galaxy to the closer galaxy can be used to find the distance to the further one. The technique of using distances of closer objects as a tool for determining the distance to farther objects is called using a distance ladder. Astronomers use the cosmological distance ladder to estimate the size of the universe.

Creating A Distance Ladder for Your School:

The goal of this activity is to measure the approximate length of your school without the aid of any conventional measuring tools. Start by choosing a small object in your classroom, such as a book, and a larger object, such as a table. Now build a distance ladder with at least the following four rungs:

I. How many of the small objects equal the length of the larger object.
II. How many of the large objects equal the length of the classroom.
III. How many classrooms equal the length of the corridor.
IV. How many corridors equal the length the school.

4. Find the length of the school in units of the small object.
5. Do you think this is a close approximation?
6. Where did possible errors come from?
7. For each rung, estimate the percent error in your distance calculation in terms of the previous rung as your measuring stick. (0% error at any step is not believable, however.)
8. Using an estimated error at each step of 10%, what is the uncertainty in your answer to question 4 for the length of the school? Answer as a range; e.g., anywhere from 6900 to 7800 books long.
9. How would the accuracy of your estimation change depending on how many steps, or rungs of the ladder, you used to get your final measurement?

HANDS-ON UNIVERSE™
SUPPLEMENTARY ACTIVITY 19

USING A LIGHT BULB TO SEE HOW BRIGHTNESS VARIES WITH DISTANCE

- Hook the photocell to the ohm meter and check that the reading on the ohm meter changes as light to the cell changes (you can do this by turning off the lights or by shielding the cell with your hand).

- Place a lit light bulb in an otherwise darkened room. It is important not to have any background light behind the light bulb or objects obstructing light from the light bulb.

- Hold the photocell one meter away from the light bulb and take a reading from the ohm meter. The reading from the ohm meter is a measure of the light detected by the photocell.

1. Record your data.

2. Before taking additional readings make predictions for what you would expect at two and three meters.

3. Take readings at two and three meters, record your data, and compare these with your predictions.

4. Gather and record data for five additional distances.

5. Plot your data (there should be at least eight points) on a graph with distance on the horizontal axis and light reading on the vertical axis. Draw a smooth curve that approximately connects the points.

6. On the basis of your graph, which of the following relationships between brightness, B, and distance, D, can you rule out?

a) $B \alpha D$ b) $B \alpha D^2$ c) $B \alpha 1/D$ d) $B \alpha 1/D^2$

7. What function most matches this curve ?

8. Square each of your distance measurements. Plot light reading vs. distance squared. Draw a straight line through the points on the graph.

A. What is the slope of this line?

B. What is the math function for the light reading in terms of the distance?

HANDS-ON UNIVERSE™
SUPPLEMENTARY ACTIVITY 20

MEASURING SPHERICAL DISTRIBUTIONS

Activity I

Use a balloon that becomes spherical when inflated. While the balloon is deflated, lay it flat and draw at least 200 dots evenly spaced over one half of the balloon. On the other side of the balloon, draw a small square. Also cut a 1 cm by 1 cm square window out of a piece of paper. Blow up the balloon just enough so that it becomes round. Determine the radius of the balloon at this point and call this radius1.

1. Use the clear square as a window, place it on the balloon, and count the number of dots you can see on the balloon through the window. For the most accurate reading, take an average of several places on the balloon.

2. Measure the area of the box you drew on the balloon.

3. Blow up the balloon so the new radius, radius2, is two times radius1 and then three times radius1 (radius3). For each new radius repeat steps 1 and 2.

4. By what factor does the number of dots within the window decrease when the radius is doubled?

5. By what factor does the number of dots within the window decrease when the radius is tripled?

6. By what factor does the area of the square increase when the radius is doubled?

7. By what factor does the area of the square increase when the radius is tripled?

8. Explain your findings.

Activity II

Light coming from a point spreads out in all directions. At any distance away it can be thought of as spread out on an imaginary sphere surrounding the light. To understand this better, you will measure the surface area of spheres of various radii.

USEFUL FORMULAE
area of a rectangle = length x width
area of a circle = πr^2
area of a triangle = 1/2 x base x height
circumference of a circle = $2\pi r$

9. Develop a method to measure the radius of each sphere provided by your teacher. Record your measurements.

10. Calculate the ratio of the radius of each sphere to the radius of the smallest sphere.

11. Develop a method for measuring the surface area of each sphere. There are many possible ways to do this. They just require some creativity and a lot of care to get accurate measurements.

12 Calculate the ratio of surface area of each sphere to the surface area of the smallest sphere.

13. What do you think is the function for the surface area of a sphere in terms of its radius?

14. Plot your function and compare the graph to a plot of the surface area vs. radii for the spheres. If they do not correspond, look again at your guess of the function.

HANDS-ON UNIVERSE™

SUPPLEMENTARY ACTIVITY 21

A THOUGHT EXPERIMENT FOR BRIGHTNESS AND DISTANCE

Imagine you are out in space where gravity is negligible, and you have a small ball that is being pumped full of paint (pretend there is an endless amount of paint so you never run out). Suppose the paint ball has a large number of tiny holes punched uniformly over its surface so that the paint sprays out evenly in all directions. Since you are in outer space, gravity does not pull the paint down in any given direction, so imagine that it continues to spray evenly in all directions. Suppose the paint is constantly pumped out of the paint ball at a rate of 1000 grams per second.

You also have large spherical shells you can put around the paint ball to collect the sprayed paint. The radius of SHELL1 is 10 cm, the radius of SHELL2 is 20 cm, the radius of SHELL3 is 30 cm etc., and the radius of the paint ball itself is so small it is negligible relative to the radii of the shells.

If you place the paint ball in the center of SHELL1 for one second, 1000 grams of paint will coat the inside of the shell since 1000 grams of paint are pumped each second.

1. Consider the following situations where the paint ball is placed in the center of different shells for various amounts of time. How much paint will be collected in each case:

A. SHELL1 for 1 sec?
B. SHELL1 for 2 sec?
C. SHELL1 for 10 sec?
D. SHELL2 for 1 sec?
E. SHELL3 for 1 sec?
F. SHELL3 for 10 sec?

You can now determine the amount of paint collected per square centimeter. The paint is spread out evenly over the entire surface area of the inside of a shell. The surface area of a sphere is proportional to r^2. The full equation for the surface area of a sphere is $SA = 4\pi r^2$. In each second, 1000 grams of paint are spread out over an area of $4\pi r^2$ square centimeters.

2. Calculate the surface area of the inside of each shell.

A. SHELL1:

B. SHELL2:

C. SHELL3:

D. SHELL4:

3. Suppose you place a patch on the inside of SHELL1 that covers one half of the surface area of the shell.

A. How much paint would land on the patch each second?

B. What if the patch was one quarter of the surface area of the shell?

4. Suppose the area of the patch is 1 cm^2.

A. What is the ratio of the area of the patch to the total surface area of SHELL1?

B. How much paint would land on the 1 cm^2 patch each second?

5. Using the 1 cm^2 patch, how much paint will it collect on:.

A. SHELL1 for 2 sec?

B. SHELL1 for 10 sec?

C. SHELL2 for 1 sec?

D. SHELL3 for 1 sec?

E. SHELL3 for 10 sec?

F. SHELL5 for 1 sec?

6. Using the analogy between a light source and a paint ball, what is the "luminosity" of the paint ball ?

7. Using the analogy between a light source and a paint ball, what is the "apparent brightness" of the paint ball as observed from:

A. SHELL1 ?

B. SHELL2 ?

C. SHELL3 ?

D. SHELL4 ?

Date: _______________ Name: ______________________

Answer Sheet

Supplementary Activity 21

A Thought Experiment for Brightness and Distance

1. Paint on:

A. SHELL1 for 1 sec:

B. SHELL1 for 2 sec:

C. SHELL1 for 10 sec:

D. SHELL2 for 1 sec:

E. SHELL3 for 1 sec:

F. SHELL3 for 10 sec:

2. Each shell's inside surface area:

A. SHELL1:

B. SHELL2:

C. SHELL3:

D. SHELL4:

3. **A**. On Shell 1 the paint that would land on half the surface area each second:

B. Paint that would land on one quarter the surface area of the shell:

4. For a 1 cm^2 patch:

A. The ratio of the area of the patch to the total surface area of SHELL1:

B. The amount of paint that would land on the 1 cm^2 patch each second:

5. How much paint a 1 cm^2 patch will collect on:

A. SHELL1 for 2 sec:

B. SHELL1 for 10 sec:

C. SHELL2 for 1 sec:

D. SHELL3 for 1 sec:

E. SHELL3 for 10 sec:

F. SHELL5 for 1 sec:

6. The "luminosity" of the paint ball:

7. The "apparent brightness" of the paint ball from:

A. SHELL1:

B. SHELL2:

C. SHELL3:

D. SHELL4:

HANDS-ON UNIVERSE™

DETERMINING DISTANCE OR LUMINOSITY USING APPARENT BRIGHTNESS UNIT

In this activity you will determine the apparent brightness of stars and use this to determine their distance and luminosity. Light spreads out spherically in all directions, so the star appears dimmer and dimmer the further away it is. Dimming follows the inverse square rule, the same rule that applies to the strength of the gravitational field of a planet. Apparent brightness varies directly with the luminosity and inversely with the square of the distance as described in the following equation:

$$\textbf{Apparent Brightness} = \frac{\textbf{Luminosity}}{4\pi d^2}$$

where d = the distance to the star

For definitions and further explanations of apparent brightness and luminosity, please refer to the *Photometry Techniques Discussion Sheet* in the Measuring Brightness module. For details on using **Auto Aperture** and calibrating an image to get the apparent brightness of a star, please refer to the *Photometry Techniques Unit* in the Measuring Brightness module.

Screen Setup: *ABLstar*

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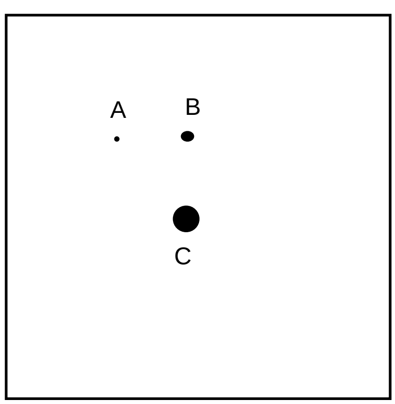
1. Use **Auto Aperture** to measure the Counts for the three brightest stars on the image as identified in the Finder chart below.



Finder chart for *ABLstar*

2. Assume the distance to the dimmest and brightest stars (A and C) is the same. Since the stars are on the same image, thus were taken using the same CCD and under the same observing conditions, the ratio of Counts is equivalent to the ratio of apparent brightness for the stars. Use the ratio of the Counts of the two stars to calculate the ratio of their luminosities.

3. Assume the two brighter stars measured have the same luminosity, but not necessarily the same distance. Use the ratio of their Counts to calculate the ratio of their distances.

4. The image used in this activity was taken through a V filter that lets through predominantly yellow light. Given that the magnitude of star C through the V filter is 6.4, use the Brightness Conversion Table in the front of this module to convert this to apparent brightness in V and then calculate the apparent brightness of the other stars in the image in V.

5. Use the distance values for each star given below to calculate their luminosity in V. This is the amount of yellow light emitted by the star per second. Find the luminosity of each star in units of solar luminosity (how many times the luminosity of the sun). The luminosity of the Sun through a V filter = 5.7×10^{25} Watts.

Star A $d = 3.4 \times 10^{18}$ m
Star B $d = 1.0 \times 10^{19}$ m
Star C $d = 2.8 \times 10^{18}$ m

Date: ______________ Name: ____________________

Answer Sheet

Determining Distance and Luminosity
Using Apparent Brightness

1. Counts for Star A:

Counts for Star B:

Counts for Star C:

2. Star C is ____________ more luminous than Star A.

3. Star A is ____________ times farther away than Star C.

4. Apparent brightness of Star C:

Apparent brightness of Star A:

Apparent brightness of Star B:

5. Luminosity of Star A in Watts:

Luminosity of Star B in Watts:

Luminosity of Star C in Watts:

HANDS-ON UNIVERSE™
DISCUSSION SHEET
CEPHEID VARIABLE STARS AS DISTANCE INDICATORS

In 1784 a star in the constellation Cepheus was observed night after night by John Goodricke, and he noted that the star became brighter and then dimmer. The fluctuation in brightness repeated over and over again approximately every five days. This was the discovery of the first Cepheid Variable star.

In 1908 at Harvard College Observatory, Henrietta Leavitt was examining many photographic images of two small galaxies orbiting the Milky Way, called the Magellanic Clouds. She was studying the Cepheids in the Magellanic Clouds and noticed a pattern in their brightness fluctuations: the brightest Cepheids had the longest fluctuation cycles and the dimmest stars the shortest. Since Leavitt was only studying Cepheids in the Magellanic clouds, the distance to all her Cepheids was the same which meant comparing their apparent brightness was equivalent to comparing their luminosity. This enabled her to state a general correspondence between luminosity and period which she published in 1917 as what is now called the period-luminosity diagram. (See *Cepheid Variable Stars Unit*, p.28.)

The period-luminosity diagram allows an astronomer to infer the luminosity of a Cepheid simply by measuring the period of its brightness fluctuation. Luminosity generally cannot be measured directly, but knowing it from the period of a Cepheid Variable allows one to determine much more valuable information such as distance. Leavitt's discovery of the period-luminosity relationship is a milestone in astronomy. Before her research, no one had a reliable tool for measuring the distance to objects farther away than the closest stars. The technique for determining the distance of a Cepheid requires three basic steps:

1) Measure the period of fluctuation and infer the luminosity of the Cepheid.
2) Use a standard star to calibrate the image and determine the Cepheid's apparent brightness.
3) Use the equation for apparent brightness to calculate the distance to the star, d:

$$\textbf{apparent brightness} = \textbf{luminosity}/4\pi \mathbf{d}^2$$

To measure the period of fluctuation, the Cepheid must be observed at least every few nights for several weeks. The number of Counts measured for a Cepheid will change from night to night for two reasons:

1) the changing observing conditions and
2) the changing luminosity of the star.

In order to get a plot of the Cepheid's changing luminosity you must remove the effects of the atmosphere by including a reference star. Since the Cepheid star and the reference star are on the same image, the observing conditions are the same for both stars. If the observing conditions did not change from night to night, the reference star would appear just as bright each night. In general, observing conditions do change, so the number of Counts measured for the reference star will increase or decrease depending on how much light the atmosphere lets through. If the atmosphere blocks out a large amount of light on one night, both stars will appear dimmer; on a clear night, both stars will appear brighter.

If the Cepheid had constant luminosity, the ratio of Counts between the Cepheid and the reference star would remain constant. A Cepheid is not constant, however. As the luminosity of the Cepheid increases, because of internal changes in the star, the ratio of Counts measured for the Cepheid to the Counts measured for the reference star will increase. By measuring this ratio for each image, you can plot the true brightness fluctuation of the Cepheid.

HANDS-ON UNIVERSE™

CEPHEID VARIABLE STARS UNIT

Activity I: Plotting the Light Curve for a Cepheid

A Cepheid was monitored for a 15-day time span, but on only eight of those nights were the skies clear enough to get good images. You are to measure the brightness of the star on each image and create a light curve for the star. A light curve is a plot with brightness on the vertical axis and time (days) on the horizontal axis.

Perform the following procedure on each of the images listed below. The name of the file gives you the date of observation.

May06cep, *May08cep*, *May10cep*,
May11cep, *May14cep*, *May15cep*,
May18cep, *May21cep*

Each file contains an image of the Cepheid star and a reference star observed on a given night. The Cepheid is the star on the left and the reference star is on the right.

1. Use **Auto Aperture** to measure the brightness in Counts of each Cepheid and reference star. Record the data.

2. Find the Count ratio, C_c / C_r, where C_c = the Counts of the Cepheid and C_r = the Counts of the reference star.

3. Plot your series of Count ratios and corresponding dates on the graph axes provided. Be careful to skip nights when dates are missing from the observations.

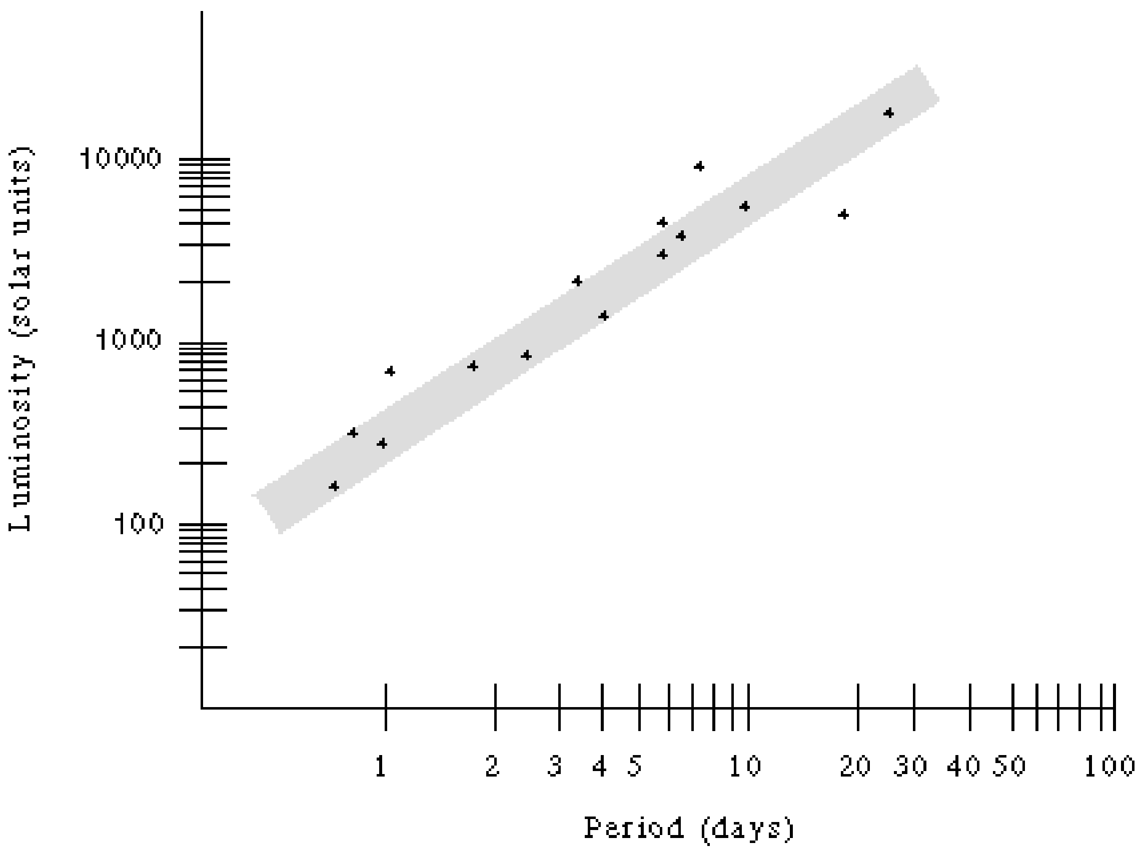
4. What is the period of this Cepheid?

Activity II: Find the Luminosity of a Cepheid

The observations of the Cepheid were made through a Visible(V) filter. This filter blocks out almost all light except that in the yellow-green part of the color spectrum. When you calculate the luminosity and apparent brightness of the Cepheid you must remember that these only refer to the amount of light coming through the V filter. This is fine for your measurements because you can compare them to other measurements taken through the same kind of filter. However, it is not valid to compare these values to the apparent brightness or luminosity of a star over all wavelengths. In this unit, all measurements are through the V filter.

5. Use the Period-Luminosity diagram to estimate Luminosity (V) of the Cepheid measured in Activity I. Note: Both axes are logarithmic scales and luminosity is given in solar units; e.g., 1000 means 1000 times the luminosity of the Sun.

6. Use the value for the luminosity of the sun through a V filter to calculate L(V) of your Cepheid in Watts. L(V) of the Sun = 5.7×10^{25} Watts.



Period-Luminosity Diagram for Classical Cepheid Variable Stars

Activity III: Find the Distance to a Cepheid

The apparent magnitude in V of the reference star is 8.0. From the Brightness Conversion Table, this is equivalent to an apparent brightness in V of 2.28×10^{-12} Watts/m^2.

7. Calculate the apparent brightness of the Cepheid.

8. Use the luminosity in V for the Cepheid and the equation for apparent brightness to determine the distance, d, to the Cepheid in meters. (For the equation go to the *Cepheid Variable Stars As Distance Indicators Discussion Sheet.*)

9. Convert the distance to light years. 1 light year = 9.5×10^{15} m.

Date: ______________ Name: ___________________

Answer Sheet

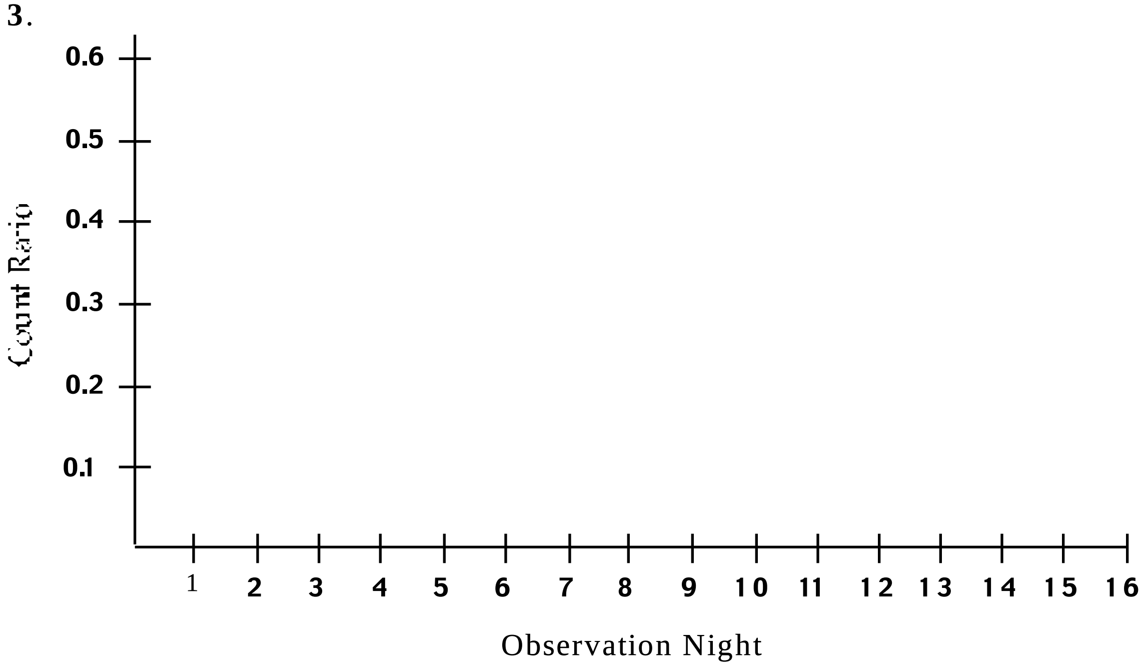
Cepheid Variable Stars Unit

Activity 1: Plotting the Light Curve for a Cepheid

1. and **2**.

	May 06	May 08	May 10	May 11	May 14	May 15	May 18	May 21
Counts of Cepheid								
Counts of Reference								
Count Ratio								

3.



4. Period of the Cepheid:

Activity II: Finding the Luminosity of a Cepheid

5. Luminosity of the Cepheid in solar units:

6. Luminosity of the Cepheid in Watts:

Activity III: Finding the Distance to a Cepheid

7. Apparent Brightness of the Cepheid:

8. Distance to the Cepheid in meters:

9. Distance to the Cepheid in lightyears:

HANDS-ON UNIVERSE™
SUPPLEMENTARY ACTIVITY 22
EXAMINING PERIODICITY

Imagine a pendulum swinging back and forth. It completes one cycle by swinging from the farthest point on one side, down through the middle and up to the other side, back through the middle and finally returning to the original side. The time it takes to complete a cycle is called the period. The pendulum's motion is called periodic because it continues to swing with the same period over and over again.

There are many periodic motions in our daily lives. The period of the moon's orbit around the Earth is about 27.5 days. The period of a guitar string vibrating when it is creating a middle C note is 1/262 of a second.

1. Consider the following examples and try to estimate the period of the motion:

A. The Earth's orbit around the sun.
B. A human heart beating.
C. An adult's lung motion when breathing normally.

Another example is bouncing a basketball. In the following activity you will use a relationship you learn through observation, to infer data from a more limited observation.

3 a). Bounce the ball repeatedly with your hand at waist level and then bounce the ball with your hand at knee level. Try a couple of other heights above the ground. Describe how the period of the motion changes as you change the height of the bounce.

3 b) Now have one person go around a corner or outside in the hall where s/he can be heard but is out of sight. Have her bounce the ball at various heights. You estimate the height of the bounce by listening to the frequency of the bounce. Have the person bouncing the ball record the actual heights (in terms of ankle high, knee high, waist high, etc.) and the observers record their predictions

3 c) Suppose one pair of people took the time to bounce the ball at several different heights while still in the room together, while another pair just bounced it at waist high and then went right to the second part of the activity (where one person is out of the room). Would this make a difference in the ability to predict the height of a bounce? Why?

4. Some motions have periods that are dependent on another characteristic of the motion. For example, consider the orbits of all the planets in the solar system as they travel around the sun.

A. Which planet has the shortest period?

B. Which planet has the longest period?

C. How does the period of a planet's orbit depend on its distance from the sun?

HANDS-ON UNIVERSE™
SUPPLEMENTARY ACTIVITY 23
DEMONSTRATING GAS LAWS

Wrap the opening of a deflated balloon tightly around the mouth of an empty bottle. Using tongs, place the bottle in very hot or boiling water so that most of the bottle is submerged. Let it sit for a few minutes and observe the balloon. Remove the bottle from the hot water and place it in very cold water so that most of the bottle is submerged. Observe the balloon.

1. What causes the balloon to expand?

2. Why does it contract?

3. What do you think would happen to the temperature of the air in the bottle if we pushed the air out of the balloon back into the bottle?

Test your hypothesis with the following activity. Using a plastic 2-liter soda bottle with a temperature strip inside and keeping the soda bottle in the same location, have one partner squeeze it to compress the air inside. Have the other partner read the temperature strip for the next few minutes while the first continues to squeeze on the bottle. Stop squeezing the bottle and let it return to its original shape. Check the temperature for a couple of minutes.

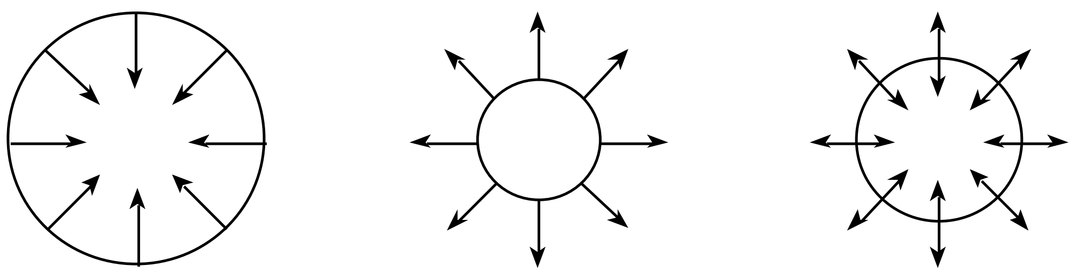
4. What happens to the temperature of the air inside the bottle when it is compressed?

5. What happens to the temperature when the compressing force is removed?

6. Make a general statement about your findings on the relationship between temperature and the compression and expansion of a gas.

HANDS-ON UNIVERSE™
DISCUSSION SHEET
THE SCIENCE OF A CEPHEID VARIABLE STAR

The gas that makes up a star reacts to forces pushing inward and forces pushing outward. (See Figure 1). The force pushing inward is gravity. All of the particles in the star are attracted to all of the other particles, and this in effect holds the star together. During most of a star's lifetime, the primary force pushing outward is created by heat. As gravity causes a star to collapse inward the gas heats up. The heat causes the particles making up the star to move around faster and they need more room so the star expands. This in turn cools the star. Most stars find a balance between the force inward and the force outward and remain a stable size for almost their entire lifetimes.



i. Gravity causes star to collapse inward and heat up

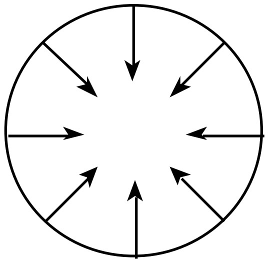
ii. Heat causes star to expand outward and cool down

iii. An ordinary star reaches a balance and the radius remains constant

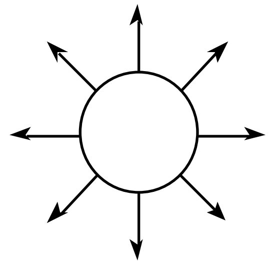
Figure 1:
The Balance of Forces in an Ordinary Star

Some stars never reach this balance. (See Figure 2) In this case, the star shrinks in size because the gravity is too strong, then it heats up and expands outward because it is too hot, then shrinks again because it got too cool, and then expands again, and on and on. These are called pulsating or variable stars. In some cases the variation of brightness is periodic. One type of periodic variable stars is Cepheids.

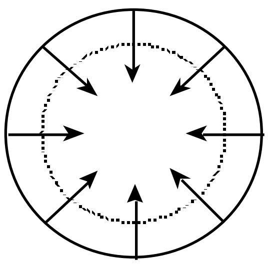
The reason some stars become Cepheids while others do not depend upon the star's mass and the original composition. The conditions have to be exactly right during the final stages of a star's life for it to become a Cepheid. Though Cepheids are relatively rare, they are valuable as distance indicators.



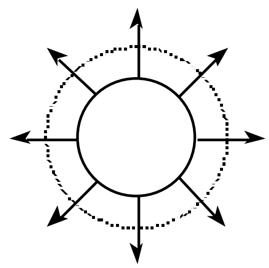
i. Gravity causes star to collapse inward and heat up



ii. Heat causes star to expand outward and cools down.



iii. A Cepheid variable star overshoots its balance point. It expands too far and gets too cool so gravity causes it to collapse again.



iv. The Cepheid collapses past the balance point and gets too hot so it must expand again. The star continues to pulsate in and out at a constant frequency.

Figure 2:
Pulsation of a Cepheid Variable Star

As a Cepheid contracts and expands, the luminosity fluctuates according to the change in the radius and change in temperature. Plotting Luminosity vs. time is a light curve. Astronomers have grouped different types of Cepheids into different categories depending on the shape of their light curve. Brighter Cepheids generally have larger radii and take longer to complete one cycle of expansion and contraction than their dimmer counterparts. This fits with Leavitt's period-luminosity relationship. (See the *Cepheid Variable Stars as Distance Indicators Discussion Sheet*). Understanding the theory behind Leavitt's findings gives astronomers reason to assume that the period-luminosity relation should hold for all Cepheids and thus can be used to find the distance to Cepheids throughout our galaxy and beyond.

