ASTROEDU
Peer-reviewed Astronomy Education Activities

Measure the Sun's Rotation Period

How much time does it take the Sun to complete a full rotation?

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9-APR-97 09:41:00
6-APR-97 06:29:00
8-APR-97 06:29:00

AGE

16 - 19

LEVEL

Secondary

TIME

1h30

GROUP

Group

SUPERVISED

No

COST PER STUDENT

Low Cost

LOCATION

Small Indoor Setting (e.g. classroom)

CONTENT AREA FOCUS

Astronomy

ASTRONOMY CATEGORIES

The Sun

CORE SKILLS

Planning and carrying out investigations, Analysing and interpreting data, Using mathematics and computational thinking, Engaging in argument from evidence

TYPE(S) OF LEARNING ACTIVITY

Structured-inquiry learning

KEYWORDS

Sun, Rotation, Sunspot, Galileo

GOALS

To apply the simple equation for the average speed to a real-case astronomical phenomenon, in order to determine the Sun's rotation period.

LEARNING OBJECTIVES

- Define the rotation period of an object.

- Apply the kinematic definition of average speed to a “real-case” (where input values are not given in a problem statement but must be measured)
- Distinguish between measurement errors and model assumptions.
- Recognize the Sun as a constantly changing and dynamic celestial object on the basis of observable surface features and its rotating motion.

EVALUATION

To test if the students are able to apply the Kinematics concepts of average speed and rotation period after the activity, one can give them another object to work on, such as the planet Jupiter and use the big red spot.

Example: With a plastic ruler, estimate Jupiter’s rotation period using these two images of its Giant Red Spot. The images were taken on the same day at 16h08 and 17h27.

Besides the live in-class discussions, we propose the following alternatives to evaluate how students have understood the scientific methodology behind this inquiry-based activity.

Each group could make a:

- Road map on an A3 page (poster) summarizing the different steps of their investigation, including illustrations.
- Lab report.

The first option presents the advantage of being doable in class and fosters more interaction within student groups.

MATERIALS

Paper version: Ideally, students will perform the activity in pairs. Thus, for each pair provide one set of:

- PDF file of drawings of sunspots by Galileo Galilei ‘astroedu1801_Galileo_drawings’, to tell the story of Galileo’s measurement in Introduction;
- PDF or PPT file with images of the Sun by Solar Dynamics Observatory (SDO) ‘astroedu1801_SDO_images’ (at least one page with two consecutive images per student pair, see Description of the Activity: Measuring the speed of a sunspot);
- Plastic ruler.

Electronic version: This activity can also be performed on computers either by opening daily images of the Sun in the website www.solarmonitor.org, and taking measurements with an on-screen ruler. Alternatively, they can also open the

.png format images in the astronomy software SalsaJ and take the measurements in the software.

- All the images in .png format and .jpg in the folder ‘astroedu1801_SDO_images_set’ file
- On-screen ruler (Edge web-ruler app for Chrome)
- SalsaJ software: http://eu-hou.net/index.php/salsaj-software-mainmenu-9?task=view&id=7
- A movie of the SDO dataset compiled with SalsaJ ‘astroedu1801_dataset_movie’ file
- A movie of Galileo’s drawings ‘astroedu1801_Galileo_drawings_movie’ file

If you want to show an animated movie of the rotation of the Sun based on the dataset you are using, you will need SalsaJ and a computer with beamer (see Introduction part in the Description of the activity).

Note about SDO images: The image set we provide was directly downloaded from the website solar monitor (http://www.solarmonitor.org). This dataset was close in time to the last solar maximum (2013) and carefully chosen to (1) display a large number of sunspots, allowing students to look at different sunspots to look and compare their results, and (2) have the solar equator quasi horizontal (perpendicular to the observer’s line-of-sight), which makes the apparent motion of the sunspots quasi-linear (minimizing measurement errors with a straight ruler).

Feel free to choose any other set of images from this website, provided you select enough consecutive days to cover, at least, a solar rotation.

BACKGROUND INFORMATION

Teachers should be aware of *Galileo’s dilemma about the nature of sunspots*, the later discovered *magnetic nature of sunspots as well as the differential (non-rigid) rotation of the Sun*.

Here we provide a brief overview of the structure of the Sun, Galileo’s historical observations, the nature of sunspots, the non-rigid rotation of the Sun and an introduction to the satellite mission that produced the data used in this activity. At the end of each subsection, we provided links where teachers can read more about these topics.

The composition of the Sun

The Sun is a giant gaseous ball composed of mostly hydrogen and helium. Due to the extremely high temperatures in the Sun, the electrons can detach from their atom’s nuclei and are free to move. This state of matter is called “plasma”.

The Sun can be divided into 5 layers: the core, the radiative zone, the convective zone, the photosphere, and the atmosphere. The core is the innermost layer and it is the place where energy is produced by nuclear fusion (~ 15 million °C). The radiative zone extends from the core to about 70% of the solar radius and here the energy is transported mainly through radiation (photons are emitted, absorbed and re-emitted continuously). In the next layer, the convective zone, energy is transported by convection (upward movement of hot matter and downward movement of cold matter, similar to the boiling of a soup). The photosphere, at ~ 6000 °C, sits right above the convective zone. Since it is the layer from which most of the light comes, we call it the solar surface, although we would not be able to stand on it.

Beyond the photosphere, we find the solar atmosphere, which is composed of two other layers: the chromosphere and the corona. The chromosphere is a thin reddish gaseous layer immediately above the surface. The corona is the Sun's very thin plasma atmosphere, extending millions of kilometres into space.

Visit http://solarscience.msfc.nasa.gov for more information.

Galileo's sunspot observations

In 1612 Galileo Galilei pointed a telescope at the Sun. He was one of the first to do this, preceded by Thomas Harriott and Johannes Fabricius. Galileo knew that if he looked directly through the telescope, he could burn his eye. Instead, he projected the image on a screen to make careful drawings. In Galileo's time people believed that the Sun was a still, perfectly immaculate object. To his great surprise, he saw dark spots on the Sun. He was very intrigued by the nature of these spots, and therefore he observed and sketched them on a daily basis to study them.

Visit http://galileo.rice.edu/sci/observations/sunspots.html for more information.

The magnetic nature of sunspots

The nature of sunspots remained an enigma until 1905, when the astronomer George Ellery Hale detected intense magnetic fields within these dark regions. Using a spectroheliograph he found that a certain property of the light (polarisation) emitted by the Sun was altered in a way that is specifically caused by magnetic fields. Today, satellites like Solar Dynamics Observatory (SDO) are equipped with special instruments to detect the location of magnetic fields on the Sun and infer their intensity. Figure 1 shows two images of the same day, obtained by SDO: a visible-light image of the whole solar disc and a map of the orientation and intensity of the magnetic fields present on the solar disc (magnetogram).

Sunspots are seen in the photosphere as dark features in contrast to the rest of the solar surface, because the matter within them is about 2000 °C cooler than their surroundings at ~ 6000 °C. The intense magnetic fields are responsible for this cooling. Since magnetic fields produce pressure, plasma inside sunspots is forced out to maintain pressure equilibrium between the sunspot (gas pressure plus magnetic pressure) and the surrounding plasma (gas pressure). Therefore the plasma inside the sunspot is less dense and a little cooler.

Sunspots usually clump together in groups and have lifetimes between several days and weeks. Sunspots are dynamic and evolve together with the magnetic field: they appear, change, disappear. Their number varies periodically with time together with the amount of magnetic field of the Sun, following the so-called 11-year sunspot cycle: every 11 years, the sunspot number and the amount of magnetic field reach a maximum (called "solar maximum"), followed by a minimum with barely any spots on the Sun. The dataset proposed in this activity is chosen close to the solar maximum, in order to display a large number of sunspots.

Sunspots are found in patches like storms on Earth and are usually located in bands in both the northern and southern hemispheres. The bands that sunspots form in, move from mid-latitudes to almost the equator throughout the 11-year sunspot cycle. Note that individual sunspots do not drift much in latitude since they only exist for a few weeks - just the latitudes where new spots form move towards the equator.

Fig. 1: Magnetogram and visible light image of the solar disc on the same day (see text for more details).

- Visit http://solar-center.stanford.edu/solar-images/magnetograms.html for more information on solar magnetograms.
- Visit https://www.nasa.gov/content/goddard/how-sdo-sees-the-sun for more information on visible-light images of the Sun.

The rotation of the Sun

As seen from the Earth the Sun rotates about its axis in about 27 days. The Sun's equator is almost in the plane of the Earth's orbit so the Sun's north pole is in the same direction as the Earth's north pole. Seen from above the solar north pole, the Sun rotates counter-clockwise. Most modern images of the Sun are oriented so that the solar north is up and features on its surface then move from left to right as the Sun rotates. Note that Galileo's drawings of sunspots (Fig. 3) are not oriented this way.

The non-rigid rotation of the Sun

Rigid objects do not change shape (i.e. they are non-deformable). Therefore, when rigid objects spin every part rotates at the same rhythm. This means that every part of the object takes the same amount of time to complete a turn. This is called rigid rotation. This is the reason why every spot on Earth takes 24 hours to complete a turn.

In non-rigid objects, i.e. deformable objects, rotation is different in different parts of the object. This is the case of the Sun since it is made up of a gaseous matter called plasma. Like the Earth, the Sun has a North pole and a South pole, and rotates around its axis. However, the Sun's plasma near the equator completes a full turn in a little less than 27 days, whereas plasma near the poles can complete a full turn in as much as 35 days. This means that plasma can rotate at different speeds, depending on the latitude they are at: i.e. faster at the equator than at the poles. This is called differential rotation.

If you measure the Earth's rotation by measuring winds or the motion of clouds, you will find that the rotation of the Earth's atmosphere also varies with latitude. This is because the Earth's atmosphere is a gas and not a solid. As seen from space, the atmosphere rotates in less than 24 hours at mid-latitudes and in more than 24 hours near the equator. We call this the "Westerlies" and "Trade winds" respectively. Differential rotation is not a unique aspect of the Sun; it is common for rotating bodies such as other stars and gaseous planets to have different rotation rates at different latitudes.

Visit http://astronomy.swin.edu.au/cosmos/D/Differential+Rotation for more information.

The Solar Dynamics Observatory

The Solar Dynamics Observatory (SDO) is a satellite mission from NASA. It was launched into an orbit around the Earth in 2010 and it has been observing the Sun since then. SDO's main goal is to study the solar atmosphere to understand better the relationship between the solar magnetic fields and energetic, short-term phenomena such as solar flares and coronal mass ejections.

Visit http://sdo.gsfc.nasa.gov for more information.

Other useful links about the solar cycle

http://solarscience.msfc.nasa.gov/SunspotCycle.shtml

FULL ACTIVITY DESCRIPTION

Tips to the teacher:

This part requires students to carefully follow steps of actions, so it is advisable to have a lab worksheet prepared to distribute to them.

If you have a beamer and an internet connection, we encourage the use of a google spreadsheet for students to list their results (see Discussion part). This enables them to work collaboratively and compare their results. It also allows you to easily average their results as well as to graph them. Otherwise, you can draw a large measurement table on the blackboard for students to write their measurements (and easily erase them if they find calculation errors).

Observed student difficulties:

In this activity, students want to compute the rotation period T by using the speed v of a sunspot and the length of its trajectory L: T = L/v. Some students are confused by the fact that neither L nor v is known (unlike in a conventional problem statement), and the teacher must insist that this is precisely why they should be measured.

This activity requires students to use twice the equation for average speed: To calculate the displacement speed of a sunspot, and to compute the rotation period. Some students confuse the two. To guide the students, the teacher can, for instance, write in big the equations on the blackboard with the link between them, as in Fig. 2 below. We suggest not to do so right at the beginning, for students to come up with those links themselves, but later in the activity, once they've figured it out.

Fig. 2: Equations used in the activity and the link between them.

1. INTRODUCTION

1) Engage students in the historical context of this activity, by telling them how Galileo "surprisingly" discovered moving sunspots on the Sun.

2) Tell them how, at the time of Galileo, the heavens were considered "still and immaculate". But Galileo was curious and determined to test ideas by himself. When he pointed his telescope to the Sun, he discovered, to his great surprise, that the Sun had dark spots and that from one day to the next, these were moving across the solar surface.

3) Distribute to the class copies of Galileo's drawings (file 'Galileo drawings.pdf'), also shown in Fig. 3

Fig. 3: Galileo Galilei's drawings from 24-27 June 1613. Note that the solar north pole is not oriented straight up, as it usually is in modern scientific images.

4) If you have a beamer, you can project the movie ‘Galileo drawings’.

5) Ask them what they think these sunspots could be, and tell them that Galileo himself was puzzled (we only know their “magnetic” nature since 1905, see Background).

6) Ask them why they think sunspots appear to be moving.

7) If you have a beamer, play a movie of the Sun rotating with the SDO images provided by the activity (in .jpg format, as these do not have latitude lines). This way the students can “see” and “feel” the solar rotation. You can use the free astronomy-for-classroom software SalsaJ (see “How to create an animation with several images” at http://eu-hou.net/index.php/salsaj-software-mainmenu-9/manual-salsaj-2)

8) While they watch the movie, insist on the idea that everything is in motion in the Universe and everything spins!

9) Make students come up with the idea of measuring the rotation period and how to do it.

Ask them:
- Knowing that the Sun is rotating, what could we try to measure?
- If you had these images (the ones shown in the movie) in your hands, how do you think you could determine the rotation period?
They might say that we could wait for a sunspot to make a complete turn and reappear at the same position. Unfortunately, most sunspots do not “live” that long.
- What if you could measure the average speed of a sunspot?

10) Group students in pairs and give each pair an example of a printed dataset (at least two images) or show them how to find the images on the computer if doing the activity electronically (www.solarmonitor.org).

11) Now that students are convinced that the Sun is a rotating celestial body, their task as scientists will be to calculate as precisely as possible the time it takes to complete a full rotation, that we call the rotation period T.

2. MODELLING THE TRAJECTORY OF SUNSPOTS

Model– We will assume that the Sun is perfectly spherical and that it rotates as a rigid body at a constant pace. In that case, the Sunspots on the solar surface are moving at a constant speed.

With this simple model, calculating the rotation period is equivalent to determining the time needed for a sunspot to complete a full turn around the Sun.

Students should first grasp how we can describe the motion of a sunspot on a spherical Sun and how the rotation period relates to the sunspot speed and trajectory length.

Fig. 4: Sketch of a sunspot’s trajectory as seen from Earth (front view), and the same trajectory if we could see the Sun in top view, evidencing a circular trajectory (in green).

1) Draw schematics of the Sun along with a sunspot and its trajectory as viewed from the front (i.e. as we would see it from Earth). See Fig. 4.

2) Let students complete the top view (i.e. if we were looking at the Sun from above its North pole) and add the trajectory of the Sunspot represented in the front view (in green in the image below). We will note the length of this trajectory as L. What is the shape of this trajectory? Figure 4 shows the correct circular trajectory as a dashed-green line.

3) Ask students: If they knew the speed of a sunspot v, and the length of the trajectory L, how could they compute the rotation period of the Sun? We will note this period as T.

4) Let students write their equation for T: they should find T = L/v.

5) Write their equation in big letters on the board.

6) Explain to students that in this problem, L and v are unknowns. How to find them? They'll need to measure them from the images.

7) Ask the students to check the units in the equation: To compute the rotation period with their equation, do they need to know the scale of the images (i.e. to have distances in km), or can they simply use a ruler and measure distances in cm and speeds in cm/h? Students should find that the distance units cancel out in the equation for T. Although images are smaller spatial representations of reality, the time dimension is unchanged.

3. MEASURING THE SPEED OF A SUNSPOT

To benefit the final discussion, it is best that each student group works with a different sunspot, in order to compare the measurements performed on different spots.

1) Depending on the number of students and the activity timing, you can either let them choose a sunspot number (indicated on the images) within the complete dataset or assign a sunspot number to each student pair from the start. In the latter case, it is sufficient to give them two consecutive images featuring that spot near the disk centre.

2) If you did not assign a specific sunspot to each group, tell students to look at the dataset, choose a sunspot and find its 5-digit number. Make sure that different student pairs chose different sunspots (write them on the blackboard or on a google spreadsheet if you can project it);

3) Tell them to look at consecutive images of that spot and think about how they could measure the average speed of that spot in [cm/h].

4) Assuming that sunspots move at a constant speed on the surface of the Sun, their instantaneous speed at any instant in time is equal to their average speed. We can then simply apply the equation of the average speed between two images :

v = d/tel = (distance travelled between the two images) / (elapsed time between the images) [cm/h]

5) By using a flexible ruler on a spherical ball (simulating the Sun) as in Fig. 5, ask students where is it easier to read the ruler to estimate distances: near the centre or near the edge of the ball? This should guide the students to the idea of taking two consecutive images of a sunspot near the disk centre. Otherwise, the distances will appear foreshortened. For the same reason, it is best that the images are close in time (in the case of this dataset, the minimum separation is one day).

Fig. 5: A flexible ruler on a ball illustrates that in an image of a spherical object, only the distances measured near the disk centre are accurate because the distances nearer the limb are foreshortened.

From here, student teams can follow these steps:

1) Pick two consecutive images of their numbered sunspot near disk centre.

2) Think about a method to measure as precisely as possible the distance travelled d (cm) by the spot between the two consecutive images, with the help of a ruler. As an example, Fig. 6 shows the displacement of sunspot 12218 between the 29th and 30th November. (With the paper version of the activity, students can use the left edge of the images as a reference to place the ruler, or the white longitude lines on the images as help to place their rulers.)

3) Find the elapsed time t (h) between the two consecutive images (the time at which an image was taken is indicated at the top of each image).

4) Compute the speed v.

5) Write the measurements on the blackboard or in a google spreadsheet.

Fig. 6: Measuring displacement. Letter “d” represents the distance travelled by a spot between two consecutive images (see text for more information).

4. MEASURING THE LENGTH OF THE TRAJECTORY

Students should :

- Draw the diameter D of the trajectory on the front and top views of the sketches of they did at the beginning of the activity (see Fig. 7).

Fig. 7: Sketch of the full diameter travelled by a sunspot.

- Measure the diameter D of the sunspot’s trajectory on the images as shown in Fig. 8. How can this measurement be used to compute the length of the trajectory L? Students are expected to use the perimeter-diameter relationship for a circle: $L = \pi D$

Fig. 8: Measuring the diameter D of the spot trajectory (in this case sunspot 12236)

5. COMPUTING THE ROTATION PERIOD

- Students can use their previous measurements to compute the rotation period T in hours and in terrestrial days (1 day = 24 h) using the formula: $T = L/v$.
- When they finish, students should write all their values on the blackboard table or the google spreadsheet.
- Using the blackboard or a google spreadsheet will make all their results visible to the class and facilitate the discussion (see Table 1 for an example).

Table 1: Measurements taken for all sunspots that were near the disk centre for two consecutive days. The mean value of T is 26.8 terrestrial days for this dataset.

6. COMPARING AND DISCUSSING THE MEASUREMENTS

Now the student teams will compare their results between themselves and with the official value. They should obtain rotation period values close to 26 or 27 days, otherwise, check for calculation errors.

Also, pay attention to whether students have chosen images where their spot is near the disk centre, otherwise they will underestimate the distance travelled by the spots between the two images, and therefore underestimate the velocity and overestimate the rotation period (see below).

- Show them the official value from Wikipedia (https://en.wikipedia.org/wiki/Solar_rotation) or NASA (https://www.nasa.gov/mission_pages/sunearth/science/solar-rotation.html), or tell them to search for it if they are on a computer. You have to search for the “synodic” rotation period (about 27 days).

How close are they from the official value?

You can make them compute a relative error.

- Ask them to examine all results of T: *Did all student pairs agree on the same value? Let’s find out why!*

- Each team shall explain to the rest of the class how they performed their measurement (especially of the distance travelled d).

Can you find some measurements errors or calculation errors?

As scientists, it is crucial to discuss why we did not obtain a single “true” answer to our question. The experimental nature of science means that we never get a unique answer: Measurement results fluctuate either because the phenomenon itself fluctuates or because WE fluctuate in our way of measuring things! So let us consider explanations for the discrepancies.

- If you recorded the measurements of students in a spreadsheet, you can plot their values of T against sunspot number to make them see the dispersion in their results (see Fig. 9).

Fig. 9: Rotation period vs. Sunspot number for all the spots measured in Table 1. The horizontal line is the mean value of the dataset.

- Make students think about the phenomenon of solar rotation and the model they used to describe it:

Think about the model we considered to start with… can we really model the Sun as a rigid body? Why or why not?

How about the sunspots, do they look exactly the same on two consecutive days? Why or why not?

Scientists have shown that the rotation period is longer near the poles (sidereal rotation period of up to 38 days) than at the equator (about 25 days), a phenomenon called differential rotation or non-rigid rotation. Yet students won’t be able to clearly see this on your dataset because most spots are close to the equator.

- Ask students: How can we combine all measurements to compare them with the official value?

We can compute an average value and its uncertainty. At school level, the uncertainty can simply be taken as a "dispersion" or "rank", taking care of removing outlier measurements: (max value - min value)/2. Here we find a dispersion of ±2 days (a more proper standard deviation yields 1.4 days).

- Average the measurements of T obtained by all teams to get a class average (see Table 1 and Fig. 9). Compare again with the official value.

How close is it to the official value?

Do they agree within the uncertainty of our measurement? That's great teamwork!

- Make students realize that they succeeded in measuring the rotation period of a star using only one Kinematics equation (average speed)!

- Make students reflect about the meaning of their average value of T:

Compare the rotation period of the Sun you calculated with the rotation period of the Earth: is it shorter? longer? Does it make sense to you (think about the relative sizes)?

Suppose you are a solar astronomer and find a new sunspot appearing near the left border of the solar disk. How long do you have to observe this spot before it disappears on the right side?

- Finally, let us question the observer's perspective on the average rotation period. Does it really represent the time that the Sun actually takes to rotate on itself, or is it also a matter of the observer's perspective? Think about the fact that the images were taken from Earth, which revolves around the Sun.

Since we have not taken into account the motion of the Earth around the Sun in our treatment, all we can say is that as viewed from the Earth (in this case, from the SDO satellite that orbits the Earth), a feature on the Sun's surface completes one rotation on around the Sun in about 27 Earth days (which is called "synodic" rotation period). Yet because the Earth orbits the Sun in the same direction as the Sun rotates (see Fig. 10), this rotation period as seen from the Earth is longer than the rotation period of the Sun seen from a static observer, which is about 25 days (called the "sidereal" rotation period).

Fig. 10: Sketch showing how the Earth revolves around the Sun in the same direction as the Sun's rotation.

CURRICULUM

ADDITIONAL INFORMATION

This activity demonstrates to students the power of a simple definition from classical Kinematics and how it can be used to perform a rather precise calculation. It fits well inside an introductory physics course such as a first-year high-school, where Kinematics and basic Astronomy are studied.

CONCLUSION

Students start the activity with some evidence that our star, the Sun, also rotates about its own axis, like the Earth.
With the aim of determining the rotation period of the Sun, they use modern satellite images of the Sun and apply simple kinematics (average speed) and geometry (perimeter of the circular trajectory) concepts.

By finding a value close to the official synodic value of 27 days, they realize just how powerful the kinematics equations are to describe motion.

By comparing their results, they become also aware of their dispersion and of its possible sources: measurement errors by them, and non-rigid rotation by the Sun.

ATTACHMENTS

- astroedu1801_Galileo_drawings.pdf
- astroedu1801_SDO_images_PDF.pdf
- astroedu1801_SDO_images_PPT.pptx
- astroedu1801_SDO_images_set.rar
- astroedu1801_dataset_movie.mp4
- astroedu1801_Galileo_drawings_movie.mpg

ALL ATTACHMENTS

All attachments

CITATION

Kobel, P.; Espuig, M. D.,; Scherrer, D., 2018, *Measure the Sun's Rotation Period*, astroEDU,

ACKNOWLEDGEMENT

Eva Ntornousi for reviewing the activity. The GalileoMobile team who tested the activity in schools in India and Uganda. Teachers and students who provided feedback. This activity is part of the GalileoMobile Handbook of activities www.galileo-mobile.org