Teacher’s guide

CESAR Science Case – The differential rotation of the Sun and its Chromosphere

- **Material that is necessary during the laboratory**

  - CESAR Astronomical word list
  - CESAR Booklet
  - CESAR Formula sheet
  - CESAR Student’s guide
  - CESAR images of the Sun
  - The software for this Science Case
  - Paper, pencil, ruler, calculator, protractor

Introduction

This Science Case is separated into two sections. The first section is about to understand how the Sun rotates i.e. to understand that the Sun is not a solid body and it moves faster close to the equators and slower as we get close to the poles. That is the Sun’s differential rotation of the Sun. The other section is about visualizing the different structures of the Sun’s chromosphere. The students have to identify as much structures as they could and understand what they are. This is an easier Science Case compared with the others solar Science Cases, for this reason this one is focused in the understanding of the Sun and has not many calculus or measurements.

To do this Science Case a set of 3-7 images of the Sun separated by 24h (or more) in the time of acquisition has to be acquired with both the visual telescope and the h-Alpha telescope. Then the students have to calculate the heliographic coordinates of at least two sunspots that have to be as much separated in latitude as possible. It will be all explained later. Then they have to track the selected sunspots using all the images, writing its coordinates. To get the coordinates it is highly recommended to use the software that CESAR provides but a general method is going to be included here for you (note that is the method included in the Science Case: “Solar activity and the solar cycle” for calculating the sunspots coordinates). Using these coordinates, they will be able to see how the angular velocity of the Suns depends on the latitude.

To get the images there are two possible solutions. If the robotic CESAR solar telescope is available for observation and image capturing, you can download images from the archive. If the CESAR solar telescope is not available or if you don’t want to use it, the other option is to download a set of preselected images from the CESAR website for this Science Case and use them. Obviously part of the educational purpose is to approach professional telescopes to the students so they could learn how professional observatories works. Moreover they would be able to see how remotely a telescope moves as they want (pointing the Sun in this Science Case).

It could happen that the day of observation no sunspots are visible. In that case, it’s impossible to do this laboratory. For this reason you could check if there are sunspots available before at http://soho.nascom.nasa.gov/sunspots/.

To achieve a good knowledge of the Sun’s surface give them the booklet. There are a lot of structures in the Sun’s surface explained that they will have to identify on the h-Alpha images.

Sunspots tracking

Choosing the sunspots from the set of images

As mentioned in the laboratory description, your students need to get the images and its dates for the observations. They need to name some of the sunspots to keep them on track. What name it does not matter, but each spot should have its individual name. Furthermore it's important to choose those spots that are closer to the centre of the Sun. It is preferable because it's easier to appreciate the displacement of a sunspot on the images if it is near to the centre and consequently it's easier to do the measures.

After taking the images with the CESAR telescope, decide if it's worth to process the images or not. It should not be necessary since the quality probably will be good enough. The sunspots must be clearly visible and not blurred. If you consider that sunspots are not clearly visible, try to increase the contrast with an image processing program in order to distinguish them.

A very important thing that has to be mentioned is that the images have to be aligned in E-W direction in the solar disk. This is the first requirement to determinate the orientation of the Sun and its heliographic coordinates. The CESAR images will already been aligned but if you have considered to do this Science Case using your own telescope with an equatorial mount a trick to get the E-W direction is to take pictures while moving in Right-Ascension. If you take two pictures for example and superpose them into a single one, draw a line that connect the same sunspot of the two frames. That is the E-W direction, and you can now rotate the image to see the E-W direction parallel to the mark frame as showed below.

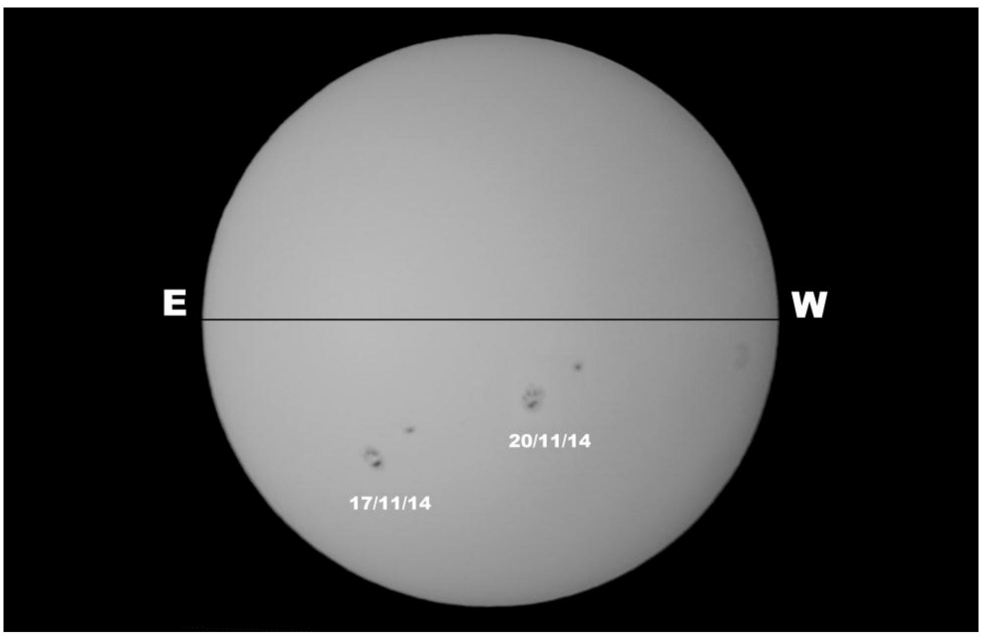

Figure 1: Image showing the *E-W direction where two pictures taken at two separated dates where superposed.* *Credit: CESAR*

Until now, we have a set of images on visible and h-Alpha captured at different times and oriented on E-W direction. Now we are going to determinate the heliographic coordinates for the sunspots.

Heliographic coordinates

Determine the heliographic coordinates of the sunspots

The heliographic coordinates are the coordinates of the Sun. As well as a place in the Earth has a longitude and a latitude in the Sun is exactly the same. A sunspot has a longitude and latitude on its surface too. Its latitude is divided into 90 degrees north to the equator, and 90 degrees south to the equator. Its longitude is divided into 360 degrees to the West in the direction of the solar rotation. The Sun as the Earth has a place from which to start counting the longitude degrees.

As well as the Earth has a rotational axis, the Sun too. It's well known that the Earth' rotational axis is tilted 23,5 degrees while the Sun's rotational axis is tilted 7 degrees. If both Earth and Sun rotational axis were parallel between them and perpendicular to the ecliptic, then the E-W direction that we mentioned before would be the equator of the Sun.

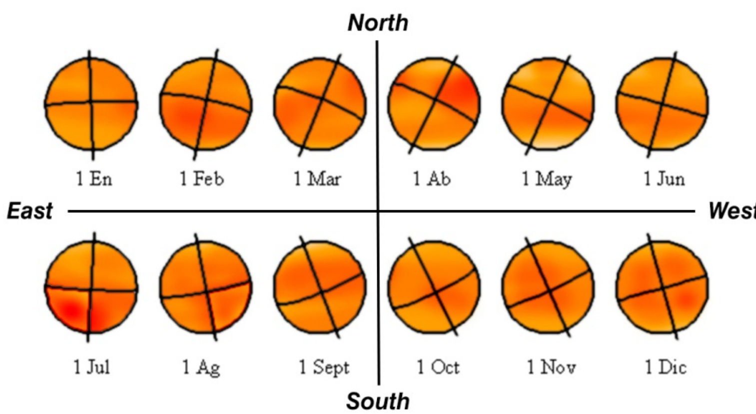

Figure 2: *Inclination of the solar axis along a year viewed from Earth. Credit CESAR*

What we are going to do now is to calculate the heliographic coordinates of the sunspots using the coordinates of the sunspots in the E-W and N-S coordinate system. In order to do this, students first have to measure the position of the sunspots from the center of the Sun using the first images, not the h-Alpha images. The center of the Sun has to be located because is the center of our reference system. Students have to create a table like this:

Sunspot	X coordinate	Y coordinate	R_m	R
1	356 pixels	232 pixels	425 pixels	3115 pixels
…	…	…	…	

Where R_m is $\sqrt{X^2 + Y^2}$ and R is the diameter of the Sun that they have to measure too (only once).

We need now to calculate other values using the X and Y coordinates of the sunspots. This values are the position angle of the sunspot measured from N-S direction (that we call P_m) and the angle between the sunspot with the visual (that we call ρ). Their formulas to are:

$$P_m = arc\ tg(^X/_Y) \quad (1) \quad \text{and} \quad \rho = arc\ sin\ (R_m/R) - \alpha/2(R_m/R) \quad (2)$$

Where α is de angular diameter of the Sun (on degrees).

This values are going to be automatically calculated by the CESAR software for this Science Case.

As well as in the first table, the students have to note the values of P_m and ρ for each sunspot in a table:

Sunspot	P_m(°)	ρ (°)
1	56,9	7,8
…	…	…

As we said, the Sun's axis is tilt so we see different angles with the N-S direction along a year. Furthermore the center of the heliographic coordinate system is not the place where E-W and N-S lines cross each other. For all of this, we need to take some values which are:

P: Is the position angle of the solar rotation axis measured from the N-S direction. Positive when it's to the East and negative when it's to the West.

B_0: Heliographic latitude of the solar disk center.

L_0: Heliographic longitude of the solar disk center.

To make this Science Case easier, we could take these values from the Ephemeris. There are some websites such as: http://alpo-astronomy.org/solarblog/wp-content/uploads/ephems/ephem2015.html or http://bass2000.obspm.fr/ephem.php. Here there is a picture showing all these values.

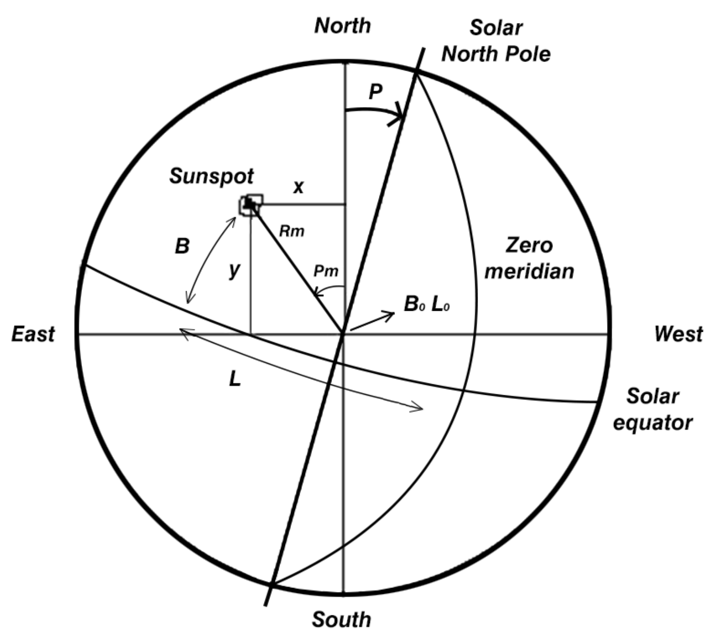

Figure 3: *Picture showing all mentioned values. Credit: CESAR*

At this point, the students will obtain the heliographic coordinates of any of the sunspots by filling the values: $R_m, R, \rho, P, P_m, L_0$ and B_0 in the gaps. The formulas besides to calculate the coordinates are:

$$sen(B) = sen(B_0)\,cos(\rho) + cos(B_0)\,sen(\rho)\,cos(P - P_m) \quad (3)$$

$$sen(L - L_0) = sen(P - P_m) sen(\rho) cos\,(B) \quad (4)$$

Where B is the latitude and L the longitude. Note that all of the values that are used in the formula are expressed in degrees as well as the results.

To sum up, the most important part is to write down all the data on a paper. The students should create a final table as the one below:

Date/time	Sunspot	Longitude(˚)	Latitude(˚)	Observations
17/11/14 – 12:00	1	242,813	-18,209	
…	…	…	…	

As we have said, the software at the website simply ask the students to do some measurements of the sunspots and then automatically calculate the heliographic coordinates.

It was said that the students have to choose at least two sunspots at different latitudes. The reason for that is because the differential rotation of the Sun is more appreciable if you compare the angular rate at the equator with the angular rate of a sunspot close to a pole. For example a good choice would be to get a sunspot at 5-10 degrees and the other at 20-25 degrees. It doesn't matter if they are on different hemispheres, just consider the of latitude in absolute value.

Grid alignment

Align the images with a grid of heliographic coordinates

As it was mentioned there is an easy way to estimate the coordinates. Using a grid of the Sun with the coordinates, a sunspot could be easily located without doing all the measurements that we explained before.

The first step for this is to download the exact grid for the day when the images were taken. Here is the website for this: http://bass2000.obspm.fr/ephem.php At the website you just have to select the date and time and select "grid" to compute.

Once it has been downloaded we need to superpose it to the image. There are two ways to do this, the first one is to print both (the image and the grid) and draw the sunspot over the grid. The other option is to superpose the grid using software. With this Science Case we provide software to do that. In both cases, is essential to rotate the image the angle P to align the image with the north solar pole.

Now it's very easy to estimate the position of any of the sunspots. We are also able to determinate the size (in terms of heliographic coordinates) of a filament (if for example a h-alpha filter were used) or the size of a group of sunspots as showed in the Science Case: Sun's differential rotation.

The picture result of superposing the image and the grid should be similar to the one below:

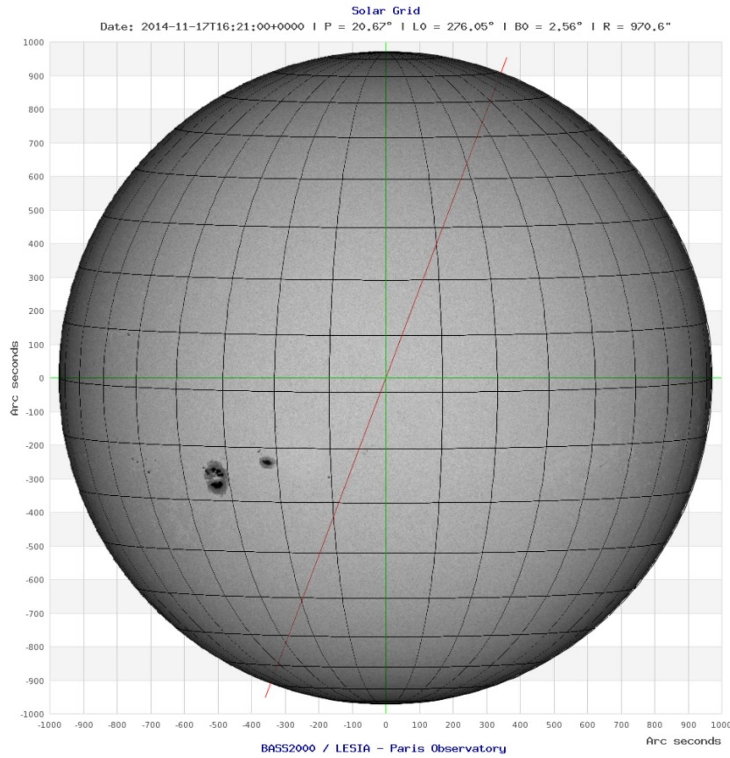

Figure 4: *Heliographic coordinates superposed to an image of the Sun. Credit: CESAR/LEISA*

Sun's differential rotation

Different angular velocity depending on the sunspot latitude

As we have said, the angular velocity of the Sun depends on the latitude. As we now have the position of the sunspots for all of the days students can calculate that different angular velocity.

After the student has the change in angle written down for each day and each sunspot, they can calculate the angular velocity of the Sun. You should first explain what angular velocity is. A brief explanation can be that it is a measure of how fast something is moving on a sphere (or in a circle). It is the angle by which an object turns in a specific time that is the rotation rate. This is a pretty straightforward exercise and the mathematics is not complex.

Now to the calculations. First the students have to calculate the period of time between each pair of images i.e. the period of time between the first and the second image, then the time between the second and the third and so on. They could express that time in days or seconds. Once it has been done, they have to calculate the number of longitudinal degrees that the sunspot have been moving during each pair of images expressed in degrees. To make it easier, they could create another table with only the necessary values and the intervals. Here is an example of that table that has to be filled for each sunspot:

Sunspot 1		Latitude 16
Pair	**Longitude difference (°)**	**Time difference (days)**
1-2	12,325	0,987
2-3	12,380	0,991
…	…	…

They now have to calculate the mean of the longitude differences and the mean of the time difference and simply use the formula:

$$Angular\ vlocity = \frac{Longitude\ difference}{Time\ difference}\ \ [degrees/day\ \ or\ degrees/second] \qquad (5)$$

To compare with the real angular velocity and see if they did well, here is a table:

Sun's angular velocity	
Latitude (°)	**Velocity (°/day)**
0	14.71
5	14.69
10	14.64
15	14.54
20	14.41
25	14.23
30	14.00
35	13.73
40	13.42
45	13.07
50	12.69
55	12.30
60	11.91
65	11.54
70	11.20
75	10.92
80	10.71
85	10.58
90	10.53

It's very important for the students to understand that if the Sun were a solid body, all the surface should then rotate at the same angular velocity. That means that if the equator rotates at 14.71 degrees per day, also the poles should be rotating at that rate but they actually move slower than the equator.

As we said the students had to try to measure at least two spots at with very different latitudes but most of the time it is difficult to find two sunspots separated more than 5-10 degrees so don't be worried about that.

Finally, they can compare the angular velocity of the Sun with the angular velocity of the Solar System planets. They should have a short discussion about this and they can compare their results with this table:

Planet's angular velocity	
Planet	**Velocity (°/day)**
Mercury	6,14
Venus	1,48
Earth	360
Mars	350,89
Jupiter	870,53
Saturn	818,96
Uranus	501,16
Neptune	536,27

Elements of the chromosphere

Find different structures of the Sun using CESAR h-Alpha images

Now it is time to use the other set of photos those that were taken with the h-Alpha telescope. An h-Alpha telescope basically restricts the incoming light of the Sun in the way that we could only see its chromosphere instead of the photosphere.

Using an h-Alpha telescope we could for example watch the evolution of a mass ejection, the protuberances and spicules. Most of these structures have a very fast dynamic so they could appear and disappear in the same day. This is the reason why we provide you a whole set of images with the h-Alpha telescope instead of only one despite there is no sunspot tracking this time. Maybe the first day of observations the Sun seems to be calmed but the next days a lot of activity on its chromosphere could appears.

The task for the students is to identify these structures and get some knowledge about what they are. For this, there is a sample picture of the Sun in their Student's Guide with a short description of each element on the chromosphere.

Follow the instructions of the CESAR software or just tell the students that they have to count the number of each element and have a discussion for each founded element. The teacher should have a good clear knowledge about the differences between each element. For example, a protuberance may looks like a dark filament on the Sun's surface but when you look at them when they are in the limb they looks like a loop out of the solar disk.

Here is an example of an h-Alpha image where all the chromosphere parts are indicated:

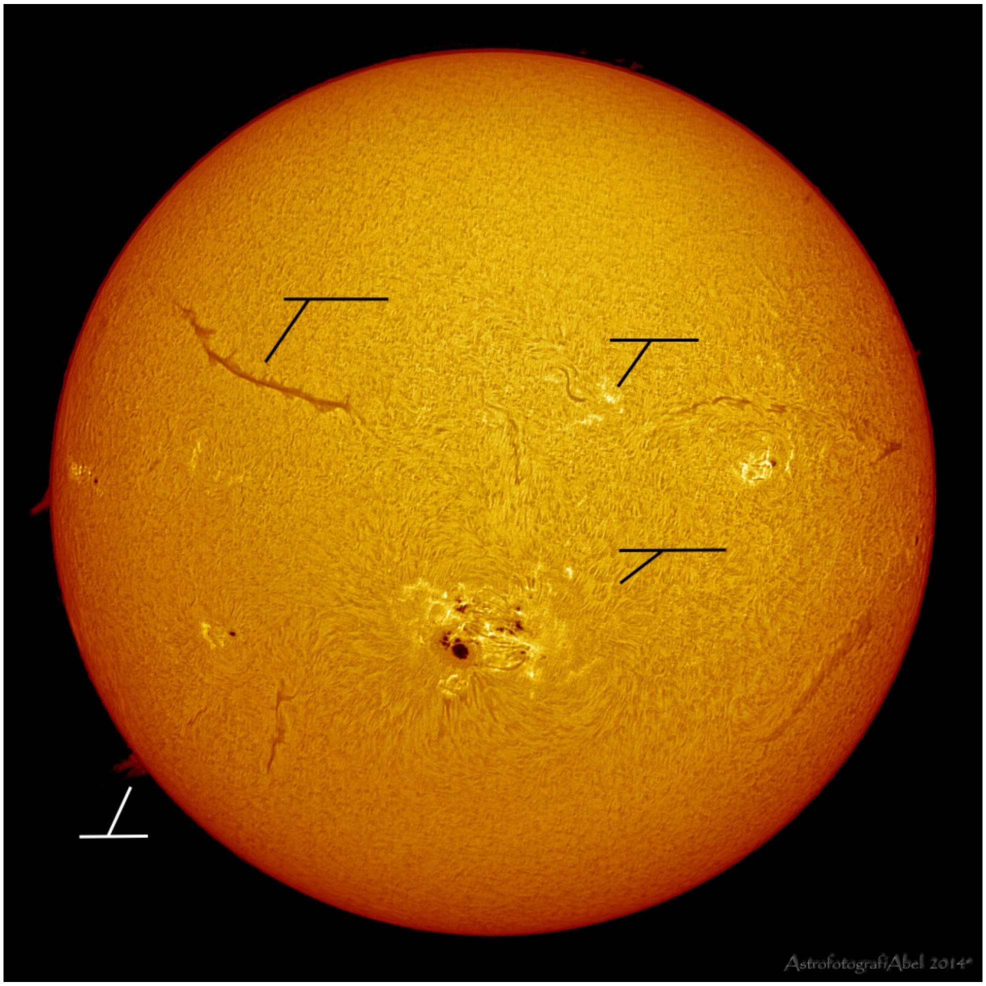

Figure 5: *Sun´s characteristics. Credit: CESAR*

The laboratory is now done. End by having a discussion about what they have done and summarize the laboratory too see if every group have understood the laboratory.