Sunspots and the Solar Rotation

Introduction

Humans have noticed dark spots on the surface of the Sun for thousands of years. The first written record of sunspots was made by Chinese astronomers in 364 BC, and Chinese astronomers regularly recorded sunspot observations starting in 28 BC. These naked eye observations were quite difficult, and we know today that only the largest sunspots (diameters greater than about 40 arc seconds) can be seen with the naked eye. **You should never try to observe the Sun directly, as doing so can lead to blindness!** Modern observers of the Sun always use special filters to reduce the glare and safely observe the Sun.

Europeans did not know about the observations of sunspots by Chinese astronomers. The ancient Greeks thought that the heavens were perfect and unchanging. A spot observed on the Sun would imply that the Sun changed and was not perfect. Hence, there is little record of European observations of sunspots prior to the seventeenth century. A sunspot observed for 8 days in March 807 by an advisor to Charlemagne, was interpreted as a transit of Mercury. The first serious study of sunspots in Europe did not occur until after the invention of the telescope. Sunspots were first observed through a telescope in late 1610 in Europe. A lively scientific debate ensued as European astronomers debated the nature of spots on the Sun. The German Jesuit Christoph Scheiner started observing sunspots in March 1611 and wrote a letter to his friend Marc Welser in January 1612. Jesuits were conservative on cosmological issues, and insisted that the heavens, including the Sun were perfect. As a result, Scheiner hypothesized that sunspots were shadows created by planets crossing the disk of the Sun.

During the summer of 1612 Galileo observed the Sun on most clear days. Galileo used his telescope to project an image of the Sun, so that he could safely view the projection (note carefully that he did **not** look through his telescope directly at the sun). He made detailed drawings of his observations, an example of which is shown on the next page. Galileo concluded that sunspots were features on the surface of the Sun and that the Sun was rotating. This contradicted the prevailing cosmological view, in place since Aristotle’s time, that the Sun was perfect and unchanging.

In response to the observations made by Scheiner, Galileo wrote several letters to Mark Welser in the fall of 1612. Galileo describes his observations of sunspots and his interpretation of them as surface features on a rotating Sun. He made a number of arguments as to why the sunspots must be on the surface of the Sun, and not due to shadows of planets passing in front of the Sun. These included *"First, to see twenty or thirty spots at a time move with one common movement is a strong reason for believing that each does not go wandering about by itself. . . ”* and

*To begin with, the spots at their first appearance and final disappearance near the edges of the sun generally seem to have very little breadth, but to have the same length that they show in the central parts of the sun’s disk. Those who understand what is meant by foreshortening on a spherical surface will see this to be a manifest argument that the sun is a globe, that the spots are close to its surface, and that as they are carried on that surface toward the center they will always grow in breadth while preserving the same length.*
In this lab, you will (1) directly observe the Sun using a special filter (safely recreating the observations of ancient Chinese astronomers), (2) observe the Sun using a telescope to project an image of the Sun and sketching the image (recreating Galileo’s observations), (3) use a special solar telescope to observe the Sun, (4) verify that sunspots change their apparent shape as they rotate across the surface of the Sun, (4) determine if sunspots share a common movement, (5) measure the location of sunspots as a function of time to determine the solar rotation rate and (6) determine the range of sizes of visible sunspots and the number of sunspots which are visible on the Sun on a given day.

The lab is done in two parts. The solar observing will take place on the hill behind Wilder Lab, near the campus observatory. The detailed study of the sunspots will utilize images of the Sun.
taken by the Solar Dynamics Observatory (currently orbiting the Earth with a nearly continuous view of the Sun) and will be done using the computers in room 200 Wilder. **The pre-lab questions are due on Wednesday, May 13.**

### References

Review section 9.4 in your textbook (‘*Investigating Astronomy*’) before coming to the lab.

### Solar Observing

Solar observing will occur on a sunny day, instead of a lecture or quiz. An e-mail announcing solar observing will be sent to you about 15 minutes before our class is scheduled to start. The observing will be done in two sections; if you are signed up for an afternoon observing section, they will do the solar observing first, at the start of our regularly scheduled class time. If you are in an evening lab section, you will start observing 30 minutes after the start of class. On the day of solar observing, do not go to the lecture hall, but instead go directly to the hill behind Wilder lab. Bring a pen, pencil, paper to record your observations and a camera (cell phone is fine). If you do not have a camera, do not worry as you will work in groups of two and only one camera is needed per group.

**AGAIN: Never directly look at the Sun with your naked eye. This can lead to blindness.**

You will observe the Sun in three different ways, and the order that you do these observations is not important.

1. **Direct Observations:** Obtain a pair of solar viewing glasses (“eclipse shades”) from the TA. These glasses contain a special filter which makes it safe to view the Sun. Put the glasses over your eyes and look at the Sun. Do you see anything on the surface of the Sun? If so, record your observations in words. Briefly describe what you see, indicating the sizes, locations, colors, etc of anything you see. Make a sketch of your observation (using the attached data sheet), showing the Sun as the circle and drawing any features you see.

2. **Direct Observations using a Solar Telescope:** The solar telescope is equipped with a special filter, centered on the Hydrogen-alpha line. This allows you to clearly observe surface detail, and prominences on the Sun. We only have one solar telescope, so you will need to take turns using the solar telescope, which the TA will operate. When you are at the telescope, carefully sketch what you observe, using the data sheet included at the end of this lab manual.

3. **Observing the Sun in Projection:** We have 15 refracting telescopes (Figure 2) which can be used to observe the Sun in projection. Each group of two students will use their own telescope to observe the Sun.

Using the paper clips, put a folded piece of paper onto the paper holder. Extend the silver tube at the end of the telescope so that you are close to focus (as in Figure 2). Loosen the screw at the base of the telescope (circled in white in Figure 2), so that the telescope moves freely, and point
the telescope at the Sun. Do not look through the telescope! You can tell if you are pointed at the Sun by looking at the shadow of the telescope. You want the shadow of the telescope to be visible on the paper holder, as in Figure 2. Once you see the shadow on the paper holder, tighten the screw so the telescope is fixed. The round knobs near the base of the telescope move the telescope by small amounts and are used to center the image of the Sun in the middle of the telescope shadow. Rotate the focus knob near the eyepiece until you see a sharp image.

Take a picture of the projected image of the Sun, ensuring that the image of the Sun takes up most of picture. After taking the picture, carefully trace the image onto the paper.

Figure 2: Refracting telescope set up to view the Sun in projection.
Sunspots & the Rotation of the Sun

You will work in pairs for this part of the lab. You and your lab partner will download visible light images of the Sun taken over the course of the previous 15 days and analyze these images to study sunspots and their motion.

When examining the images of the Sun, it is important to remember that although the Sun is a sphere, it appears as a flat, 2-dimensional disk since it is so far away. When a sphere is projected onto a 2-dimensional surface, then the image is distorted. The regions near the edge of the sphere are not face on to us and objects near the edge are foreshortened. This is illustrated by the longitude-latitude grid in Figure 3. Galileo used the observed foreshortening of sunspots to successfully argue that sunspots were located on the surface of the Sun.

Figure 3: A longitude-latitude grid of the solar disk (as viewed in May, when the Earth is 3 degrees below the solar equator). The longitude (vertical lines) and latitude (horizontal) lines are spaced a constant 10 degrees apart. The lines get closer together near the edge of the disk due to the foreshortening which occurs when viewing a distant spherical surface.
Procedure

1. Go to the Solar Dynamics Observatory (SDO) web page (bookmarked in the lab computers) and click on ‘AIA/HMI Browse Data’ (on the left menu). Download the previous two weeks of visible light observations. The visible light images you should examine are labeled ‘HMI Intensitygram (orange)’ in the ‘Telescopes’ pull down menu on the web page. Click ‘Frames’ for the display option and a resolution of 2048x2048. The visible light images are obtained every 15 minutes (with an occasional gap), so select every $\approx 96^{th}$ image (nth = 96 on the webpage) to download one image per day.

   The images are downloaded as a tar file, which you will need to open and click down through a number of directories before you get to the images. The image filenames start with the year and date of the observation, followed by the UT (universal time) of the observation.

2. Examine the images, starting with the oldest. Notice that the spots on the Sun move from day to day. Find a single spot which is near the edge of the Sun on one image and near the center of the Sun on another image. Print out the two images and label your chosen sunspot on the printed image. Open each image using the ‘Paint’ program and carefully measure the length and width of the sunspot on each image. Note that a large sunspot consists of a central dark area, the umbra and the surrounding lighter penumbra. For this part of the lab you should measure the height and width of the entire sunspot, including the penumbra.

   Zoom in on the sunspot to make your measurement more accurate. Make sure you use the same Zoom factor when examining each image. You can measure the height and width in pixels (displayed in the bottom right corner of ‘Paint’, or in mm using the clear ruler). Record your data, including an estimate of the uncertainty in your data.

3. Repeat your height and width measurements for a different sunspot.

4. Find a pair of images five or six days apart where you can clearly observe a sunspot near the center of the solar disk. Print out the images and label your chosen sunspot. Using the PictureMerge program on the lab computer, overlay the longitude-latitude grid onto each of your images. Carefully measure the longitude and latitude of your chosen sunspot in each of the images. Zoom in on the image, and use the clear rulers to obtain an accurate measurement of the position of the center of your chosen sunspot. Record your data, including an estimate of your measuring uncertainty. Record the time and date each image was taken as part of your data sheet. The time and date are shown on the bottom left corner of each image.

5. Repeat your central longitude-latitude measurements for two other sunspots.

6. From the SDO data page download the 2048x2048 visible light image which was obtained closest in time with your observation at the telescope. Our observations occurred around noon EDT (16:00 UT), and you can download images for a time period of of about 1 hour centered around your observation to find the the image which is closest in time to when you did your observation. If you have not yet done the solar observing, then do this part of the lab on your own computer after you have completed the solar observing.

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1We are currently on Eastern Daylight Time, and UT = EDT - 4 hours.
Print out the SDO image, and compare to your projected sketch and picture of the Sun. Label the features (with letters) in common between your sketch of the Sun observed in projection, and the SDO image. Refer to these labels when answering the questions below.

Overlay a longitude/latitude grid onto the SDO image. Carefully measure the height and width in degrees and pixels of the penumbra and umbra of the largest and smallest sunspot you can see. Zoom in on the sunspot to make your measurement more accurate. Record the height, width and label for each sunspot you measure. Include an estimated uncertainty for the height and width measurements. If you can’t distinctly see the penumbra and umbra, just measure the total height and width of the sunspot and note this fact on your data sheet.

Measure the diameter of the Sun in pixel units and record your data. Take this measurement twice, once in the horizontal direction and once in the vertical direction. Average these two numbers together, and use the difference in the two numbers to estimate the uncertainty in your measurement.

Carefully examine the image on the computer (zooming the image as needed) and identify all of the sunspots on the image. Circle the sunspots on the printed image. If you see a number of sunspots which are close together and not fully distinct, label them with a ‘G’ for group.

**Analysis**

**Solar Observing: Question 1:** Compare the three sketches you made of the Sun (direct observation, with the solar telescope and projected image), and discuss the similarities and differences between the different ways of viewing the Sun.

**Q2:** Compare the photograph you made of the projected image of the Sun to your sketch, commenting on the similarities and differences. Which one allows you to see more detail?

**Q3:** Discuss the similarities and differences between your sketch and the SDO image. What cause(s) these differences?

**Foreshortening: Q4:** How does the height and width of a sunspot vary as it moves across the face of the Sun? Does your data support the idea that sunspots are foreshortened near the edge of the Sun? Explain your answer, and what it implies about sunspots.

**Sunspot sizes & Numbers:** Determine the height and width in kilometers of the two sunspots whose size you measured in degrees. To convert your angular measurements to kilometers, recall that the Sun has a radius of 695,980 km and hence a circumference of $4.373 \times 10^6$ km. Lines of latitude are parallel so that the distance between each degree remains constant. Given that there are 360 degrees in a sphere, this implies that one degree in latitude on the Sun is 12,150 km. Lines of longitude converge at the poles, as a result

$$\text{length of one degree of longitude} = \cos(\text{latitude}) \times 12,150 \text{km}.$$ 

**Q5:** How do the sizes of the sunspots you measured compare to the size of the Earth? Be quantitative in your answer.
Q6: Astronomers estimate that a naked eye observer with good vision can see sunspots whose umbral diameters, as seen on the plane of the sky, are greater than 40 arc seconds. Determine the size in arc seconds of the umbra of the sunspots whose sizes you measured in pixels. To convert your measurements of the size of the sunspots from pixels to arc seconds, determine the scale of the SDO image by using your solar diameter measurement and the fact that the current angular diameter of the Sun is 1897 arc seconds.

Are any of the sunspots on the SDO image bigger than 40 arc seconds? If so, were you able to see these sunspots when you directly observed the Sun using the solar viewing glasses? If you should have seen the sunspots, but did not, why?

The number of sunspots varies with time, and a number of researchers have attempted to look for long term trends in the sunspot number by examining the records recorded by Chinese astronomers over the last 2000 years. Do you think such an analysis would yield reliable results?

Q7: Since the 1700’s astronomers have been recording a daily sunspot number. In 1848, the daily sunspot number $R$ was defined to be

$$R = k(10g + s)$$

where $g$ is the number of sunspot groups (regions), $s$ is the total number of individual sunspots in all of the groups on the solar disk and $k$ is a variable scaling factor that takes into account observing conditions and experience of the observer.

Look up the official daily sunspot number (for the day that the image you analyzed was obtained by SDO) at [http://www.sidc.be/silso/datafiles](http://www.sidc.be/silso/datafiles). You can download either a plain ASCII text file (click on TXT1), or a file that can be important into MS Excel (click on CSV). In either file, column 1 is the calendar date (in format YYYYMMDD), column 2 is the date in fraction of the year and column 3 is the daily sunspot number. You can ignore column 4. The data starts in 1818, and you will need to go to the end of the file to find the current sunspot numbers.

Calculate $k$ for your data. What does your value of $k$ imply about how you counted sunspots, to those counted by experienced observers who use the SDO data set for the same purpose for whom $k = 0.6$?

**Solar Rotation:** Calculate the angular velocity for each your sunspot longitude-latitude measurements. The angular velocity of a spot is the distance in degrees (of longitude, or latitude) it travels in a given period of time (hours, days; whichever unit you are working with):

$$\text{angular velocity} = \frac{\text{distance in degrees}}{\text{period}}$$

Use days for time when calculating the angular velocity (remember that 1 hour = 1/24 of a day).

Calculate the uncertainty in each of your angular velocity measurements using the uncertainties in your observed longitude/latitude measurements.

Q8: Do your 3 separate angular velocity measurements agree with each other? Explain why or why not.
Average together your three individual angular velocity measurements. Estimate the uncertainty in your averaged angular velocity by using the difference between your largest and smallest individual angular velocity measurements.

Use your average angular velocity measurement to calculate the synodic rotation period of the Sun from your data. The angular velocity for a sunspot tells you how many degrees around the sphere of the Sun the spot traveled in a day. The period of time it will take a given spot to travel all the way around the Sun once (the Sun’s rotation period) is simply the full 360 degree rotation divided by the spots angular velocity:

\[
\text{period of rotation} = \frac{360 \text{ degrees}}{\text{angular velocity in degrees/day}}
\]

**Q9:** Does your answer agree with the known synodic rotation period (at a latitude of 26 degrees) of 27.28 days? Explain why or why not.

The rotation period you determined is how long it takes a sunspot to return to the same point on the Sun as viewed from the Earth. Since the Earth is orbiting the Sun, this will be longer than the time it takes the Sun to rotate 360 degrees on its axis as viewed from a fixed point in space (the sidereal rotation rate). Figure 1–24 (page 21) in your textbook (which discusses the sidereal and synodic lunar months) illustrates the concept. The sidereal period \( P_{sid} \) is related to the synodic period \( P_{syn} \) by the equation

\[
P_{sid} = \frac{P_{syn}}{1 + P_{syn}/365.25}
\]

where \( P_{sun}/365.25 \) is the fraction of a year the Earth moves in its orbit during one synodic solar rotation.

**Q10:** Using your data, what is the sidereal rotation rate of the Sun?

**Writing up the Lab**

Make sure your names are on your data sheet, and have the TA or the professor sign your data sheet before you leave the lab. If you and your partner are handing in individual lab reports, one of you will hand in the original data sheet, while the other student can hand in a photocopy.

**Lab reports are due one week after you complete the lab.**

Follow all of the guidelines for lab reports which are posted onto Canvas. Aside from your data sheets, you must use complete sentences throughout your report.

Lab reports are to be put into the A1 box which are located to the left of the main stairs when you enter Wilder Lab.
Pre-Lab Questions

Due Date: Wednesday, May 13 in class.

The answer to all these questions can be found in your textbook and the lab itself. The pre-lab questions will account for 15% of your lab grade. By reading the lab and thinking about it in advance of performing the lab, you will find that the lab makes much more sense when you start collecting data.

1. Describe two observations made by Galileo which proved that sunspots are on the surface of the Sun, and not the shadows of planets passing in front of the Sun.

2. What could happen to you if you look directly at the Sun? Do you look through the refracting telescope? How do you point the refracting telescope at the Sun?

3. What are the two parts of a sunspot?

4. If I measure an angular velocity of 12.0 degrees/day, what is the rotation period?

5. If I measure a synodic period of 26.7 days, what is the sidereal period?
Appendix: Analyzing the SDO image on your own computer

Go to the Solar Dynamics Observatory (SDO) web page and click on ‘AIA/HMI Browse Data’ (on the left menu). Download the 2048x2048 visible light image, ‘HMI Intensitygram (orange)’ which was obtained closest in time with your observation at the telescope. Our observations occurred around noon EDT (16:00 UT), and you can download images for a time period of about 1 hour centered around your observation to find the image which is closest in time to when you did your observation.

In the lab area in the Canvas course web site, download the solar longitude/latitude grid.

To overlay the two images go to http://pixlr.com/editor/ and do the following:

1. Open the SDO image.
2. In the top menu bar, click Layer > Open Image as Layer. Choose the longitude/latitude grid.
3. In the Layer Editor (right side of screen), Click the Toggle Layer Settings Icon in the bottom left, and adjust the opacity of the longitude/latitude grid to a low value.
4. Choose the Move Tool (top right icon in the ‘Tools’ panel on the left side of the screen) and carefully adjust the location of grid so that it correctly matches the solar sphere.
5. Use the navigator panel (right side of screen) to zoom into different areas of the image as needed. The navigator panel displays the x,y coordinates of the cursor, which is useful for measuring the pixel sizes of features.