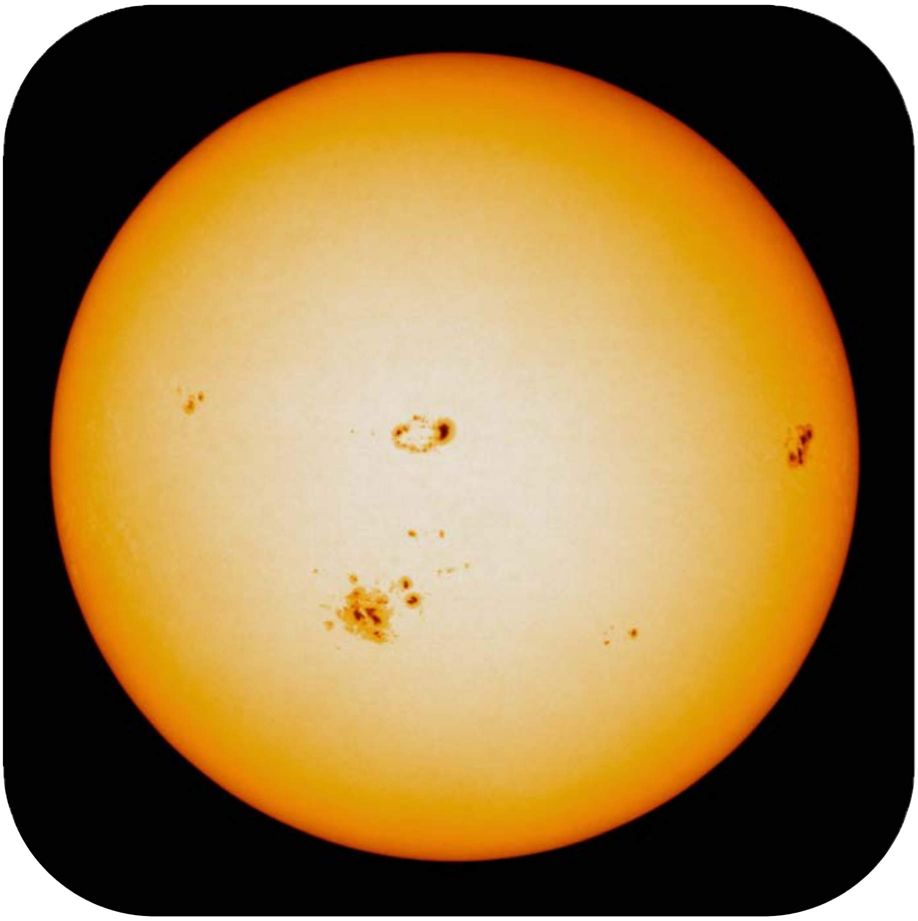
CESAR Science Case

Tracking sunspots

Using sunspots to calculate the rotation of the Sun

Teacher Guide



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Fast Facts

FAST FACTS

Age range: 14 - 18 years old

Type: Student activity

Complexity: Medium

Teacher preparation time: 30 - 45 minutes

Lesson time required: 1 hour 15 minutes

Location: Indoors

Includes use of: Computers, internet

Curriculum relevance

General

- Working scientifically.
- Use of ICT.

Physics

- Light waves. The electromagnetic spectrum.
- Temperature. Blackbody radiation.

Space/Astronomy

- The Sun
- The Solar System

You will also need…

The Sun rotation web tool
http://cesar.esa.int/tools/14.differential_rotation/

To know more…

CESAR Booklets:

- *The Sun structure,*
- *The Magnetic Sun*

Outline

In this activity, students measure the Sun's rotational period by tracking sunspots at different latitudes. They use time-separated images from the CESAR Education Solar Observatory (CESO) to make measurements of the positions of sunspots to calculate the rotation period of the Sun. Finally, they make conclusions about how the rotation period depends on the Sun's latitude.

Students should already know…

- The concept of 'rotation'.
- The concepts of longitude and latitude.

Students will learn…

- How to explain the concept of 'differential rotation'.
- Describe the Sun's rotation and how the gas on its surface moves.
- What information can be seen and extracted from an astronomical image.

Students will improve…

- Their understanding of scientific thinking.
- Their strategies of working scientifically.
- Their teamwork and communication skills.
- Their evaluation skills.
- Their ability to apply theoretical knowledge to real-life situations.
- Their skills in the use of ICT.

Summary of activities

Title	Activity	Outcomes	Requirements	Time
1. Getting to know the Sun.	Students compare the Sun and the Earth, and look into the structure and physical characteristics of the Sun.	Students learn: • About the Sun as a star Students improve: • Their understanding of scientific thinking.	None.	10-15 mins
2. The colours of the Sun	Students find out how the Sun looks in different types of light and in which wavelength of light sunspots are visible.	Students improve: • Their understanding of the electromagnetic spectrum.	None.	10-15 mins
3. Sun rotation calculation.	Students calculate the rotation period of the Sun.	Students improve: • Their skills in the use of ICT. • Their knowledge of coordinate systems	None.	20 mins
4. The Sun's rotation at different latitudes.	Students repeat their calculation of the Sun's rotation using different sunspots in different images of the Sun.	Students learn: • About the differential rotation of the Sun Students improve: • Their understanding of scientific thinking. • Their strategies of working scientifically. • Their teamwork and communication skills. • Their evaluation skills. • Their ability to apply theoretical knowledge to real-life situations. • Their skills in the use of ICT.	• Completion of Activity 2.	20 mins

Introduction

The Sun, our closest star, is a ball of hot gas or “*plasma*” that is mostly made out of hydrogen and helium. The temperature at the surface of the Sun is about 5500ºC (5800 K). Just like the Earth, the Sun rotates. However, unlike the Earth, the Sun is not a solid body. This means that the gas that forms its surface does not move as one piece, and therefore does not move at the same speed. This phenomenon, called ***differential rotation***, can be observed simply by tracking the movement of sunspots on the Sun surface over several days.

WARNING – Never look at the Sun directly it can cause serious damage to your eyes.

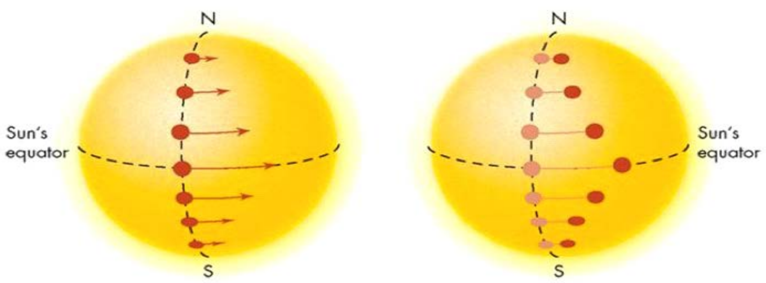


Figure 1: The gas at the surface of the Sun does not move at the same speed as the Sun rotates. Credit: McGraw-Hill.

Background

Sunspots are seen as dark patches on the surface of the Sun. They appear darker than the rest of the Sun’s surface (known as the photosphere) because they are about 1000 K cooler. Sunspots can vary in size, from those that are comparable to the size of the Earth, to the largest that are about the size of Jupiter (see left-hand image of Figure 2).

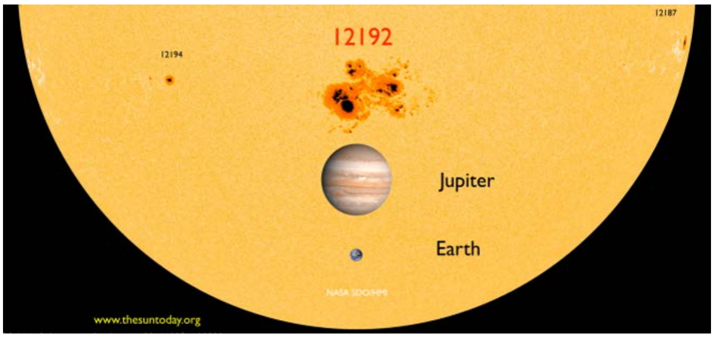


Figure 2: Sunspots size comparison. Credit: thesuntoday.org, Dra, Anik de Groof presentation.

The Earth has a magnetic field that resembles a bar magnet (Figure 3). Just like the Earth, the Sun has a magnetic field, and sunspots occur because of the effect the Sun’s differential rotation has on it.

Figure 3: Similarity between the Earth's magnetic field (left) and a bar magnet (right).
Credit: NASA, Dra. Anik de Groof presentation from ESA/SOLO Team.

Over time, as the Sun rotates, its differential rotation causes the magnetic field lines to become twisted and tangled, as shown in Figure 4. These tangles in the field lines can produce localised magnetic field lines that poke up through the surface of the Sun forming a sunspot. Sunspots often appear in pairs, so where one sunspot is created as field lines rise through the surface, a second appears where they fall back down.

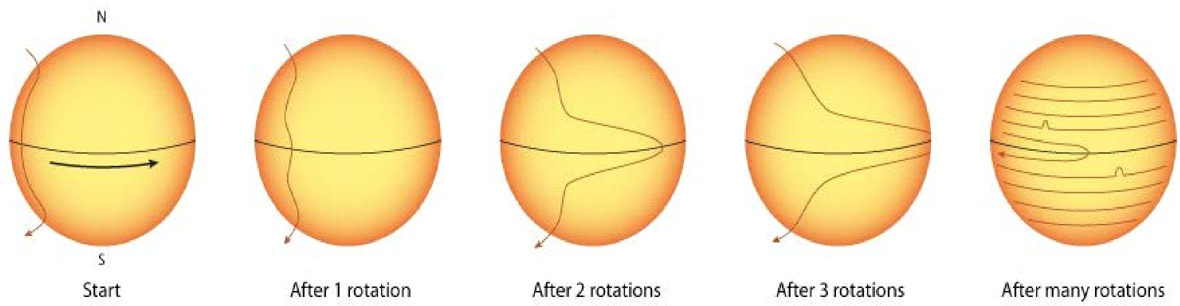


Figure 4: How the Sun's differential rotation builds over several days. Credit: NASA/IBEX.

The rotational period of an object is the time that it takes to spin around, or rotate, once. In the case of the Sun, we can deduce this value by measuring how long it takes a sunspot to move across part of the Sun's surface; or the number of degrees it covers, knowing that a complete rotation is 360 degrees.

Activity 1: Getting to know the Sun

This activity serves as an introduction for students to the Sun. They make a comparison between stars and planets, using the Sun and the Earth as examples and look into some detail of the structure of the Sun as a typical star, as well as some physical characteristics.

To begin the activity discuss with the students what type of celestial objects the Sun and the Earth are and their main differences. The students can then further compare the two objects by completing the table in their Student Guide (see Table 1).

Property	Sun Value	Earth value	(Sun/Earth) comparison
Radius (km)	~ 700 000	6400	~ 109
Mass (kg)	~ 2×10^{30}	~ 6×10^{24}	~ 3×10^{5}
Average density (kg/m^3)	1400	1217	1,2
Surface temperature (^{o}C)	~ 6073	17	~ 357
Age (years)	4 600 000 000	4 540 000 000	~ 1

Table 1: Comparison of some basic properties between the Sun and the Earth

Answers to questions in the Student Guide

2. What gases make up the Sun?

The Sun, as are most stars, is ***made up of 90% hydrogen and 9% helium.*** Figure 5, provides a breakdown of what elements make up the Earth and the Sun.

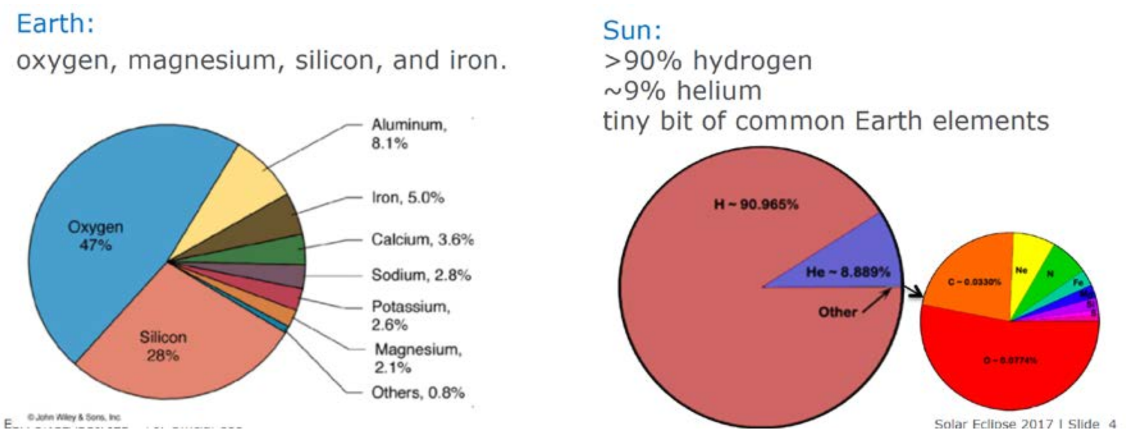


Figure 5: Comparison of the constitutes of the Earth and the Sun.
Credit: Dra. Anik de Groof, ESA/SOLO scientist, presentation for the 2017 CESAR Solar Eclipse Event.

3. **In what part of the Sun are sunspots are seen? Draw a sketch.**

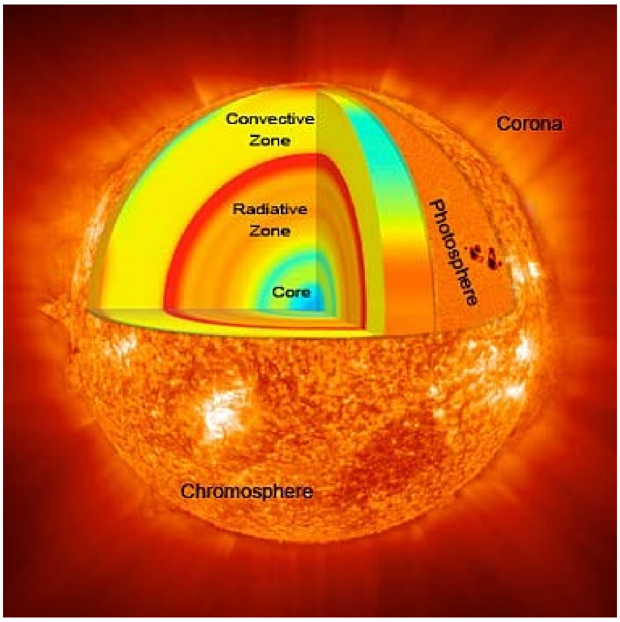
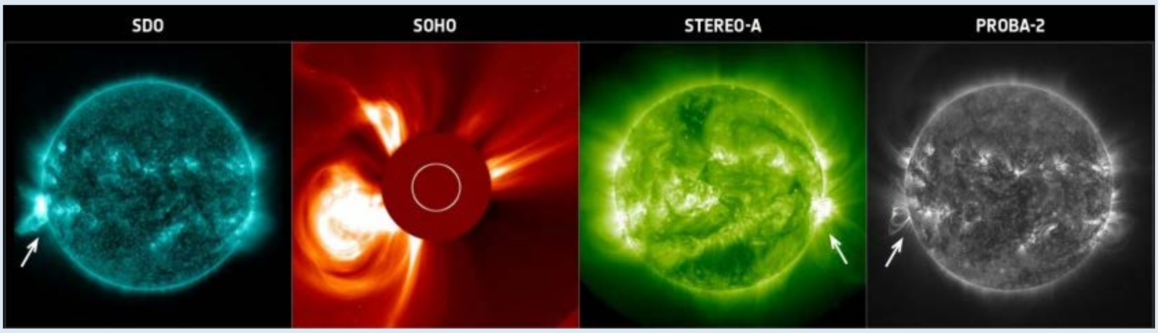


Figure 6: Diagram showing structure of the Sun.
Credit: Dra. Anik de Groof, ESA/SOLO scientist, presentation for the 2017 CESAR Solar Eclipse Event.

Sunspots are seen on the surface of the Sun, called the photosphere. The students can find the answer in the background information of their Student Guide and use the diagram in the 'Did you know?' box. The students should produce a labelled sketch that shows the features as marked in Figure 6.

Did you know?

The Sun is constantly being observed by many space telescopes. Examples of such telescopes, are ESA's PROBA-2 **mission** and the ESA/NASA SOHO observatory. A new spacecraft, ESA's Solar Orbit will soon join this fleet and is scheduled for launched in 2020. These space telescopes provide a wealth of data about the Sun. The branch of physics that studies the Sun is known as ***Heliophysics***.



Sun observed in with different filters. (Credit: kiri2ll.livejournal.com)

Activity 2: The colours of the Sun

In this activity students are introduced to some telescopes that observe the Sun and access the CESAR Education Solar Observatory (CESO). Students will look for sunspots in the live solar observations and then consider what type of light would be best to study sunspots.

The students begin the activity by accessing the CESO and looking at the live images of the Sun to see if any sunspots are present on the surface.

Answers to questions in the Student Guide

1. **If sunspots are at a temperature of 4500ºC (4800 K), what type of light should we use to study them (X-rays, visible light, infrared, etc.)? Tip: Use Figure 8 (in Student Guide) to help.**

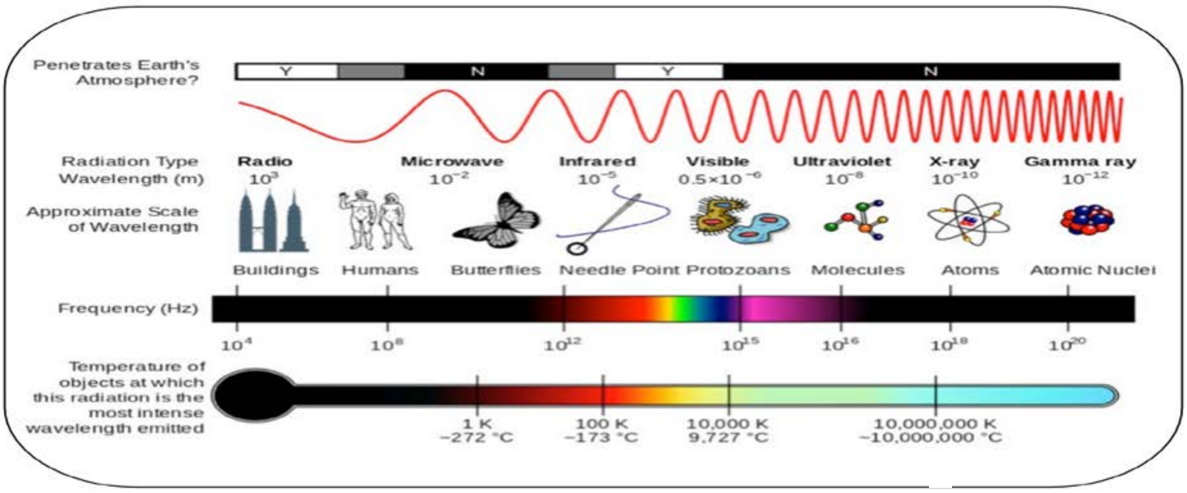


Figure 7: The properties of the electromagnetic spectrum. Credit: Wikimedia Commons.

Sunspots should be studied in visible light. This is because objects in the temperature range of 4000 - 6000 kelvin degrees emit most light at these wavelengths, see Figure 7 (Figure 8 in Student Guide).

Clarify to the students that they will use sunspots in the next activity to calculate the differential rotation of the Sun, and that sunspots are caused by magnetic processes in the Sun. The students will use images of the Sun taken in visible light in which sunspots are identified as darker (colder) patches on the Sun's surface.

To extend the discussion of the Sun's structure it may be interesting to mention to students that the different external layers of the Sun have different characteristics (temperature, density) and for that reason they can be observe at different wavelengths. However, there is a single magnetic process in the Sun, with different features detectable in different parts of it.

Activity 3: Sun rotation calculation

In this activity, students will use images of the Sun taken by the CESAR Education Solar Observatory (CESO) to measure the movement of a sunspot over several days in order to calculate the rotation of the Sun. Students will access the images and complete the activity using a specially designed web tool.

This activity is structured in a similar way to an experiment, the students begin by making a hypothesis, they conduct their experiment by measuring the movement of a sunspot and finally make conclusions from their results. Detailed instructions for this activity are given in the Student Guide and web tool.

Hypothesis

How long do you think it takes the Sun to complete a full rotation (to spin around once)?

The students should base their answer on their current knowledge and from reading the Background information provided in the Student Guide.

The Sun is a ball of hot gas, or plasma, not a rigid body, and so the gas that forms its surface does not move as one piece. Therefore, the rotation speed of the Sun varies across the surface. The Sun rotates faster close to the equator, with a rotational period of 25 days. Closer to the poles, approximately 90 degrees in absolute values, the Sun rotates more slowly, with a rotational period close to 35 days.

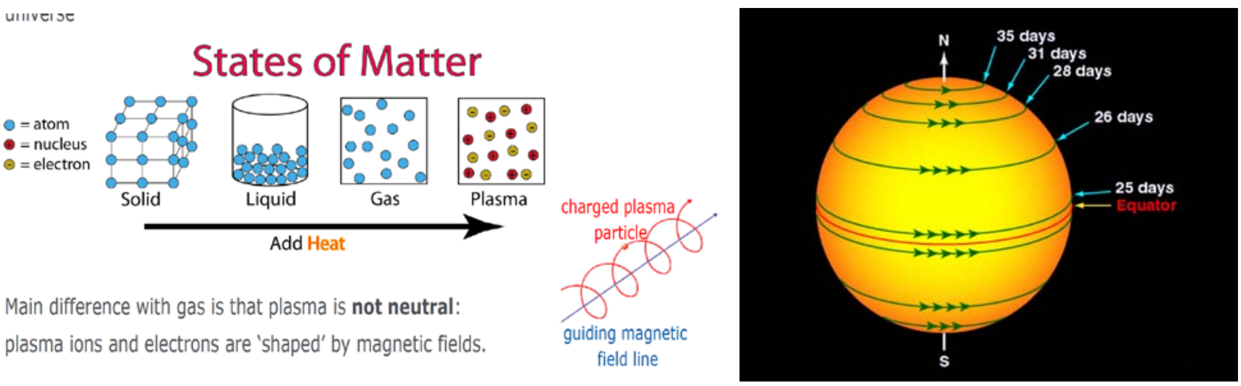


Figure 8: Diagram of the four states of matter (left). Diagram showing how the rotation period of the Sun varies across its surface (right). Credit: Dra. Anik de Groof, ESA/SOLO scientist, presentation for the 2017 CESAR Solar Eclipse Event, NASA.

In what direction, do you think sunspots move across the surface of the Sun? Draw a sketch to illustrate your answer.

a. **North to South**
b. **South to North**
c. **East to West**
d. **West to East**
e. **Other. Draw a sketch to illustrate your answer.**

As sunspots are a result of magnetic processes in the Sun, they move in the direction of its magnetic field lines. As shown in Figure 4 the Sun's magnetic field lines are extended parallel to the equator and become twisted. Therefore, sunspots move mainly parallel to the equator. In this activity, their position will change in longitude for a certain value of latitude.

Do you expect sunspots to move at the same speed in different locations of Sun's surface? Explain your answer. Tip: check Figure 1.

The answer to this question is given in Figure 1. As the Sun is made of gas it moves faster where the rotational radius is greatest. It follows that the lineal velocity, v, is proportional to the angular velocity, w, and the rotational radius, *r,* as $v = w \, x \, r$.

Exercise

To access the web tool, go to: http:/cesar.esa.int/tools/14.differential_rotation

Step 1: Explore the image database:

In the web tool, the students begin by selecting a set of images to investigate from one of the available options. If students choose Option 1 and explore the CESO database, they must make sure that the same sunspot is visible in all the images they select; they can use the magnifier to see the sunspots better. Options 2 and 3, allows direct access to a set of preselected images where sunspots are definitely visible.

Answers to questions in the Student Guide

From your observations, does the sunspot move in a particular direction? Draw a sketch to explain your answer.

The main movement of sunspots is approximately along the horizontal axis or parallel to the Sun's equator, from left to right.

If so, is it in longitude or in latitude?

This is the longitude axis.

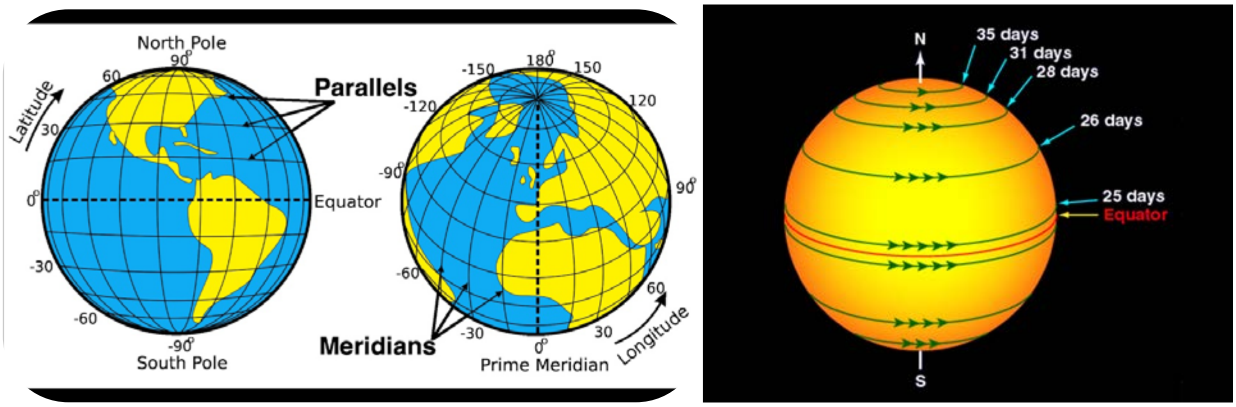


Figure 9: Diagram to show longitude and latitude on Earth, which can also be applied to the Sun (left); Diagram to show the direction that sunspots move across the Sun's surface (right). Credit: http://nishalspace.com, NASA.

Step 2: Get the coordinates of the sunspot.

The students need to measure the radius of the Sun in the images.

The radius of the Sun, measured in pixels, is needed for the web tool to transform the measurement from plane coordinates (*x* and *y* in pixels) to spherical coordinates with the centre of the Sun as a point of reference. For this conversion, it is necessary to know how many pixels are needed to make up the Sun's radius. The equations used (internally) by the web tool are given in Figure 10.

Between Stonyhurst heliographic and heliocentric-cartesian:

$$\begin{aligned} x &= r\cos\Theta\sin(\Phi-\Phi_0), \\ y &= r[\sin\Theta\cos B_0 - \cos\Theta\cos(\Phi-\Phi_0)\sin B_0], \\ z &= r[\sin\Theta\sin B_0 + \cos\Theta\cos(\Phi-\Phi_0)\cos B_0], \end{aligned} \qquad (11)$$

$$\begin{aligned} r &= \sqrt{x^2+y^2+z^2}, \\ \Theta &= \sin^{-1}((y\cos B_0 + z\sin B_0)/r), \\ \Phi &= \Phi_0 + \arg(z\cos B_0 - y\sin B_0, x), \end{aligned} \qquad (12)$$

where B_0 and Φ_0 are the Stonyhurst heliographic latitude and longitude of the observer. If the r dimension is missing, then we make the assumption that $r = R_\odot$. If the z dimension is

Figure 10: Equations used by the web tool to transform plane coordinates to spherical coordinates. Credit: paper "Coordinate systems for solar image data" W. T. Thompson, Astronomy & Astrophysics, 2005 Dec 15.

The values x and y (from the equations in Figure 10) are measured in pixels by the tool when clicking on the sunspot position. $B_{0,}$ is the reference longitude of the Sun per date, collected from a database and, Φ_0, is the reference latitude, based on the date.

As this is done by the web tool the students do not need to do this calculation.

Task 1 asks the students to identify the Sun's radius graphically. They need to click on the black cross at the centre of the image of the Sun and then on the edge of the Sun. This action can be repeated as many times as required should it need to be corrected.

The students will see the radius of the Sun displayed in pixels and in kilometres (an explanation of a pixel can be found in the Student Guide).

Students then measure how much the sunspot appears to have moved across the images they selected.

The date and the time the images where taken is displayed in the web tool. This information is given as year (YYYY), month (MM) and day (DD) and the time is given in hours (hh) and minutes (mm).

The students need to make a note of the date and time each image was taken as well as the longitude and latitude of the sunspot in each image. Some examples of tables to record this information are given in Tables 2.

Image number	Image date (DD-MM-YYYY hh:mm)	Sunspot latitude (degrees)	Sunspot longitude (degrees)
1	07/07/2017 07:24	-6.3	-58.19
2	08/07/2017 10:53	-6.52	-42.65
3	09/07/2017 09:05	-6.77	-29.23
4	10/07/2017 08:08	-6.96	-16.06

Table 2: Example table of results

Step 3: Calculate the Sun rotation period (for a sunspot):

Finally, the students input their measurements into the web tool to calculate the rotation period of the Sun.

Convert minutes into hours:

Image 2, taken at 10:53, so 53 minutes/60 = 0.88 hours.

Image 1, taken at 07:24, so 24 minutes/60 = 0.4 hours

Subtract time of Image 2 from time of image 1:

10.88 -7.4= 3.48 hours, so 3.48/24 = 0.145 days

Next look at the dates the images were taken. They were taken 1 day apart. So, the time difference between the image is:

1 + 0.145 = 1.145 days

Difference between longitude values (in absolute values):

-58.19º - -42.65º = 15.54º

Pair (n,m)	Date(m) – Date(n) (days)	Average Latitude(n,m) (degrees)	Longitude(m) - Longitude(n) (degrees)
(1 , 2)	1.145 days	-6.4	15.54 º
(2 , 3)			

Table 3: Example table of results

If, at the latitude of -6.4 degrees, 1,145 days is the time the sunspot takes to cover 15.54 degrees. To complete one rotation the sunspot will take 26.53 days, this is therefore the rotation period of the Sun at this latitude.

The students should try repeating the calculation of the Sun's rotation period with another set of images that have a sunspot at the same latitude and then calculate an average value.

Step 4: Compare the Sun's rotation period with those of other Solar System bodies.

Do you expect the Sun to rotate faster or slower than the Moon? And compared to Earth?

The Earth rotates much faster than the Sun, which is expected for a smaller body. However, this is not the case of Mercury and Venus. It might be interesting to consider with the students what different processes might be slowing down the rotation of these planets. Table 4 provides the list of rotation periods for other Solar System bodies. The Moon and the Sun rotate at similar velocities.

Celestial object	Rotation period (days)	Rotation period (dd hh mm ss)
Mercury	58.64	$58^d\ 15^h\ 30^m\ 30^s$
Venus	243	$-243^d\ 0^h\ 26^m$
Earth	0.99	$0^d\ 23^h\ 56^m\ 4.09^s$
Moon	27.32	$27^d\ 7^h\ 43^m\ 11.5^s$
Mars	1.02	$1^d\ 0^h\ 37^m\ 22.6^s$
Ceres	0.37	$0^d\ 9^h\ 4^m\ 27.0^s$
Jupiter	0.41	$0^d\ 9^h\ 55^m\ 29.37^s$

Table 4: Rotation periods of various Solar System bodies

Conclusions

Answers to questions in the Student Guide

Are your values of the Sun's rotation period what you expected? Compare your results with those from other groups, are they similar? If not, what could be the reasons for the differences?

The students should compare their result with the hypothesis they made at the beginning of the activity. When comparing results with other groups they should consider the position of the sunspot on the surface – whether it is close to the equator or closer to the poles of the Sun. In addition, errors in the measurement should also be considered as a reason for different results.

Are the values of the Sun's rotation period exactly the same when calculated with a different set of images? Did you expect this? Why?

The different images were collected at different times on different days. Making the calculation with a different pair of images should yield different values. The reasons for these differences could be due to errors in the measurements because the position was selected by hand. The error in identifying the position of the centre of a sunspot the size of Jupiter is higher than for one that is Earth-sized. In addition, only two decimals were used for position (degrees) and time (hours) units and different numbers of sunspots appear at different periods that can make taking the measurements more confusing.

How do you calculate the average of a measurement? Do you think that scientists do it often?

At least 4 images of the Sun are used for this activity to have a sample from which to calculate the result (the rotation period of the Sun). Scientists collect a set of data to have as many values as possible in order to increase the accuracy of calculating their results. From these calculations average values can be estimated, along with the mean and deviations. Measurements that may be corrupted or are outliers are disregarded.

An example of how some statistical values are calculated are given below. This example if taken from http://mathcentral.uregina.ca

Consider the following data points: 1,1,2,3,4

- *The mean or average is (1+1+2+3+4)/5 = 2.2*
- *The median is "2" (the central value).*
- *The mode is "1" (it occurs most often).*
- *The midrange is (4+1)/2 = 2.5*

Activity 4: The Sun's rotation at different latitudes

In this activity students repeat Activity 3. Students will calculate the rotation period of the Sun again using another set of images with sunspots either closer to the poles or closer to the equator than the sunspot they tracked in previous activity.

The students should select another set of images from the CESO database calendar (Option 1) or from any of the selected sets of images provided (Options 2 and/or Option 3). They should record the rotation period they calculate for the each of images in a table with the average latitude of the sunspot.

Answers to questions in the Student Guide

Does the Sun rotate faster depending on:

a) the hemisphere, b) the date, c) the position in latitude? Explain the reasoning for your answers.

The database of the images used in these activities cover a timescale of just 2 years, therefore for these images, the main parameter that effects the rotation speed is the latitude of the sunspot. The Sun's activity has been found to vary over a period of 11 years – this is known as the 'Solar cycle'. Over the timescale of this cycle, different numbers of sunspots appear in different periods.

Does the Sun rotate faster closer to its equator or closer to its poles (in other words where is the value of the rotation period smallest)?

At latitudes close to the equator, the rotational speed is higher; therefore, the Sun's rotation period is lower.

Links

…about Sun

- CESAR Booklet: *The Sun structure, The Magnetic Sun*

…about stars

CESAR Booklet: *Stellar evolution*

…about the electromagnetic spectrum and ESA missions

Ulysses mission:
http://sci.esa.int/ulysses/
SOHO mission:
http://sci.esa.int/soho/
PROBA2 mission:
http://sci.esa.int/proba2/
Solar Orbiter (SOLO) mission:
http://sci.esa.int/solar-orbiter/

CESAR Booklet: *The electromagnetic spectrum*
http://cesar.esa.int/upload/201711/electromagnetic_spectrum_booklet_wboxes.pdf
Science@ESA: *The full spectrum* (video)
http://sci.esa.int/education/44685-science-esa-episode-1-the-full-spectrum/
Science@ESA: *Exploring the infrared universe* (video)
http://sci.esa.int/education/44698-science-esa-episode-3-exploring-the-infrared-universe/

…References:

https://www.windows2universe.org/sun/activity/sunspot_history.html