Lab 1: The Surface of the Sun

Purpose

These experiments will familiarize you more with our Sun, specifically we will investigate how large the Sun is and what the temperature on the surface is. You will use geometric principles and physical relations to derive each of these properties.

Warning! Need we tell you that the light of the Sun is very intense? At no time here or elsewhere should you attempt to look directly at the Sun through a lens or any other instrument. Never stare at the Sun with the naked eye. Failure to observe such precautions can result in the creation of a permanent blind spot on the retina of your eye! Observation of the image of the Sun on a screen, however, as we do in this experiment, is perfectly safe.

How Big Is The Sun?

Angular size is simply the angle that something subtends, or spans, in the sky. By combining this with the distance to the object, you can calculate the true size of that object, even at huge distances.

The Sun, as the prime source of light and heat in our world, is often, understandably, elevated to the status of a deity. It is no surprise, then, that people as long ago as the classical ancient Greeks, wanted to learn as much as possible about the Sun. Primarily, they asked a fundamental question: "How Big Is The Sun?"[a]

In 434 BC, Anaxagoras, a Greek philosopher and astronomer, suggested that the Sun was a ball of molten rock as large as the Greek peninsula. Later, in the 3rd century BC, Aristarchus, another early astronomer, concluded that the Sun was at least as big as the entire Earth. After another century, yet another estimate of seven times the diameter of the Earth was calculated by Hipparchus, who we learn more about later in the class with the magnitude system. So, why the disagreement? As previously mentioned, in order to calculate the size, we need to accurately constrain the *distance* to the Sun! It was not until 1672 AD, over 1800 years later, that the Italian astronomer Giovanni Cassini, who now had the use of telescopes, arrived at what we would regard as a "reasonable" value for the distance of the Sun.

In our experiment, we will assume that we know the distance of the Sun, since it has been well constrained since Cassini's time, and use some simple geometry to calculate its diameter. Since we have a more accurate distance, our results will be much better than those of the famous Greeks, and may even improve on Cassini's, whose error, we know today, was about 10% of the true value. We will use a rudimentary solar telescope rather like the device illustrated in Figure 1.1. The principle of the solar telescope is shown in Figure 1.2: a lens, positioned at the high end of the telescope, forms an image of the Sun on a screen at the other end of the telescope. The distance from the lens at which the image is most resolved is f, more often called the focal length of the

[a]Though they probably said it in Greek

Figure 1.1: Astronomers observing a solar eclipse. The image of the sun is projected upon a screen and the limit of the obscured portion carefully recorded. From Heveluis's *Machina Coelestis*

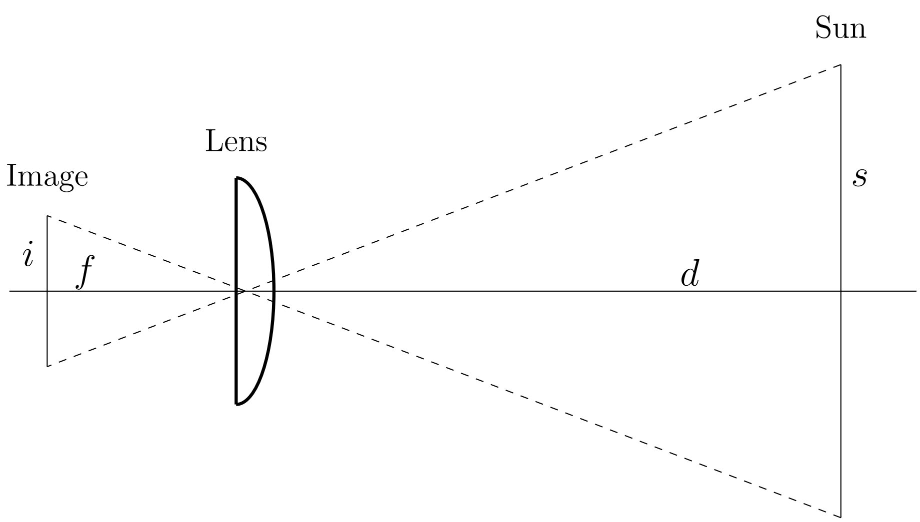


Figure 1.2: Similar triangles set-up to calculate the diameter of the Sun

lens. Once the image is fully resolved, an image of diameter i is created on the plate. Since the triangles on either side of the lens are similar triangles, meaning that they are the same shape but a different size, we can write a relationship between their side lengths:

$$\frac{i}{f} = \frac{s}{d}$$

where s is the diameter of the Sun and d is the distance to it. Since we can measure i and f in the laboratory, and d is now well-known (1 Astronomical Unit), we can readily solve for s.

How Hot Is The Sun?

Another fundamental question about the Sun is: "How Hot Is The Sun?". While, in truth, the Sun's temperature varies within, there exists a concept of an "effective temperature" for stars. This effective temperature simply corresponds to the temperature at the surface of the Sun. So a more precise question for this section might be: "What physics sets the effective temperature of the Sun?", though this is a *much* less punchy title.

To understand this concept, we need to introduce reflectivity, or albedo, of an object. An object's albedo is the fraction of light it reflects, thus it ranges from 0 to 1, where an albedo of 0 means that 0% of the incident light is reflected, and an albedo of 1 means that 100% of incident light is reflected. You probably have intuition about this very effect. If you've ever tried to read a book outside on a nice, sunny day, you've probably noticed that the pages are very bright to look at without sunglasses. Yet, looking at the grass and ground around you, it appears less bright. This is because white paper has a very high albedo (0.7), it reflects most of the incident light, while grass and soil have much lower albedos (0.25 and 0.17, respectively).

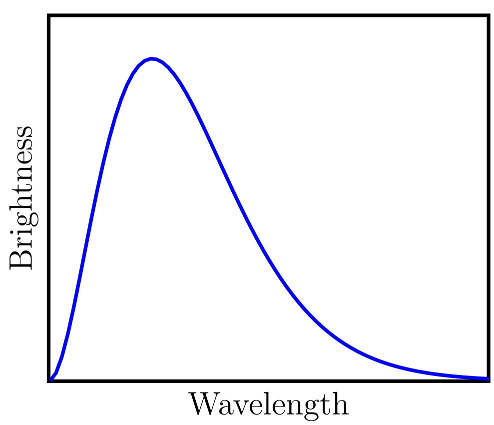


Figure 1.3: Blackbody spectrum

Every object with a non-zero (Kelvin) temperature emits electromagnetic radiation (light) because of its internal heat: you, your pet, the Earth, stars, this page, etc. When an object emits light only due to its internal heat and absorbs 100% of the incident light on it (i.e., an albedo of 0), we call that object a perfect blackbody (often referred to as simply a blackbody). "Perfect" indeed implies an idealized construct. There are no such objects in nature. However, some, like the Sun, are very close so that referring to them as blackbodies is a quite useful approximation.

Figure 1.3 shows the spectrum of a blackbody, the brightness as it continuously varies with wavelength. Notice that the blackbody spectrum peaks in brightness at a certain wavelength. The position of this peak depends only on the temperature of the object. The relationship between the peak emission and temperature of the emitting body is known as Wien's displacement law:

$$\lambda_{\max} = \frac{b}{T}$$

where b is just a constant of proportionality. Since temperature is inversely proportional to the peak wavelength, hotter objects have blackbodies with shorter peak wavelengths. In other words, hotter objects are "bluer".

Since blackbody radiation effectively tells us about the temperature of an object based only on its "color" (wavelength of light), it is particularly useful when applied to stars. So, by examining the light that the Sun gives out, we can deduce the effective temperature of the Sun.

Laboratory Procedure

You are entering the world of observational astronomy, not unlike the one shown in Figure 1.1. One of the persistent problems of this world is that you cannot observe an object unless it is visible. If there are intermittent clouds, you will likely be able to make your observations, which should take only 10 or 15 minutes, but if the cloud cover is continuous you will be unable to work.

You are provided with a rudimentary solar telescope. Position the instrument as directed by the instructor and point the lens toward the Sun. Again: Do not attempt to look through the lens! Maneuver the telescope until the image of the Sun falls on the white screen near the lower end of the instrument. Slide the screen back and forth until the image is at its smallest and sharpest; here you are "focusing" the telescope. Now use the provided millimeter scale to measure carefully the diameter i of the image. This is the most critical part of the experiment! Each person should make several measurements and average them to yield the best result. Next, use a meter-stick to measure the distance f from the lens to the screen. Record all of your data.

You have been provided with a second lens for the telescope, which will yield a different image size. Repeat the experiment with this second lens in place, again recording all data.

You are also provided with a pinhole that can be substituted for the lenses. Put it in place on the telescope and note that it yields a faint but reasonably sharp image of the Sun. The camera obscura, in which images were formed by pinholes, was known to the Arabs as early as 1000 A. D., long before the invention of telescopes with lenses. Does your pinhole have a focal length? Measure the diameter of the image for at least three different distances between the pinhole and the screen. How does the size of the image relate to the distance between the pinhole and the screen?

If you are fortunate enough to be observing when the Sun is active, you may be able to see sunspots in your images. Galileo first observed sunspots in 1611, and you'll learn more about them in Lab 2: the Atmosphere of the Sun. The solar disk shows "limb darkening", meaning that the edge of the disk is not as bright as the center, because at the edge or limb you are seeing a higher, cooler layer of the Sun's atmosphere. Can you see this effect in your images?

Blackbody Radiation

In this experiment, we will determine the blackbody spectrum by matching curves of different temperatures, a simplified approach to the way real astronomers can determine such temperatures.

Using the lab software:

- Input the desired wavelength into the box at the top of the page. Press `Plot` and a blackbody radiation curve corresponding to that peak wavelength will appear in the plot.
- Use the slider to adjust the green curve to find the temperature that best fits the blackbody emission that you just generated.
- Rinse and repeat for all the desired wavelengths.

The Surface of the Sun Worksheet

Name: ______________________ **Date:** ____________ **Section #:** ______

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

For this experiment, you will be using two lenses (A and B) of different focal lengths as well as a pinhole. Focus the image of the Sun and measure the distance f between the lens and the image (focal length of the lens). Measure the diameter i of the image. Repeat this step three times and repeat with the second lens.

Lens A

Measurement No.	f (cm)	i (cm)
	$f_{\text{avg}} =$	$i_{\text{avg}} =$

Data Table 1.1

1. Calculate the value of the diameter of the Sun, s, using the calculated averages of the focal length, f, and the image size, i. For the mean distance to the Sun, use the value $d = 1.496 \times 10^8$ km

$$s_A = d\left(\frac{i_A}{f_A}\right)$$

2. Calculate the percent error for your calculated value of s with the accepted value of 1.392×10^6 km

$$\%_{\text{error}} = \frac{s_A - s_{\text{accepted}}}{s_{\text{accepted}}} \times 100$$

Lens B

Measurement No.	f (cm)	i (cm)
	$f_{\text{avg}} =$	$i_{\text{avg}} =$

Data Table 1.2

3. Again, calculate the value of the diameter of the Sun, s, using the calculated averages of the focal length, f, and the image size, i. For the mean distance to the Sun, use the value $d = 1.496 \times 10^8$ km

$$s_B = d\left(\frac{i_B}{f_B}\right)$$

4. Calculate the percent error for your calculated value of s with the accepted value of 1.392×10^6 km

$$\%_{\text{error}} = \frac{s_B - s_{\text{accepted}}}{s_{\text{accepted}}} \times 100$$

5. Using the calculated mean values of the focal length for **each** lens, calculate the power of the lenses in diopters. (Don't forget to convert the focal length to meters!)

$$\text{Power [diopters]} = \frac{1}{f \text{ [meters]}}$$

Pinholes

Measurement No.	Distance (cm)	Diameter (cm)

Data Table 1.3

Questions

Answer the following questions, be sure to clearly explain you answers

6. Which of the two values of i should have the largest relative experimental error and why? (Hint: think about the tools we used to measure them)

7. How does the percentage error of your experimental values of s compare to the Cassini experimental error of 10%

8. How do you interpret the sign (positive/negative) of your percentage error of the value of the diameter of the sun?

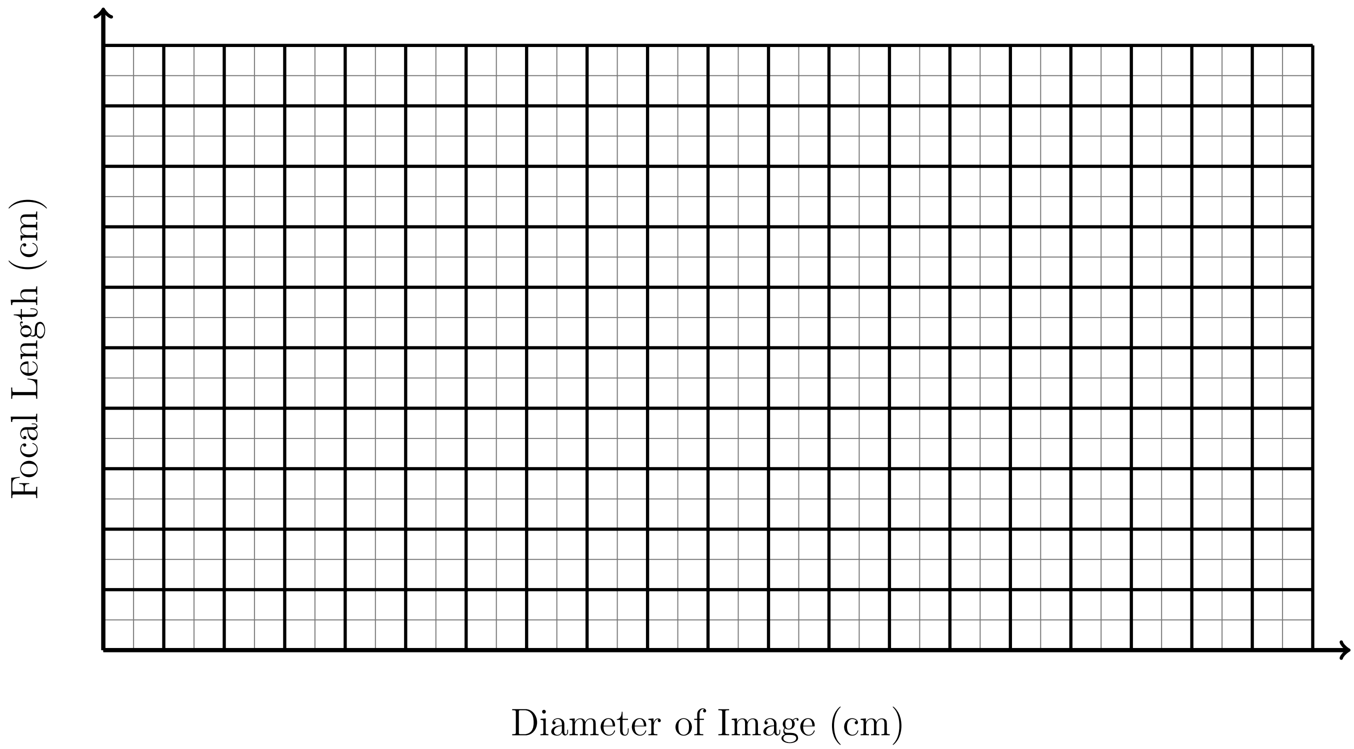
9. Which of your two experimental values for the diameter of the sun depart more from the accepted value? Is this consistent with what you found in question 6?

10. Plot all of your data points for Lens A and B on the first plot. How does the size of the image change when we change the focal length?

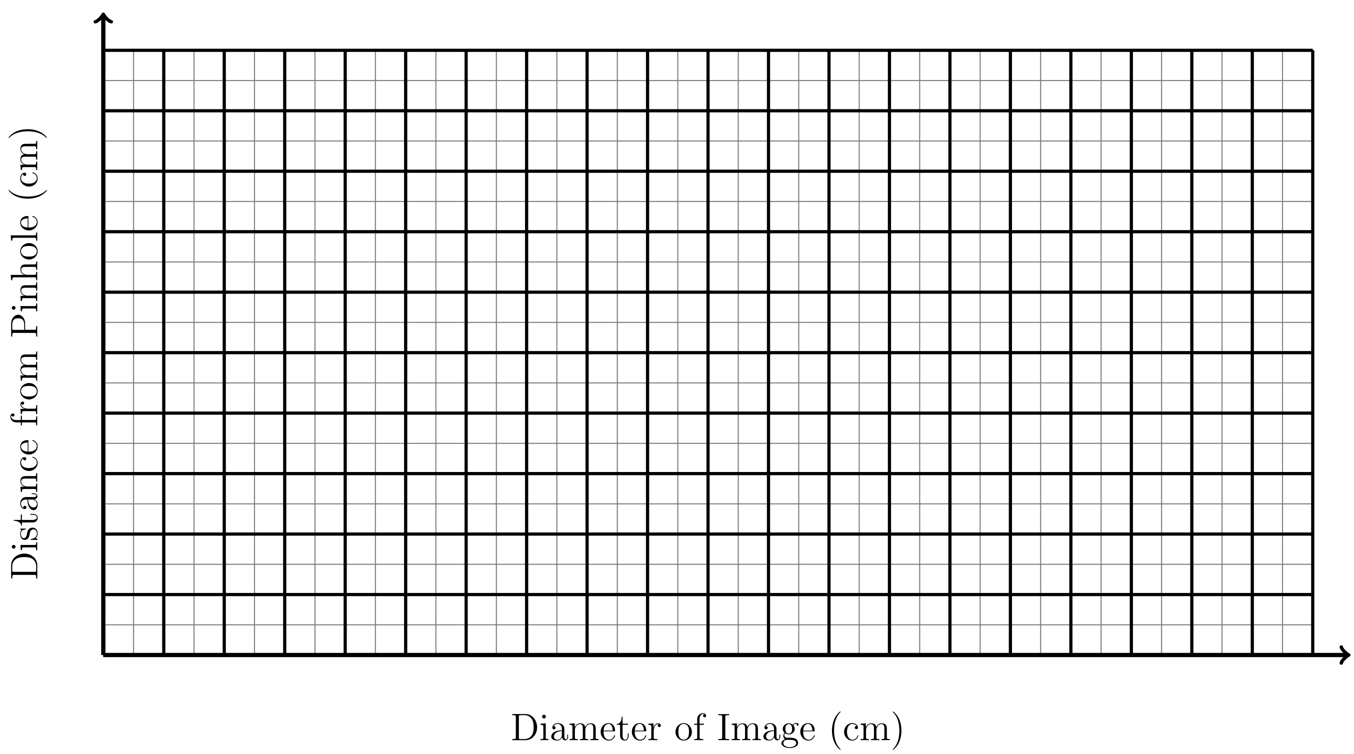
11. Use the plot of size of the image versus focal length of the lens. If you are asked to design a telescope that can produce an image of the sun of 1.4 cm in diameter, what would be the focal length of the lens that you will choose?

12. Plot your data for the pinhole on the second plot. How did the sizes of the images obtained with the pinhole relate to the distance from the pinhole?

Plots



Graph 1.1



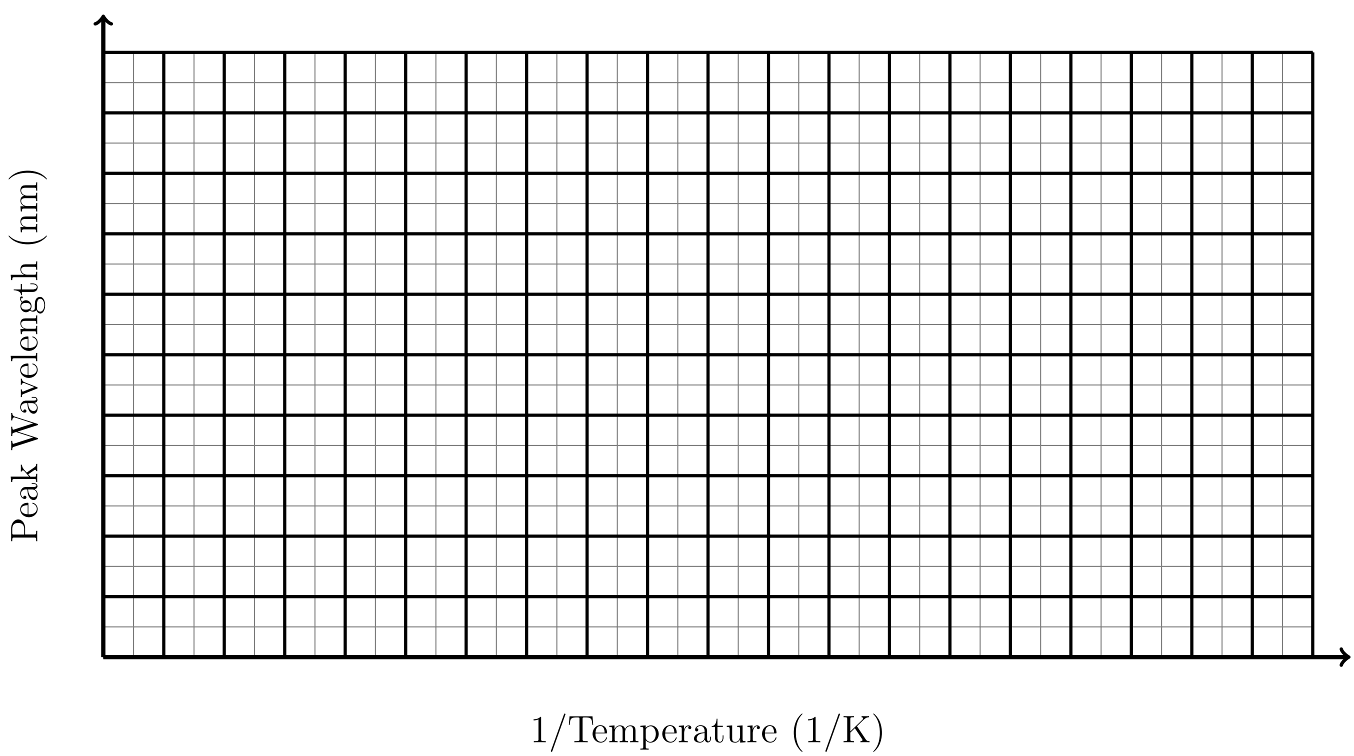
Graph 1.2

Blackbody Radiation

For this next experiment, we will reconstruct Wien's Law

Data Table 1.4

Peak Wavelength (nm)	**Temperature (K)**	**1/Temperature (1/K)**
300		
350		
400		
450		
500		
550		
600		
650		
700		



Graph 1.3

13. Draw a best-fit line for the data points. What is the slope, using rise over run ($\Delta y/\Delta x$), of this best-fit line?

14. Ask your instructor for the actual value of b from Wien's Law. Calculate the percent error of b to ascertain the accuracy of the best-fit line. What are a potential sources of error?

15. Numerically solve for the peak wavelength of the Sun (given that temperate of the photosphere of the Sun is 5,800 K) using the true form of Wien's Law. Now, use your best fit line you derived in Question 13 and compare this value to the one you calculated. What is the percent error?