Lab 2: The Atmosphere of the Sun

Purpose

After years of calm, the Sun is becoming more active, and is predicted to reach its maximum around 2025. As the Sun becomes more active, it produces more high energy particles, which create space weather. Solar activity can affect our communications, trigger displays of aurorae, cause gyrations of compasses, damage power lines, and possibly even affect our weather. In this lab you will have the opportunity to observe sunspots, which are the most visible evidence of solar activity. We will view the Sun at various wavelengths of light to view its activity in multiple ways.

Introduction

On the 2$^{\text{nd}}$ of September in 1859, the most intense geomagnetic storm in history hit the Earth, known as the Carrington Event. A geomagnetic storm is a disruption of the Earth's magnetosphere, the area around the Earth affected by charged particles interacting with its magnetic field, caused by solar wind or a cloud of particles created by a Coronal Mass Ejection (CME). The Earth's magnetic field keeps us safe from high energy particles which would otherwise tear at the atmosphere and expose the planet to harmful radiation.

On September 1$^{\text{st}}$, 1859, Richard Carrington and Richard Hodgson were observing the Sun when they witnessed an extraordinarily bright burst of light from the Sun. This was the first ever directly observed solar flare. The flare released a CME which reached the Earth in only 17.6 hours. When the CME hit, it's interaction with the Earth's magnetic field produced brilliant aurorae. These aurorae, usually only visible from the frigid North or South polar regions, became visible far closer to the equator, as far as Colombia. The aurorae were so bright that they lit up the night sky like early morning, waking gold miners for an early breakfast and letting night owls read the newspaper by aurora light.

Across the world, telegraph operators noticed strange electrical effects due to the passing storm. The telegraph systems failed, some operators received small shocks while trying to use their devices. There was even a case where a telegraph operator disconnected their device from electricity, yet was still able to send and receive messages. When a magnetic field changes, it induces an electric field, creating a current. Telegraph pylons sparked, causing minor fires as the Earth's magnetic field was warped by the CME.

The Carrington Event (illustrated in Figure 2.1) is still the most intense geomagnetic storm to strike the Earth within recorded history, but there is evidence that something like it may happen again. In 1859, the most advanced communication technology used was telegraphs. Another CME of such magnitude hitting the Earth today could cause failures in the electronics in satellites within the magnetophere. Over the years, less extreme events have caused disruptions in radio communications and problems in electronics. In March 1989, a solar storm caused an electric grid in Quebec to shut down for nine hours, causing concerns for electric grids to be shielded against currents induced by geomagnetic storms. As recent as July 2012, a solar storm on the level of the Carrington Event just barely missed the Earth. In early 2022, a relatively mild CME caused the

Earth's atmosphere to puff up like a balloon, causing 40 recently launched Starlink satellites to burn up in low Earth orbit.

Along with geomagnetic storms, which are caused by solar flares and high speed winds from coronal holes, other space weather effects are solar radiation storms and radio blackouts. Solar radiation storms are caused by major eruption events on the Sun, which launch protons at high velocities up to 10,000 km s^{-1} and can last for days at a time. Such radiation storms can cause health concerns in astronauts and people flying at high altitudes. Radio blackouts are caused by solar flares which expose the sunlit side of the Earth to high energy photons, which ionize part of the Earth's atmosphere and disrupts radio communications as the radio light is absorbed instead of refracted by the atmosphere.

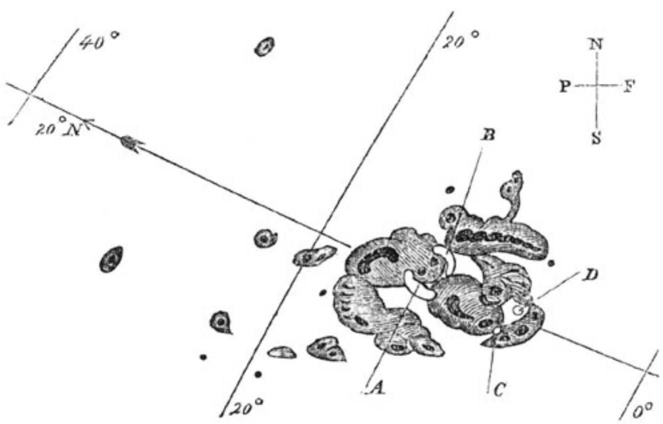


Figure 2.1: Carrington Event Sunspots

Space weather such as geomagnetic storms are different from weather on Earth. Rather than the water cycle and atmospheric pressure gradients, space weather is caused by solar activity and background radiation. The Sun goes through cycles of magnetic activity every 11 years where it's magnetic field flips, at a time when the total number of sunspots peaks. During this time, solar flares, coronal loops, the size and number of sunspots, and the amount of material and radiation that the Sun produces increases.

Solar activity can be measured in terms of the average sunspot number, which fluctuates over time, but tends to follow the solar cycle. The sunspot number is not the number of spots on the solar disc. It is a number devised in 1848 by Rudolph Wolf, who felt that the number of groups of sunspots were a better measure of solar activity than raw number. The *Wolf* or *Zurich* sunspot number, R, is defined as:

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

Where k is a fudge factor (approximately 1) related to the size of the telescope, g is the number of sunspot groups, and f is the total number of sunspots both in groups and as individuals. More modern measures of the Sun's activity exist, such as radio emissions, but R is most widely used due to the advantages of simplicity, ease of observation, and a long historical record.

In 1863, Richard Carrington also discovered that early in a solar cycle, spots tended to appear further away from the Sun's equator, at north and south latitudes near 35°. As the cycle went on, the majority of the spots appeared closer and closer to the Sun's equator, until they reached latitudes of 5 to 10 degrees by the end of the cycle. According to this measure, one can figure out in what stage of the sunspot cycle an image what taken.

Figure 2.2 shows a region of sunspots. Notice that each sunspot has a very dark center, known as the *umbra*, surrounded by a much lighter, fibrous fringe termed the *penumbra*. Spots appear dark for a simple reason: they are cooler than the rest of the solar surface. The general surface of the Sun has a temperature of 5778 K, while sunspots are 2000 degrees cooler. Since the Stefan-Boltzmann law of thermodynamics tells us that radiation from a hot body varies with the fourth power of the Kelvin temperature, the spots emit far less light than the surrounding photosphere.

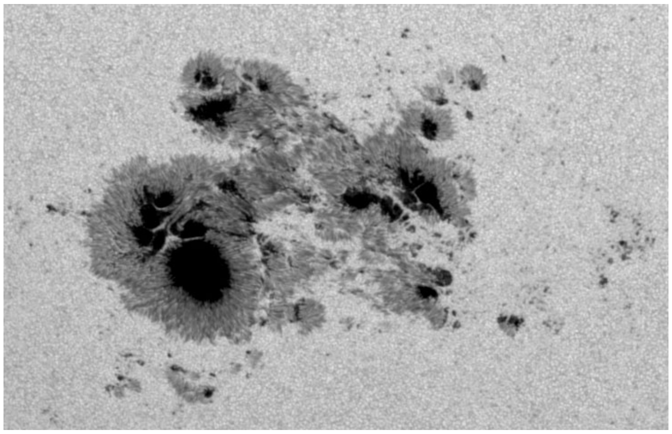


Figure 2.2: Sunspot region AR2192. Captured by NASA's Solar Dynamic Observatory on Oct. 23, 2014. Image credit: NASA/SDO. The mottled "rice grain" structure of the photosphere outside of the spots is due to small bubbles or cells of hot gas rising to the surface, somewhat like the surface of a pan of furiously bubbling water, named granules.

In 1908, George Hale made the discovery that sunspots are accompanied by strong magnetic fields. Moreover, large spots occur in pairs. Almost invariably, one spot of the pair is a north magnetic pole, while the other is a south pole, much like the poles of a horseshoe magnet. It seems that the spots are cooler than the rest of the photosphere due to the magnetic fields inhibiting the flow of hot gases to the surface of the region.

Sunspots are the surface manifestation of much deeper-lying solar activity. Near a sunspot maximum, the Sun emits copious quantities of ultraviolet radiation, X-rays, radio waves, and streams of charged particles. It is the interactions of these charged particles with the Earth's magnetic field which generate magnetic storms that can burn out transmission lines, cause compasses to gyrate, and evoke magnificent displays of aurorae. The most violent events are associated with solar flares, great explosions near the Sun's surface. The Earth's magnetic field and atmosphere shield us from the most dangerous solar radiation, but astronauts and passengers in high flying aircraft are at risk. Long distance radio communications are affected by changes in the ionosphere, a high-altitude layer of the atmosphere that is crucial in such communications.

Because of the Sun's influence, there are numerous solar observatories scattered over the Earth. Up to date images of the Sun, together with data on sunspots and other phenomena, can be retrieved daily from the internet. Useful tools for recent updates on space weather are spaceweatherlive.com and spaceweather.com.

Laboratory Procedures

Part I - Solar Atmosphere

You will be using the Coronado Personal Solar Telescope (PST) for observing the Sun. Each telescope is equipped with a special solar filter which is placed over the front of the instrument to reduce the entering light to a safe level. The PST is fit with a special Hα filter for solar observing. This Hα filter has a very narrow bandwidth of 1 Angstrom (Å). *Never attempt to look at the Sun with any instrument that is not equipped with an equivalent filter.* In particular, filters inserted at the eyepiece end of a telescope are dangerous because they may suddenly shatter with the heat. Also, do NOT use the small finder telescope that is mounted on the telescope; it is not safeguarded with a filter! Finally, do NOT look at the Sun with the naked eye or using any optical instruments such as binocular or lenses without a proper solar filter. Repeated experience has shown that failure to observe the foregoing precautions can cause permanent eye damage, do not be like Galileo. Your properly equipped telescope will allow you to view the Sun in comfort and safety through the telescope. Equipped with a very low-power eyepiece, your telescope will take in the entire disk of the Sun, which is about half a degree in apparent diameter. Your view should be similar to the image in Figure 2.3.

Focus the telescope sharply for your eye, preferably using one of the sunspots as a target. Now, using the circle provided on the data sheet, make a careful sketch of everything you can see on the Sun's disk in pencil. Do you see anything poking out from the Sun's surface, such as a solar prominence taking the shape of arcing loops or streaks of plasma above the Sun's surface? Make sure to include these in your sketch! Note what you are using to observe the Sun on the line provided under the circle, and write your observations on the lines provided.

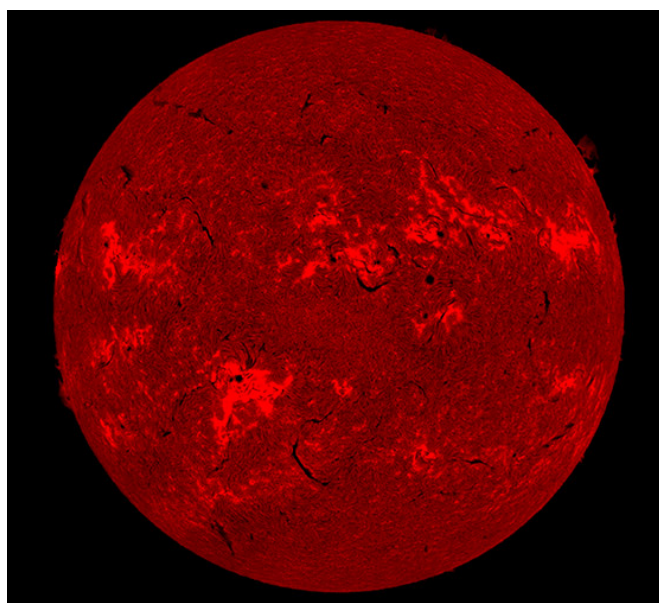


Figure 2.3: An image of the Sun with an Hα filter applied. Image credit: Big Bear Solar Observatory.

You will notice increased trembling and blurring of the image, caused by daytime thermal currents in Earth's atmosphere. This highly variable phenomenon is what astronomers refer to as "seeing" and it is normally much worse during the day than it is at night. It is a fundamental limitation on the amount of detail you can see, and on the magnification that can be usefully employed.

In Case of Bad Weather

If the weather is too poor to observe the Sun, go to gong.nso.edu and then click **H-alpha**. Click on the clearest image of the Sun, or one of the images with a green check mark below. Avoid images that look blurry. Using one of the circles provided, use a pencil to sketch the Sun. Write your observations using the lines provided. Be sure to draw anything you might see protruding from the Sun's surface. Note what you are using to observe the Sun on the line provided under the circle.

Part II - Intensity

Once you have finished your sketch of the Sun through the PST, it is time to sketch the Sun again. If available, use the solar telescope fitted with a solar filter to observe the Sun. Follow the same steps as before to focus on the Sun, and make a sketch. Note any observations you have, including differences in texture, color, and prominent features. The Sun should look a bit different when you compare your observations in Hα and with the solar filter. Can you see the limb darkening, where the Sun gradually appears less bright towards its edge? If so, try to indicate it on your sketch. The Hα filter in the PST only allows light from the Hα emission line to pass through, which lets you observe where hydrogen is excited in the Sun's atmosphere, higher than the photosphere.

In Case of Bad Weather

If the weather is too poor to observe the Sun, go to spaceweatherlive.com, click the drop-down menu that says **Solar activity**, choose SDO for the Solar Dynamics Observatory, and make a sketch of the image under **HMI Intensitygram**. Using one of the circles provided, use a pencil to sketch the Sun. Write your observations using the lines provided. Note what you are using to observe the Sun on the line provided under the circle.

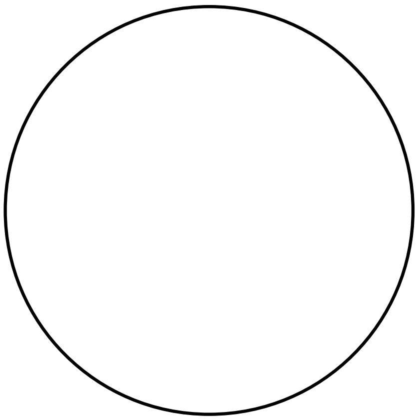
Part III - Corona

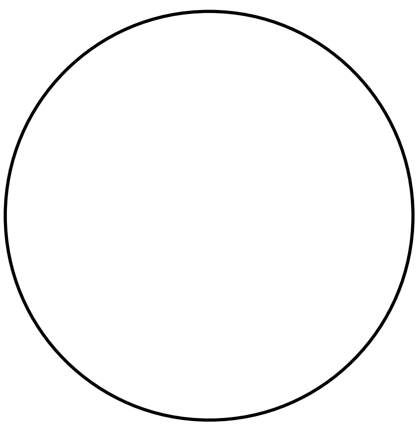
Once you have finished your sketch of the Sun through the telescope, head inside and use one of the computers to access spaceweatherlive.com. Go to the website, click the drop-down menu that says **Solar activity**, and choose SOHO for the Solar and Heliospheric Observatory. You will be greeted with two images of the Sun, but these are different from the images seen before. In order to see the much fainter atmosphere or *corona* of the Sun, we must immensely reduce the glare from its surface by using what we call a *coronagraph*, a mask conservatively larger than the Sun's surface in the middle of the telescope's field. This mask is labelled B on your data sheet. The little white circle in the center of where the Sun is blotted out represents the disk of the Sun on the sky. On your datasheet, this circle is labeled A. Measure its diameter gently with a ruler on the screen. Choose one of the two images, make a note of which on the line under the box provided. You may see several radial lines protruding from the Sun, or even the curved, lightbulb shape of a Coronal Mass Ejection. Make sketches of these features in the box. Measure how far the protrusions extend from the surface of the Sun radially. If the protrusions extend past the limit of the FOV, measure to the edge of what you can see and make a note on your observations. Write down your measurements and observations.

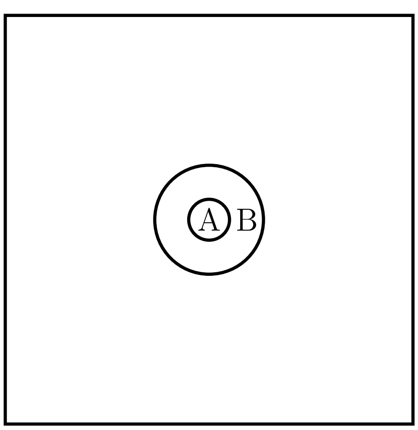
The Atmosphere of the Sun Worksheet

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.







Questions

1. What are today's weather conditions? (Sunny, partly cloudy, overcast, etc.)

2. Did you use the Personal Solar Telescope with the Hα filter, or did you view the Sun using the GONG Hα data?

3. Did you use the telescope fitted with a solar filter, or did you view the Sun using the SDO HMI Intensitygram?

4. What are the similarities and differences between the two of your sketches of the Sun (in the first two circles)?

5. What is the formula for the sunspot number, R?

6. Define each variable in the formula for the sunspot number. (R, k, g, f)

7. Rearrange the formula for the sunspot number to solve for the number of individual spots.

8. Go to spaceweather.com and find today's sunspot number on the left column. Write it down here.

9. Using either your observations of the Sun or the image of the Sun given on spaceweather.com, write down how many groups of sunspots there are. The website assigns a number to each sunspot region.

10. Taking the fudge factor to be approximately 1, solve for the total number of individual spots on the Sun today using the formula above.

11. Rewrite the measurements you took in Part III (third sketch) here. How large was the Sun (the white circle) on your screen? Where there any radial features, how long were they? Were there any coronal mass ejections? How far did they extend from the surface of the Sun?

12. If you observed a coronal mass ejection, find the ratio of its size compared to the diameter of the Sun (divide the size of the coronal mass ejection by the diameter of the Sun you measured).

13. The diameter of the Sun is 695,700 km. Using the ratio you calculated, what is the size of the coronal mass ejection?

14. The website spaceweather.com lists the current speed of the solar wind on the left column. Write the current solar wind speed here.

15. The Sun is around 1.496×10^{11} meters away from the Earth (1 AU). If a proton was ejected from the surface of the Sun at the current solar wind speed, how long would it have to travel radially out from the Sun to reach Earth's orbit? (Convert to days).

16. If a proton is directly facing the Earth at the moment it is released from the surface of the Sun, would it hit the Earth as the proton travels radially outwards? Why or why not?

17. Why does SOHO need to block out the Sun's light to learn more about the Sun?

18. Why is it important for us to monitor the Sun's activity?