1 Introduction

Sunspots are regions on the solar surface that appear dark because they are cooler than the surrounding photosphere, typically by about 1500 K. They still have a temperature of about 4500 K, but this is cool compared to the rest of the Sun’s photosphere. They are only dark in a relative sense; a sunspot removed from the bright background of the Sun would glow quite brightly.

1.1 Basic Features of Sunspots

The largest sunspots observed have had diameters of about 50,000 km, roughly 4 times the size of the Earth, which makes them large enough to be seen with the naked eye. Sunspots often come in groups with as many as 100 in a group, though sunspot groups with more than about 10 are relatively rare.

Sunspots develop and persist for periods ranging from hours to months, and are carried around the surface of the Sun by its rotation (a fact known to Galileo). Figure 1 show a single sunspot and a complex sunspot group. A typical sunspot consists of a dark central region called the umbra and somewhat lighter surrounding region called the penumbra.

Figure 1: Sunspots can appear as single spots or in complex clusters. The shape and size of a sunspot is not constant and may change quite rapidly—over a span of hours.

1.2 The Solar Rotational Period

Historically, the first measurements of the period for solar rotation were made by tracking sunspots as they appeared to move around the Sun. Galileo used this method to deduce that the Sun had a rotational period of about a month. Because the Sun is not a solid body, it does not have a well defined rotational period. Modern measurements indicate that the rotational period of the Sun is about 25.1 days near its equator, 28 days at 40 degrees latitude, and 34.4 days near the poles. This rotation is in the same direction as the motion of the planets around the Sun.

1.3 Sunspot Numbers

In 1610, shortly after viewing the sun with his new telescope, Galileo Galilei made the first European observations of Sunspots. Continuous daily observations were started at the Zurich Observatory in 1849 and earlier observations have been used to extend the records back to 1610. The sunspot number is calculated by first counting the number of sunspot groups and then the number of individual sunspots.

The “sunspot number” is then given by the sum of the number of individual sunspots and ten times the number of groups. Since most sunspot groups have, on average, about ten spots, this formula for counting sunspots gives reliable numbers even when the observing conditions are less than ideal and small spots are hard to see. Monthly
averages of the sunspot numbers show that the number of sunspots visible on the sun waxes and wanes with an approximate 11-year cycle.

![DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS](image)

Figure 2: A single sunspot tracked over the face of the Sun.

Detailed observations of sunspots have been obtained by the Royal Greenwich Observatory since 1874. These observations include information on the sizes and positions of sunspots as well as their numbers. These data show that sunspots do not appear at random over the surface of the sun but are concentrated in two latitude bands on either side of the equator. Figure 2 is called a “butterfly diagram.” It shows the positions of the spots for each rotation of the sun since May 1874. These bands first form at mid-latitudes, widen, and then move toward the equator as each cycle progresses.

2 Procedure

1. Download and unzip the SOHO images from the class website.

   Download the images from:
   

   Note the location of the folder where you have downloaded and unzipped the images.

2. Open the program Tracker and load the entire image series into Tracker as frames of a movie.

   From Tracker’s menubar, select Video > Import... and navigate to directory with the images you’ve just downloaded. Open the first image file, 20121215_017.jpg. This corresponds to a SOHO image taken at midnight on January 1, 2013. Since the files in this directory are sequentially numbered, each representing a picture of the Sun taken at midnight each sequential day—20121215_018.jpg, 20121215_019.jpg, etc.—Tracker will load them all. Press the green play button, ▶, to verify that all of the images have loaded.

3. Set the time Δt between frames to 1 second.
Right click on the video or on the video control slider and select the Clip Settings menu item. Set the Frame dt option to 1s. This displays each frame of the movie for one second, but be aware that the time between images is actually 1 day. With the 30-ish images we’re using in this lab, it means that the time frame over which we’re measuring sunspots is a little over one month long.

4. Set the origin of the coordinate system.

Select the coordinate axes icon, $\begin{array}{c}\text{i}\\\text{j}\end{array}$, to overlay $x$-$y$ axes on the images. Click on the point where the $x$- and $y$-axes intersect and drag the coordinate axes to the center of the Sun, as shown in Figure 3(a).

5. Set the scale of image.

Click on the calibration tools icon, $\begin{array}{c}\text{i}\\\text{j}\\\text{k}\end{array}$, and select New > Calibration Stick. Drag each of the ends of the stick to one edge of the Sun along the $x$- or $y$-axis. Set the length of the calibration stick to the diameter of the sun by clicking the stick’s current value of 100 to 2—as in 2 solar radii, as shown in Figure 3(b).

6. Pick a sunspot and track its position over the time.

Click the Create a new track icon, $\begin{array}{c}\text{Create}\\\text{mass} A\end{array}$, and select Point Mass. By default, the Track Control window will call this new track mass A. Right-click on the mass A name, select Name..., and change its name to Sunspot A. You can also change the tracking icon’s color by right-clicking on the name and selecting Color...

Find an easy sunspot to track that maintains its shape as it crosses the Sun. It is best to pick one that is somewhere to the left of the $y$-axis. You may want to right-click in the video to Zoom In or Zoom Out to aide your view of the sunspot. Hold down the Shift button as you click on the sunspot to begin tracking it. Tracker will step forward to the next image so that you can continue tracking the position of that sunspot for the entire sequence. You may start or stop tracking at any frame, so you do not need to choose a sunspot that is visible at the start of the image sequence. Track the sunspot until it rotates out of view. Figure 4 shows an example of one sunspot.

7. Use Tracker to calculate the $x$-position of the sunspot in each frame.

We are only interested in the $x$ position of the sunspot. The graph already shows this: $x$ vs. $t$, but the table does not. On the data table, click on the Table button, $\begin{array}{c}\text{Table}\\\text{mass} A\end{array}$. In the dialog box, deselect $y$. Close the dialog box.

8. Use Tracker to do data analysis of $x$-positions of the sunspot.

Right-click on the cells of the data table and select Analyze.... Tracker’s built-in data tool will open. In this
tool, click the Analyze button at the top, and select Curve Fit. A new display will appear at the bottom of the window, as seen in Figure 5(a). Select Sinusoid from the Fit Name pulldown at the bottom. The Fit Equation should read as

$$x = A \sin(B \cdot t + C)$$

(1)

Make sure the Autofit checkbox is selected. If the data and the fit are right on top of each other, go to step 9. If not, click on the Value cell of each of the parameter’s in the table at the bottom of the tool, as shown in Figure 5(a). A small pair of up/down buttons will appear.

(a) Adjusting the values of the parameters in the Fit Equation to match the data.

(b) An example fit of the sine curve with the sunspot data.

Figure 5: Working with Tracker’s data analysis view.

(a) Adjust the B parameter so that the frequency of the sine curve closely resembles your data. In other words, increasing and decreasing the value of B squeezes and stretches the sine curve along the x axis. Adjust B so that the sine curve is as stretched out as your data.

(b) Adjust the C parameter so that the sine curve crosses $x = 0$ at the same place in the graph as your data crosses $x = 0$.

(c) Adjust the A parameter so that the sine curve’s amplitude matches your data.

Once you’ve gotten the sine curve to match up as much as you can with the data curve, click the Autofit checkbox to have Tracker finish the job. Figure 5(b) shows an example fit.

9. Repeat for several other sunspots and note the results.
Return to step 6 and track four more sunspots. Record each sunspot’s fit parameters in Table 1. Include any negative signs for any of the parameters. The parameters for the sunspot from above is already recorded in Table 1. Remember to give each sunspot a different name and color to avoid confusion.

<table>
<thead>
<tr>
<th>Sunspot</th>
<th>A value (solar radii)</th>
<th>B value (radians per day)</th>
<th>C value (radians)</th>
<th>Sunspot Period (days)</th>
<th>Vertical Distance From Equator (solar radii)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.924</td>
<td>0.308</td>
<td>5.407</td>
<td></td>
<td>0.281</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
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<td>D</td>
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<td>E</td>
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</tbody>
</table>

Table 1: Sunspot fit parameters.

**NOTE:** An important consideration here is that the Sun is a sphere, and, when tracking sunspots, one is seeing their motion projected on a disk. The motion of sunspots, therefore, is analogous to circular motion viewed (almost) edge on, i.e. sinusoidal. To deal with this, we set the scale of the image to 2.0 (or 2 solar radii) and tracked the x position of the sunspot. We then use Tracker’s built-in Data Tool to fit the x vs. t data to equation (1), the sine function, where A is the amplitude, B is the angular velocity, and C is the phase shift of the sine function.

### 3 Analysis

1. The B parameter from the sinusoidal fit is the angular speed of the sunspot, ω. The angular speed is simply an object’s speed when moving in a circular fashion. It can be calculated using the equation

   \[ \omega = \frac{2\pi}{T} \]  

   Solve equation (2) for T and use this equation to calculate the period of each sunspot. This will be each sunspot’s period in days. Record the periods in the Sunspot Period column in Table 1. Include sunspot A as its parameters have already been recorded for you.

2. In the 1850s, Richard Christopher Carrington used low latitude sunspots to calculate a solar rotation rate of 27.27 days. What is the average sunspot period for the sunspots in Table 1 in days? How does it compare to Carrington’s average of 27.27 days? If you didn’t calculate 27.27 days as the average period, why do you think that is?

3. In Tracker’s main window, return to the table of data in the lower right corner. In step 7, we deselected y to remove the sunspots’ vertical position data from our table. For each sunspot, reselect y in the Visible Table Columns pop-up, and find the value of y from just before or just after the sunspot crosses the y-axis. Record that value in the far-right column of Table 1. The pulldown menu to the right of the Table button will let you select each sunspot. Include any negative signs. Sunspot A has been done for you.

4. Plot your data for the sunspot periods against their vertical distances from the equator in Figure 6. Label your axes, the Sun’s equator, and the Carrington Rate on your graph.
5. Do your results support the observation that the Sun rotates faster at its equator than at its poles? Use your data to support your result.