# DAY LABORATORY EXERCISE #2:
# LUMINOSITY AND BRIGHTNESS

## Goals:
- To determine the mathematical description of how light becomes fainter with distance.
- To use a differential photometer to test the distance formula for lights of different intrinsic brightness.
- To determine the luminosity of the Sun by direct measurement.

## Equipment: light bulbs, meter sticks, calculators, wax blocks, aluminum foil

## Methods:
- Mask light from a bulb and measure how the light beam grows with distance
- Gain experience using a differential photometer with light bulbs in the lab.
- Go outside, use the differential photometer to compare the Sun to a known light bulb.

**Introduction -** How do we determine the value of the Sun's luminosity or the luminosity of other stars? In this lab, you will perform a set of three activities which will explore how light becomes fainter with distance, use a simple differential photometer for comparing the brightness of two light sources, and combine these two activities to measure the luminosity of the Sun.

## Station 1: Light and Distance

Increasing the distance between a light source and an observer always decreases the perceived brightness of the source. A mathematical relationship exists which relates **apparent brightness** ***b***, the brightness which is perceived by an observer, to distance ***d***. Once the apparent brightness (and the true brightness) of an astronomical object is known, astronomers can use this relationship to determine an object's distance from the Earth. Alternatively, if we know the distance, the apparent brightness can be used as a basis for calculating the intrinsic brightness, or luminosity, of the source.

At this station (see Figure 1), you will use a light bulb and a mask located at a fixed distance to produce a diverging light beam of known brightness. This beam will be used to illuminate a screen with a checkerboard pattern for a series of different distances. By evaluating how the number of illuminated checkerboard squares changes with distance from the light bulb, you will establish the mathematical formula for decreasing light brightness with increasing distance.

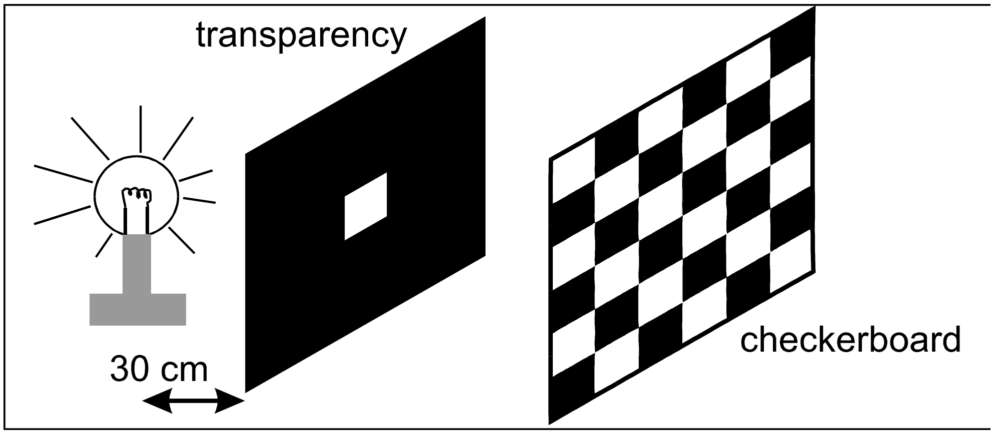


*Figure 1:* Layout showing illuminating light bulb (and filament), transparency mask, and checkerboard screen.

## Station 2: Differential Photometer

Light brightness is measured with a device called a **photometer**. Direct reading photometers are often expensive and difficult to use. However, if we only need to know when two light sources are showing the *same* brightness, we can create a fairly simple **differential photometer**. And, though simple, the results from our differential photometer can be remarkably sophisticated. By applying our knowledge of how light becomes fainter with distance, we will combine the differential photometer with meter sticks to measure the intrinsic brightness of lights and candles with good precision.

The differential photometer consists of two wax blocks and a piece of aluminum foil located between the wax blocks. When viewed from the edge, this photometer will allow you to judge when the two wax blocks are equally bright. Then, if we measure the distances to the light sources located to the left and right of the blocks (see Figure 2), we can calculate their brightness ratios. If the brightness of one light source is known, we can instead calculate the brightness of the other light source.

At this station, you will use your photometer to verify the brightness-distance relation you found in Station 1. You will also use your photometer to measure the brightness of a light bulb of unknown power as well as a candle. You will get more consistent results if the light sources you are comparing are kept at the same height.

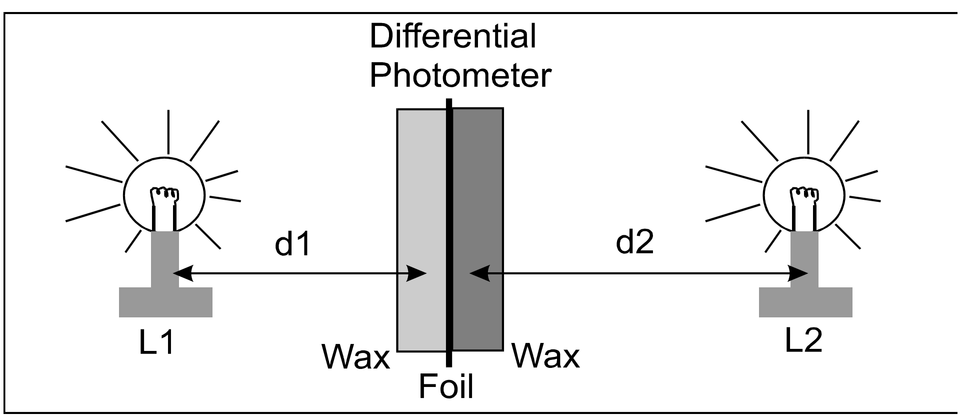


*Figure 2:* Differential Photometer, consisting of two wax blocks and a piece of aluminum foil between, viewed from the side with two light bulbs. Each bulb illuminates only one wax block.

# Station 3: Luminosity of the Sun

We can combine our new understanding of how light becomes fainter for larger distances with use of the differential photometer to measure directly the luminosity of the Sun. On a sunny day, take one 200 W light bulb, a meter stick, and your differential photometer outside. Set up the bulb, photometer, and meter stick as shown in Figure 3. Move the photometer until it shows equal brightness from the distant Sun and the nearby light bulb. Perform the necessary calculations to determine the Sun's luminosity.

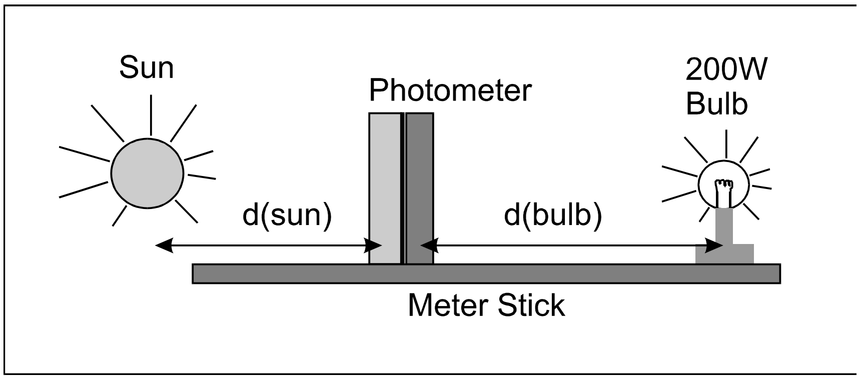


*Figure 3:* Setup for measuring the luminosity of the Sun.

## Luminosity, Brightness, and Area

A light source delivers a certain quantity of energy per second in the form of electromagnetic radiation. We define luminosity (**L**) as the amount of this energy (in Joules) delivered by a light source each second. For example, a 100 Watt light bulb emits 100 Joules of energy each second.

As electromagnetic radiation moves outward from a source, it spreads outward in all directions, covering a larger and larger spherical area. The amount of electromagnetic energy passing through each square meter of the imaginary sphere each second is the total luminosity of the source (***L***) divided by the sphere's total surface area ($A=4\pi R^2$, given in $m^2$). We call ***L/A*** the **apparent brightness** (***b)*** of the source and it corresponds to the brightness that an observer actually sees. Note that the apparent brightness measured by an observer depends on how far the observer is from the source of the light.

## Determining the Sun's Surface Temperature using the Stefan-Boltzmann Law.

The Stefan-Boltzmann law relates an object's **actual brightness** (***B***) to its **surface temperature** (***T***) via the following formula:

$$B = \sigma T^4$$

where: $\sigma$ = Stefan-Boltzmann constant = $5.672 \times 10^{-8}$ Joules/($m^2$ sec $K^4$) and
***T*** = temperature, in Kelvin degrees ($^0$K)

Rewriting this relationship in terms of **luminosity** (*L*), we obtain the following:

$$L / (4\pi R^2) = \sigma T^4$$

where ***R*** is the radius of the Sun (or other star) since the brightness (***B***) is now the brightness at the Sun's surface. This can be rewritten as:

$$L = 4\pi R^2 \sigma T^4$$

# Procedures:

## Station 1:

1. Turn off the classroom lights. Turn on the 200 Watt lamp. *Caution: Do not touch the bulb unless the bulb has been turned off and allowed to cool!*
2. Hold the clear square (the "transparency") at a distance of 30 cm from the lamp filament. Make sure that the clear square is perpendicular to the long axis of the filament so that the filament appears as small as possible when viewed from the transparency. Keep the 200 Watt light bulb filament 30 cm from the transparency throughout this activity.
3. Hold the checkerboard sheet up against the clear square until only one square is illuminated somewhere in the center of the sheet of squares.
4. Fill in the number of squares illuminated and the fraction of light covering each square in Table 1 on the worksheet on page 5. For example, if 1 square is illuminated it receives 100% of the light from the masked source, so record "1" in the middle column and "1" in the right column of Table 1.
5. Move the checkerboard sheet so that it is 60 cm from the bulb's filament.
   - Make sure to keep the checkerboard sheet parallel to the transparency sheet.
   - Count the number of squares illuminated by the light passing through the clear square and record this number in Table 1.
6. Repeat step 5 for checkerboard distances which are 90 cm and 120 cm from the filament.
7. Fill in the last column of Table 1.
   - Since the distance between the light bulb and the transparency mask is fixed at 30 cm, the total amount of light which passes through the clear square and hits the checkerboard must be a constant. However, the light is being spread out over a larger area as the checkerboard is moved away from the transparency.
   - Thus to fill in the last column, divide one by the number of squares illuminated.

## Station 2:

You will be given two blocks of paraffin wax with a folded piece of aluminum foil sandwiched in between.

1. Darken the classroom and turn on the 200 Watt light bulb.
2. Hold the photometer so that one of the paraffin sides is facing the light source.
3. Looking at the photometer edge on and describe what you see on the worksheet, page 6.
4. Slowly move the photometer towards and away from the light.
5. Record on the worksheet what you observe happening to the edge of the wax facing the light.
   - What is happening to the other side of the photometer?
6. Place the two 100 W bulbs at the ends of a meter stick.
   - Where do you predict you should place the photometer to obtain a balanced reading?

- Place the photometer where you predicted it should be placed. Does the photometer show a balance of light between the two wax sides?

7. Replace one 100 W bulb with a 60 W bulb.
    - Where do you predict you should place the photometer to obtain a balanced reading?
    - Place the photometer where you predicted it should be placed. Does the photometer show a balance of light between the two wax sides?
8. Replace the 100 W bulb with the unknown wattage bulb.
    - Adjust the distances until the photometer shows the light brightness is in balance.
    - Measure the distances.
    - Compute the wattage of this unknown bulb.
9. Replace the 60W bulb with a candle.  Put the candle on the block at the same height.
    - Adjust the distances until the photometer shows the light brightness is in balance.
    - Measure the distances.
    - Compute the wattage of the candle.

## Station 3:

1. Take a 200 W light bulb, extension power cord, meter stick, and differential photometer outside on a sunny day.
2. With the 200 W bulb located at one end of the meter stick, point the other end of the meter stick at the Sun.
    - Plug in the extension cord to light the 200 W bulb.
3. Place the photometer on the meter stick and move it until the light from the Sun and the light from the 200 W bulb are in balance.
4. Record the distance between the 200 W bulb and the photometer.

# DAY LABORATORY EXERCISE #2:
# LUMINOSITY AND BRIGHTNESS

Name/ID\#_____________________________ TA's Initials:________

Class/Section: AS102/ ______ Date due:___________

Station 1: Light and Distance

Table 1

| Checkerboard Distance from the Bulb Filament | Distance in Units of 30cm (***d***) | Number of Squares Illuminated | Fraction of Light per Square (***b***) |
|---|---|---|---|
| 30 cm | 1 | 1 | 1 |
| 60 cm | | | |
| 90 cm | | | |
| 120 cm | | | |

- What do you infer about the proportionality between the apparent brightness (***b***) of any individual square on the checkerboard and its distance from the light filament (***d***)?

- Explain your reasoning. Why is the proportionality of the form you deduce? How should the luminosity of the light bulb be incorporated into the mathematical relation?

Station 2: Differential Photometer

- With the classroom dark and the 200 W bulb turned on, what do you see happen to the photometer as you move it toward and away from the light?

- What do you see on the side of the photometer which is not illuminated?

- Based on your observations, describe how the photometer works. What is the function of the aluminum foil? Of the wax slabs?

- Meter stick with two 100 Watt light bulbs.
  - With the bulbs at the ends of the meter stick, where does your formula from Station 1 predict you should place the photometer so that it will show a balance of light brightness?

- Do the experiment. Was your prediction correct? Why or why not?

- Meter stick with one 100 W and one 60 W bulb.
  - With the bulbs at the ends of the meter stick, where do you predict you should place the photometer to see a balance of light brightness? What is the basis of your prediction?
  - Do the experiment. Was your prediction correct? Why or why not?

- 60 W bulb and unknown wattage bulb:
  - With the 60 W bulb at one end of the meter stick and the unknown at the other end, adjust the placement of the photometer until the brightness balanced from both sides of the photometer.
  - Measure the distances between the bulbs and the photometer.

- Calculate the wattage of the unknown bulb. SHOW ALL YOUR WORK!

- Wattage of unknown bulb =

- Unknown wattage bulb and candle.
  - With the unknown wattage bulb at one end of the meter stick and a candle at the other end, adjust the placement of the photometer until the brightness is in balance on both sides of the photometer.
  - Measure the distances between the bulb and the photometer and the candle and photometer.
  - Calculate the luminosity of the candle as you did for the unknown wattage bulb.

  - Wattage of candle =

## Station 3: Solar Luminosity and Temperature

- Distance between the 200 W bulb and the photometer when the photometer shows a balance of brightness for the Sun and the bulb.

- Calculate the luminosity of the Sun, SHOWING ALL YOUR WORK. Note that the Sun is $1.49 \times 10^{11}$ meters away.

- Using the luminosity you calculated for the Sun and the relationship described in the introduction, calculate the temperature of the Sun (in Kelvin degrees). The Sun has a radius of $6.96 \times 10^{8}$ meters. SHOW ALL YOUR WORK.

## Summary Questions

1. Betelgeuse is a bright red supergiant star located in the winter constellation Orion. Calculate its luminosity if its radius is 300 times that of the Sun and its temperature is $4200^0$ K. SHOW ALL YOUR WORK.

2. How many Watts/$m^2$ get to Earth from Betelgeuse if it is at a distance of 150 parsec (1 pc = $3x10^{16}$ meters)? SHOW ALL YOUR WORK.

3. What is the ratio of brightness of Betelgeuse to the Sun, as measured at the Earth? The brightness of the Sun as seen from Earth is 1400 W/$m^2$. SHOW ALL YOUR WORK.

4. From your measurement of the luminosity of an average candle, what is the absolute “candlepower” of the Sun? (The Sun’s luminosity is equivalent to how many candles?)