Name: ____________________

Sunspots and Solar Rotation

Laboratory 9

Astronomy 120. The Copernican Revolution

Name	Full	Partial	None

Purpose

In this lab you will become familiar with Galileo's observations of sunspots and why he decided they were features on the surface of the Sun. In addition, you will calculate the rotational period of the Sun from observations of sunspots. We won't use Galileo's data for this, but we will instead use images collected by the Solar and Heliospheric Observatory (SOHO), which are shown on the last page of this handout.

Background

Dark spots on the sun had been noticed at least since the 8^{th} Century AD, but prior to the 17^{th} Century no satisfactory explanation of the spots was given. Some astronomers even speculated that a few particularly noticeable spots might have actually been the planet Mercury passing between the Earth and the Sun. Sunspots were probably first observed through a telescope by the Englishman Thomas Harriott in late 1610. The first published telescopic observations of sunspots were those of Johann Fabricius, at Wittenberg (Germany) astronomer who published his observations in the summer of 1611. Later that year sunspots would become the subject of a scientific dispute involving Galileo and the Jesuit professor Christopher Scheiner (of the University of Ingolstadt, Germany). Scheiner began recording sunspot observations on October 21, 1611. The first known mention of sunspots by Galileo is in a letter dated October 1, 1611, but the letter seems to indicate that Galileo had known about sunspots for some time. Scheiner would eventually claim priority for observing sunspots, and he would also dispute Galileo's interpretation of the phenomenon. Galileo was not one to relinquish an honor he felt was due him, and his dispute with Scheiner would ultimately contribute to worsening his relationship with the Church and may have helped lead to his eventual condemnation and house arrest.

What was particularly controversial about Galileo's discussion of sunspots was that he claimed they were features on the surface of the Sun. This contradicted Aristotle's cosmology in two ways: first it indicated an imperfection in the Sun, and second the fact that the spots changed over time indicated that the Sun was not immutable. In this lab we will explore Galileo's reasons for interpreting sunspots as he did. We will also see how he used his observations to determine the rotational period of the Sun.

Galileo's Model

We will begin by exploring Galileo's model for sunspots. Galileo thought that sunspots were spots on the surface of the spherical sun. Based on his observations he concluded that the Sun rotates around a fixed axis. The spots are then carried around the Sun as the Sun rotates. Let's look at a computer simulation of this model to determine what this model predicts about the appearance of the sunspots. Run the `GalileoSunspots` program. This program simulates what Galileo saw through his telescope when he observed the sun (but magnified, simplified, and sped up). You should see several sunspots. One of these spots is blue. The latitude of this blue spot is controlled using the latitude slider in the simulation. You may want to move this spot around as you try to answer the following questions.

1. How do the sunspots move?
   - (a) Each spot moves in a different direction.
   - (b) All spots move mostly West to East.
   - (c) All spots move mostly East to West.
   - (d) The spots sometimes change the direction of their motion.
2. Look closely at the shape of a single sunspot as it moves across the Sun. Does the shape change? How?
   - (a) The shape never changes.
   - (b) The spot is generally narrower East to West when it is close to the edge, and wider East to West when it is in the center. It's North-South size does not generally change.
   - (c) The spot is generally wider East to West when it is close to the edge, and narrower East to West when it is in the center. It's North-South size does not generally change.
   - (d) The spot is generally larger (in all directions) when it is in the center and smaller (in all directions) when it is near the edge.
3. Look at the separation between two nearby spots. Closely watch the distance between the two spots *parallel to the direction of the spot's motion*. Does this distance change noticeably as the spots move? How?
   - (a) The distance does not change noticeably.
   - (b) The distance is smaller when the spots are at the center and larger when they are near the edge.
   - (c) The distance is larger when the spots are at the center and smaller when they are near the edge.
   - (d) The distance changes noticeably but it is not related to the where the spots are on the Sun's disk.

4. Look at the separation between two nearby spots. Closely watch the distance between the two spots *perpendicular to the direction of the spot's motion.* Does this distance change noticeably as the spots move? How?

   (a) The distance perpendicular to the motion does not change noticeably.

   (b) The distance is smaller when the spots are at the center and larger when they are near the edge.

   (c) The distance is larger when the spots are at the center and smaller when they are near the edge.

   (d) The distance changes noticeably but it is not related to the where the spots are on the Sun's disk.

5. Pick a single spot and pay close attention to the speed with which the spot moves. Does this speed change? How?

   (a) The speed remains constant.

   (b) The spot appears to move faster when it is near the edge.

   (c) The spot appears to move faster when it is in the center.

   (d) The speed changes in a way that it not related to the location of the spot on the Sun's disk.

6. In a series of letters written to the Augsburg merchant Mark Welser (who served as an intermediary between Galileo and Scheiner) Galileo describes his observations of sunspots and his interpretation of them as surface features on a rotating Sun. Let's examine some quotations[1] from these letters to see how they match up with various features you have observed in the simulation. Here's the first quote:

   > 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...

   This quotation seems to match what you observed in question ____________.

7. Here's the next quote:

   > 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.

   This quotation seems to match what you observed in question ____________.

[1] All quotes are taken from *Discoveries and Opinions of Galileo*, translated by Stillman Drake (Doubleday, New York, 1957), pp. 107-112.

8. The third quote:

> The spaces passed by the same spot in equal times become always less as the spot is situated nearer the edge of the sun. Careful observation shows also that these increases and decreases of travel are quite in proportion to the versed sines[2] of equal arcs, as would happen only in circular motion contiguous to the sun itself.

   This quotation seems to match what you observed in question _____________.

9. The fourth quote:

> A third thing which strongly confirms this conclusion may be deduced from the spaces between one spot and another. Some of these separations remain constant, others greatly increase toward the center of the solar disk, being quite narrow elsewhere, and insensible near the edge; still others show extreme variability. The events are such that they could be met with only in circular motion made by different points on a rotating globe. Spots located close together along the same parallel of solar latitude seem almost to touch each other at their first emergence; if farther apart, they will at any rate be much closer near the edge than near the center of the sun. As they move away from the edge, they are seen to separate more and more; at the center, they have their maximum separation; and as they move on from there they approach each other again.

   This quotation seems to match what you observed in questions _____________.

10. This evidence seems to be pretty conclusive in showing that the spots move in circles around the Sun. If we take the spots to be actually *on* the sun (as Galileo did) then we must conclude that the sun rotates. How does the plane of the sun's equator (as defined by its axis of rotation) compare to the plane of the ecliptic? In other words, what is the *obliquity* of the sun's equator (the angle between the sun's equator and the ecliptic). Adjust the obliquity slider in the simulation until the sunspots are moving parallel to the blue line representing the sun's equator. Record the value of the obliquity below.

[2]The versed sine of the angle θ is equal to $1 - \cos\theta$.

11. Now some philosophers had claimed that the sunspots were simply phenomena within Earth's own atmosphere which obstructed light from the Sun. Galileo felt that his observations, described above, easily refuted this view. But to drive in the final nail he had other observers, at distant locations, watch the sun at the same time. Here is what he reports:

    > ...spots observed simultaneously from widely separated positions on earth are nevertheless arranged in the same order and in the same places on the sun ...
    > Hence, they must be much farther away than the moon...

    In the space below, explain why Galileo concludes that the spots are farther away than the moon. If the spots really were in earth's atmosphere and we saw them blocking the Sun here in Georgia, how would they appear differently to an observer in California?

12. Another strong piece of evidence that would favor Galileo's view would be a spot that disappears at the western edge and reappears at the eastern edge of the sun's disk. Watch the simulation carefully. Do the spots that disappear at the western edge later reappear at the eastern edge? How do you know they are the *same* spots?

13. Unfortunately it was not so easy for Galileo. He found that the spots gradually change their size and shape over time. Therefore it was difficult to tell if the spot appearing on the eastern edge was the same spot that had disappeared on the western edge some time ago. Even with this difficulty, what evidence might lead you to believe that the spots appearing on the eastern edge are the same spots that disappeared earlier at the western edge?

Measuring the Sun's Rotational Period

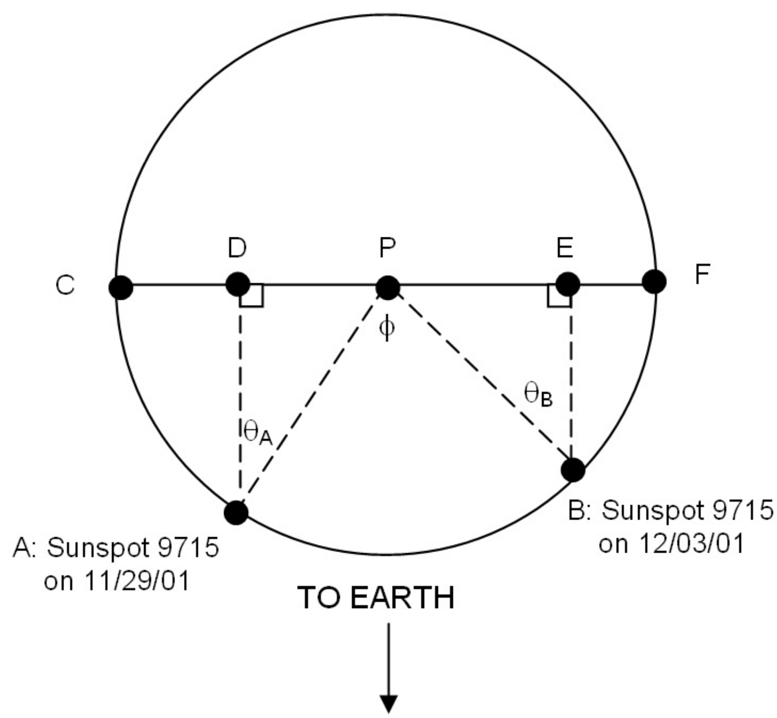
Based on his observations, Galileo states:

> From what has been said thus far, if I am not mistaken, one must conclude that sunspots are situated upon or very close to the body of the sun...
> It is also manifest that their rotation is about the sun, though it remains questionable whether this happens because the sun itself rotates and carries them along with it, or whether the sun remains motionless and the spots are conducted by a rotation of some surrounding medium. It could happen either way. Yet to me it seems much more probable that the movement is of the solar globe than of its surroundings.

He goes on to give a variety of reasons for preferring the view of solar rotation.

If we accept Galileo's view, then we can actually determine the period of the sun's rotation by observing sunspots at two different times. Scheiner was the first to determine the period of the sunspots motion around the sun - but he thought the spots were very small planets that orbited close to the Sun, so he did not interpret his value as the period of the sun's rotation. The remainder of this handout will step you through the calculations of the sidereal rotation period of the Sun, including a correction for the motion of the Earth (remember that Galileo was a Copernican).

Refer to the diagram below, which is a view of the Sun from above the north solar pole; the circle describes the solar equator.



Solar Rotation Worksheet

1. During the time span 2001 November 28 and 2001 December 3 (the dates for the two SOHO images shown on the last page of the handout), the Sun rotated through an angle ϕ *from our point of view*. It is our first goal to calculate ϕ. By simple geometry, $\phi = \theta_\mathrm{A} + \theta_\mathrm{B}$, so we can find these two angles to find ϕ.

   Now we need to measure the positions of a single sunspot at two different times. **You will make these measurements using the SOHO images on the last page of this handout, NOT the diagram shown above! Make all measurements to the nearest millimeter.** On your first (November) image, measure the distance from the center of sunspot 9715 to the point on the limb (the edge of the sun's disk) directly to the east (left) of the spot in units of centimeters; this distance in represented by the line segment CD. Also, on the second (December) image, measure the distance from the center of sunspot 9715 to the point on the limb directly to the west (right) of the spot in units of centimeters; this distance in represented by the line segment EF. Write your results in the spaces below.

   $CD =$ ____________________ cm

   $EF =$ ____________________ cm

2. Now find R, one-half the distance from the western limb to the eastern limb at the latitude of the sunspot on the SOHO images.

   $R =$ ____________________ cm

3. We wish to find the distances DP and EP. We can do this by subtracting CD and EF each from R itself. Do this and write your results below.

   $DP = R - CD =$ ____________________ cm

   $EP = R - EF =$ ____________________ cm

4. The angles θ_A and θ_B can be found by using the trigonometric sine function. As you may remember, the sine of an angle is found by dividing the length of the leg opposite the angle by the hypotenuse of the triangle. Therefore,

   $$\sin\theta_\mathrm{A} = \frac{DP}{R}$$

   and

   $$\sin\theta_\mathrm{B} = \frac{EP}{R}$$

   Now, we can find the angles θ_A and θ_B by using the *inverse* sine function. Find these angles and record them here:

$$\theta_{\mathrm{A}} = \sin^{-1}\left(\frac{DP}{R}\right)$$

and

$$\theta_{\mathrm{B}} = \sin^{-1}\left(\frac{EP}{R}\right)$$

Using your calculator and the formulas above, find θ_{A} and θ_{B} record it here:

$$\theta_{\mathrm{A}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

$$\theta_{\mathrm{B}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

5. Now we are in a position to find ϕ:

$$\phi = \theta_{\mathrm{A}} + \theta_{\mathrm{B}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

6. Now, ϕ is the angle that the Sun has rotated from *the Earth's point of view*. However, the Earth revolves around the Sun and the five days between our images is long enough for the Earth to complete about 4.9° of its roughly 360° yearly trip. Therefore this number must be added or subtracted from ϕ. Which one is it? ________________ (Remember, from above either solar pole, the Sun rotates in the same direction that the earth revolves!)

7. Calculate ψ, the angle that the Sun *actually* rotated in the time span between 28 November and 3 December:

$$\psi = \phi \pm 4.9^\circ = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

8. Now we can finally calculate the solar rotation rate. If the Sun rotates through an angle ψ in 5 days, how many degrees does it rotate in one day? The answer is $\psi/5$, of course. In the space below, set up a ratio to find T, the solar rotation period. This is the time required for it to rotate 360°. Put your answer in the space provided below.

$$T = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ days}$$

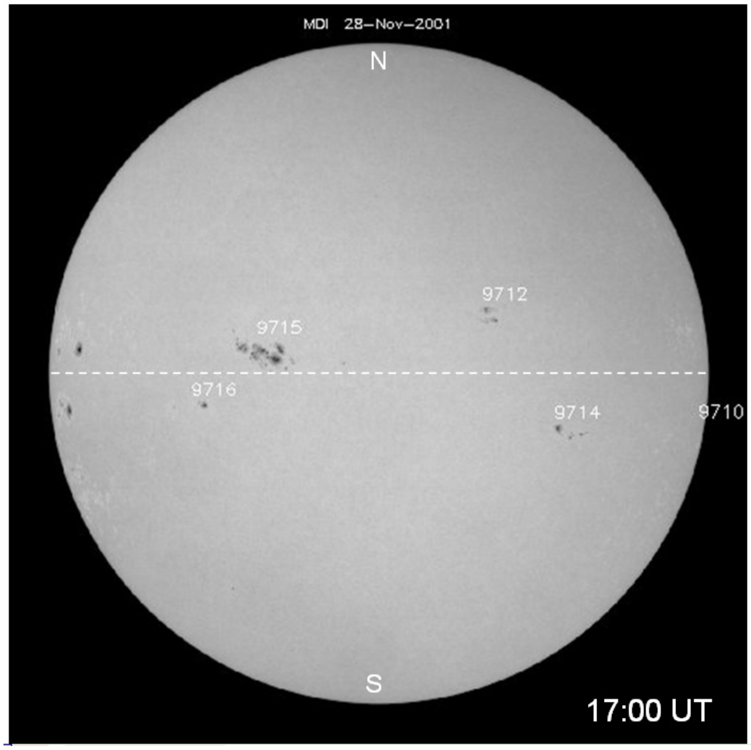
9. How does your answer compare with the known equatorial rotation period $T_{\text{known}} = 25.1$ days? To calculate your error, use the following formula:

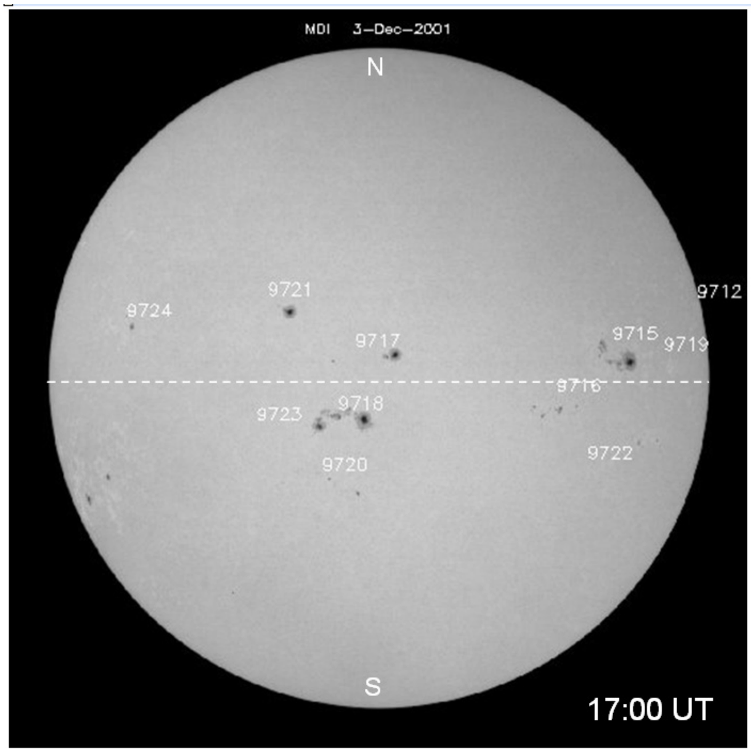
$$\%\ \text{error} = \left|\frac{T_{\text{known}} - T}{T_{\text{known}}}\right| \times 100 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

10. What is the synodic rotation period of the Sun from your data? Remember: *synodic* means "from the Earth's point of view".

11. Galileo wrote to Kepler about his observations of sunspots and his determination of the rotation of the sun. Explain why this observation would have been very important to Kepler (particularly coming, as it did, just a few years after Kepler had published his *Astronomia Nova*).

12. Recall that in the Copernican/Keplerian system Mercury has a period of 88 days. How does the rotational period of the sun fit in with the orbital periods of the planets? Does the sun's rotational period preserve the "harmonious linkage between the motions of the spheres and their size" that Copernicus found so pleasing?





These two images of the Sun were taken by SOHO in white light near the last solar maximum. Each sunspot group is labeled with a number; we will use the group labeled 9715 for this lab; the east-to-west rotation of the Sun is evident!