3. Differential solar rotation
Astrolab Landessternwarte Königstuhl

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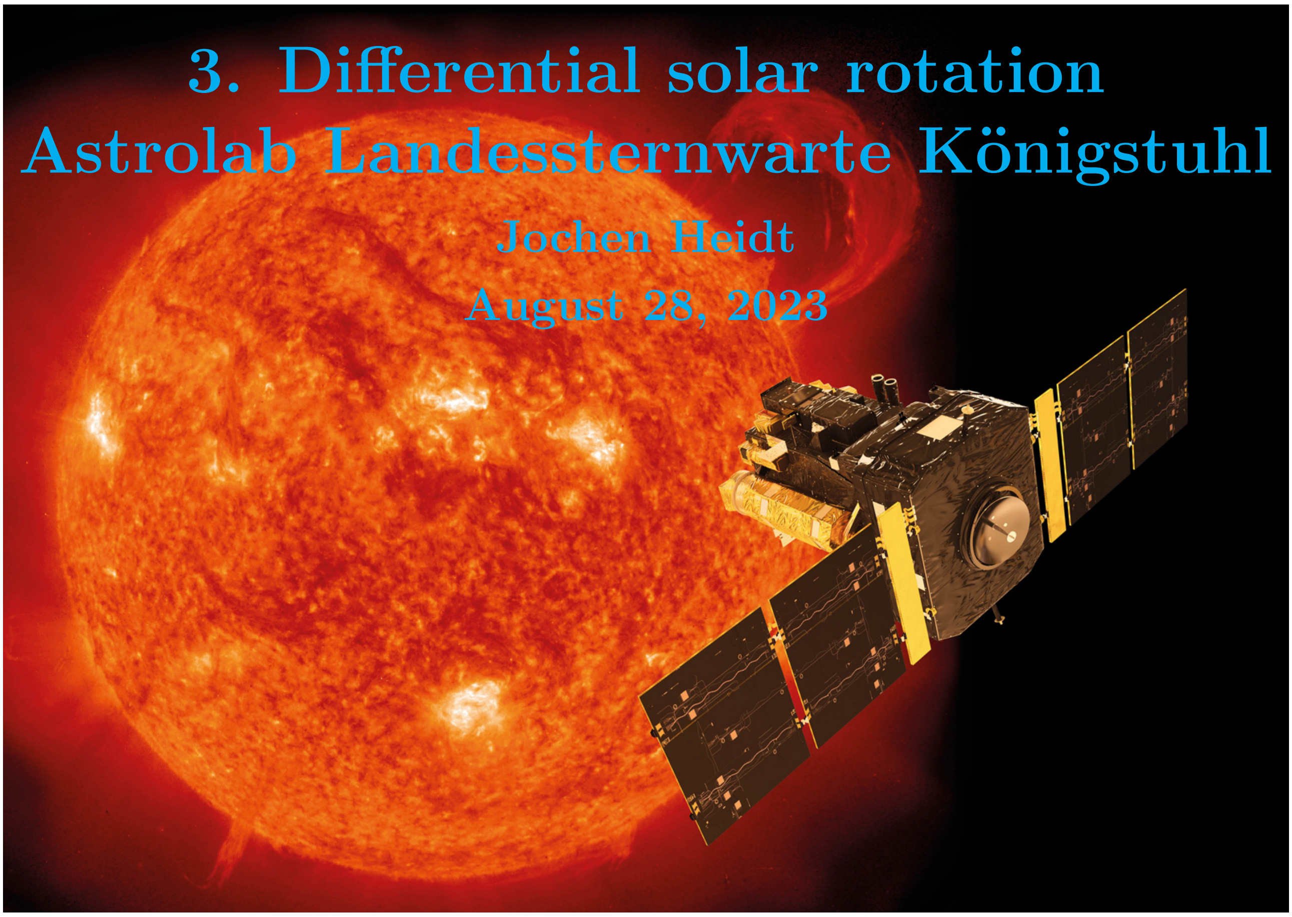

Abstract

When you look at the Sun during day it looks like a pretty boring astronomical object, shining constantly at more or less the same brightness. Thats not true. The Sun is in fact a very energetic and active star, famous for its violent corona with its prominences, its sunspots and the solar wind causing the beautiful aurorae.

In this task you will determine the solar rotation at different latitudes using the change of the position of sunspots as a function of time. This differential solar rotation of the sun is one of the great mysteries in solar research - and not understood yet. You will measure the differential solar rotation using data from the Solar & Heliospheric Observatory SOHO, an observatory launched in 1995 to explore the sun and still delivering exciting data.

This task is based on a tutorial entitled "Determining the solar differential rotation" originally developed by Luis Sánchez and modified for the use of SOHO data by Deborah Baines and Pedro Osuna from the European Space Agency (ESA).

1 Introduction

1.1 Same basic facts about sunspots

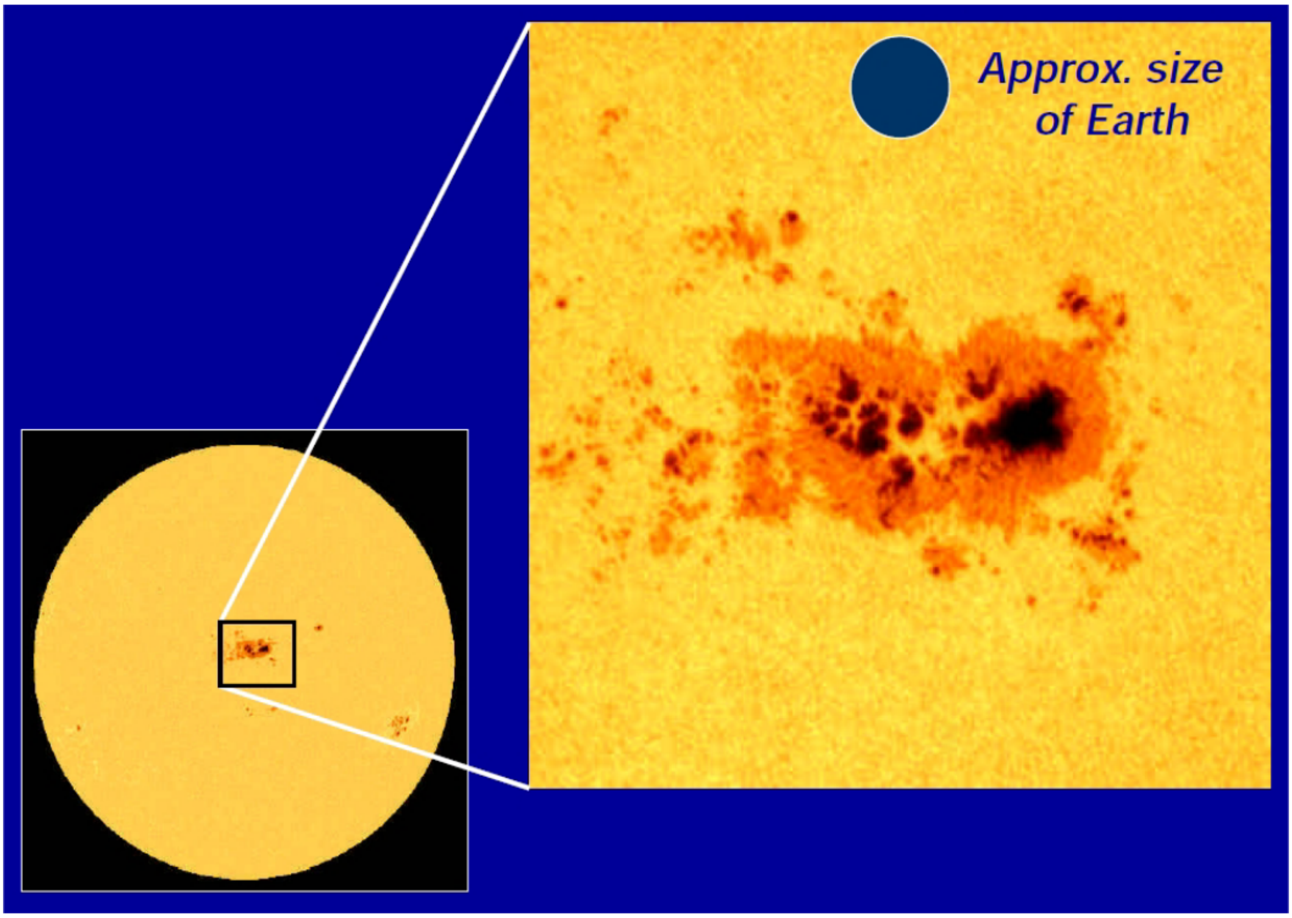

Figure 1: *Sunspots at scale*

- Sunspots are dark, cooler areas on the Sun's surface that indicate areas of strong magnetic activity.
- They appear dark only because they are not as hot or bright as the area surrounding them (4000 degrees Celsius versus 6000 degrees Celsius).
- Sunspots extend down into the Sun as well as above where loops of magnetic field lines carry charged particles.
- They can last from just hours to several months.
- Sunspots, which usually appear in groups, can grow to many times the size of Earth.
- They are caused by twisting, chaotic magnetic fields from within the Sun's convective zone. These powerful magnetic disturbances produce active regions on the Sun, which can often create solar flares and coronal mass ejections.

1.2 The Solar & Heliospheric Observatory (SOHO)

SOHO, the Solar & Heliospheric Observatory, is a project of international collaboration between the European Space Agency and NASA to study the Sun from its deep core to the outer corona and the solar wind. It was designed to answer the following three fundamental scientific questions about the Sun:

- What is the structure and dynamics of the solar interior?
- Why does the solar corona exist and how is it heated to the extremely high temperature of about 1 000 000 degrees Celsius?
- Where is the solar wind produced and how is it accelerated?

Launched on December 2 1995, SOHO maintains an orbit around the Sun at 1.5 million km (1 million miles) from the Earth. It orbits around the Lagrangian point (L1), and is always pointing towards the Sun. It was expected to complete its mission in 1998 but due to its enormous success, the mission was extended several times. As of now, SOHO is still delivering data. See e.g.

https://www.esa.int/Science_Exploration/Space_Science/SOHO.

SOHO has 12 instruments on board. The most “important” one until its termination in 2010 was the Michelson Doppler Imager (MDI). MID measured velocity and magnetic fields in the solar photosphere to learn about the convection zone which forms the outer layer of the interior of the sun and about the magnetic fields which control the structure of the solar corona. It could measure line-of-sight motion (Dopplergrams), magnetic field (magnetograms), and brightness images of the full disk at several resolutions (4” to very low resolution) and of a fixed selected region with higher resolution (1.2”).

Questions:

- What are the Lagrangian points? Why was SOHO put onto L1
- Why was SOHO put in an halo orbit around L1 and not at L1 directly?
- The sun has 6 main layers. The three inner ones are the core, radiative zone, convection zone, the three out ones the photosphere, the chromosphere and the corona. What distinguishes the three outer components from each other?

1.3 Historical determination of the differential solar rotation

The first telescope was made in Europe in 1608. Galileo, who first performed scientific observations in the 1613, concluded that the Sun did indeed have spots. If, as others suggested, these spots are planets passing in front of the Sun, they would be the same in the center as near the edges. He noted changes in size and shape. Other scientists came to similar conclusions. Thus, they couldn’t be planets!

Historically, the first determination of the differential solar rotation was conducted in 1630 by Scheiner, and only 2 decades later in 1843 by Schwabe. This is a nice example of how scientific advances can sometimes be lost to tradition, and are rediscovered much later.

1.4 The SOHO science archive

In this task, you will use the SOHO science archive. It is hosted by the European Space Astronomy Centre (ESAC), ESA, Madrid and also at NASA and contains all data from the SOHO spacecraft. It can be accessed via:

https://www.cosmos.esa.int/web/soho/soho-science-archive.

There you will find an update of the status of the instruments, a direct link for retrieving data, real time images etc. Explore the options a bit. Inspect the movie theater in particular and make you own movies over a period of 1 month, lets say. Start by using "hmiigr", which shows you sunspots based on continuum images in the optical close to 6800Å taken with the MDI. Alternatively, you can use "eit" images taken with the Extreme ultraviolet Imaging Telescope (EIT). The EIT delivers narrow-band images at 1710, 1950, 2840 and 3040Å which corresponds to 2 million, 1.5 million, 1 million and 70000 degrees Kelvin, respectively. The hotter the temperature, the higher you look in the solar atmosphere (Corona)!

If you wish, you can also explore the other options. Making a movie using the "hmimag" option from MDI shows you magnetic field images. Finally, using LASCO (Large Angle and Spectrometric Coronagraph) you can inspect visible images of the Solar Corona with the Sun masked out in the center of the images. LASCO has two field of views: C2 goes from 2 to 6 solar radii and C3 from 3.7 to 32 solar radii. Enjoy the giant solar streamers, sometimes you may even spot a rare solar mass ejection. Many bright stars can be seen behind the Sun in particular at the C3 images.
The direct link for downloading data can be found at:

https://ssa.esac.esa.int/ssa/#/pages/search

or by clicking on "Science Archive at ESAC" on the science archive page.

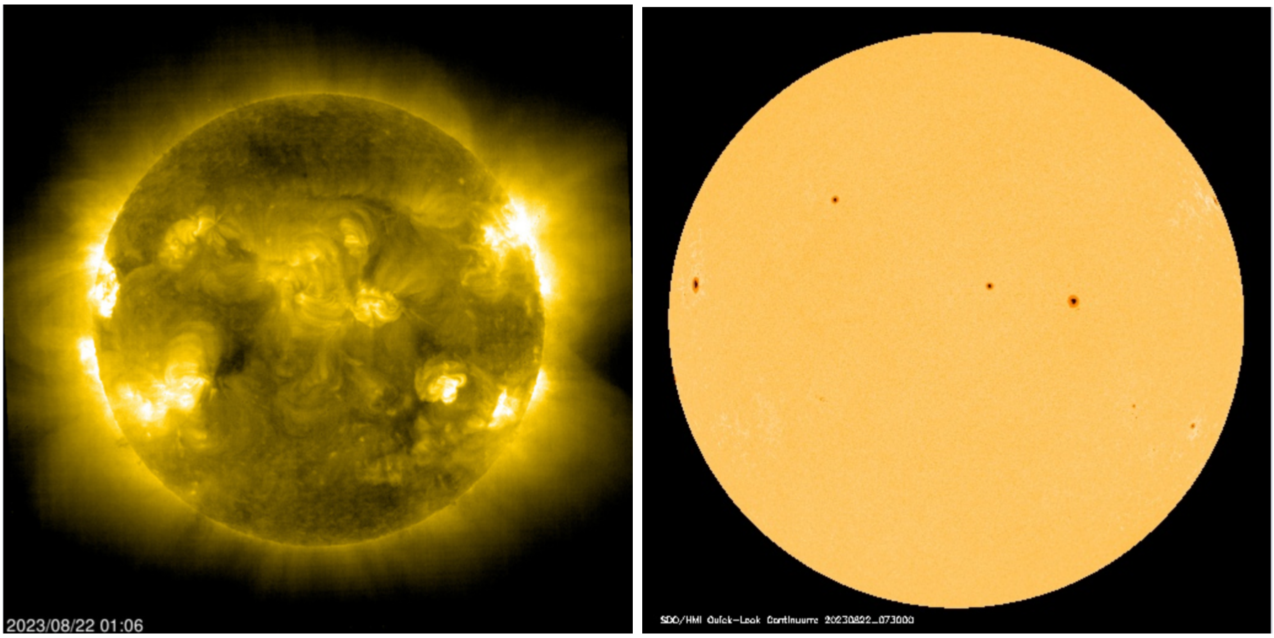

Figure 2: *Real time EIT image at 2840Å of the chromosphere and corona (left) and continuum image showing sunspots (right) on Aug 22 2023.*

Question:

- Why is the temperature gradient in the Solar Corona positive (ie the farther out one is in the Corona the higher the temperature becomes) instead of negative the latter of which one naively would assume?

1.5 Determination of the differential solar rotation using SOHO data

Since you are now familiar with the SOHO archive, we can turn to the main topic of the task, namely the determination of the differential solar rotation. We will do that for two sunspots at different solar latitudes: one close to the solar equator and one at a pretty high latitude.
Go to the SOHO download page

https://ssa.esac.esa.int/ssa/#/pages/search

and select the following in the main search section on the left hand side:

- Instrument: MID (Michelson Doppler Imager)
- Processing Level: L1_calibrated
- Date range: 9/1/2005 - 9/1/2005

and submit. This opens a set of 20 images with observation type “Continuum” and “Magnetogram 96m” (you can in principle refine that by setting Obs.Mods to “FD_Continuum” in the center of the browser). When you click now on one of the “Suns” a thumbnail image will pop up. On the right hand side you will see some information of this frame. When looking at the image you will detect sunspots close to the equator of the Sun. To download an image of this day, mark an image on the box, note down date and time of the start of the observations and download the image. Repeat the same for 17/1/2005 to have a pair of images with sunspots close to the equator and for 27/12/2009 and 02/01/2010 for a pair of sunspot images at high solar latitudes.

What you have to do next is to determine the positions of the sunspot on the two different images, the center of the sun on the images and its radius. This can be done with any tool which allows you to display fits-images. We describe here how to do that with Aladin (ds9 works as well). Unless Aladin is already installed on your laptop you can download them from the astrolab WEB at

https://www.lsw.uni-heidelberg.de/users/jheidt/praktikum/Astrolab_material/Task3.html

You can start the program via:

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java -jar Aladin.jar
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The following steps are necessary in Aladin to measure the position of the sunspots, the center of the sun and its radius (see also Fig. 3):

- Load the image. Click on *File* in the upper left, followed by *load local file* and select the file you want to load. The file is then loaded but greyish and inverted in x and y (compare with the thumbnail image on the SOHO archive). To change this click on *Image* in the upper left, followed by *Symmetry* and there on *Top/Bottom*. Redo with *Left/Right*.

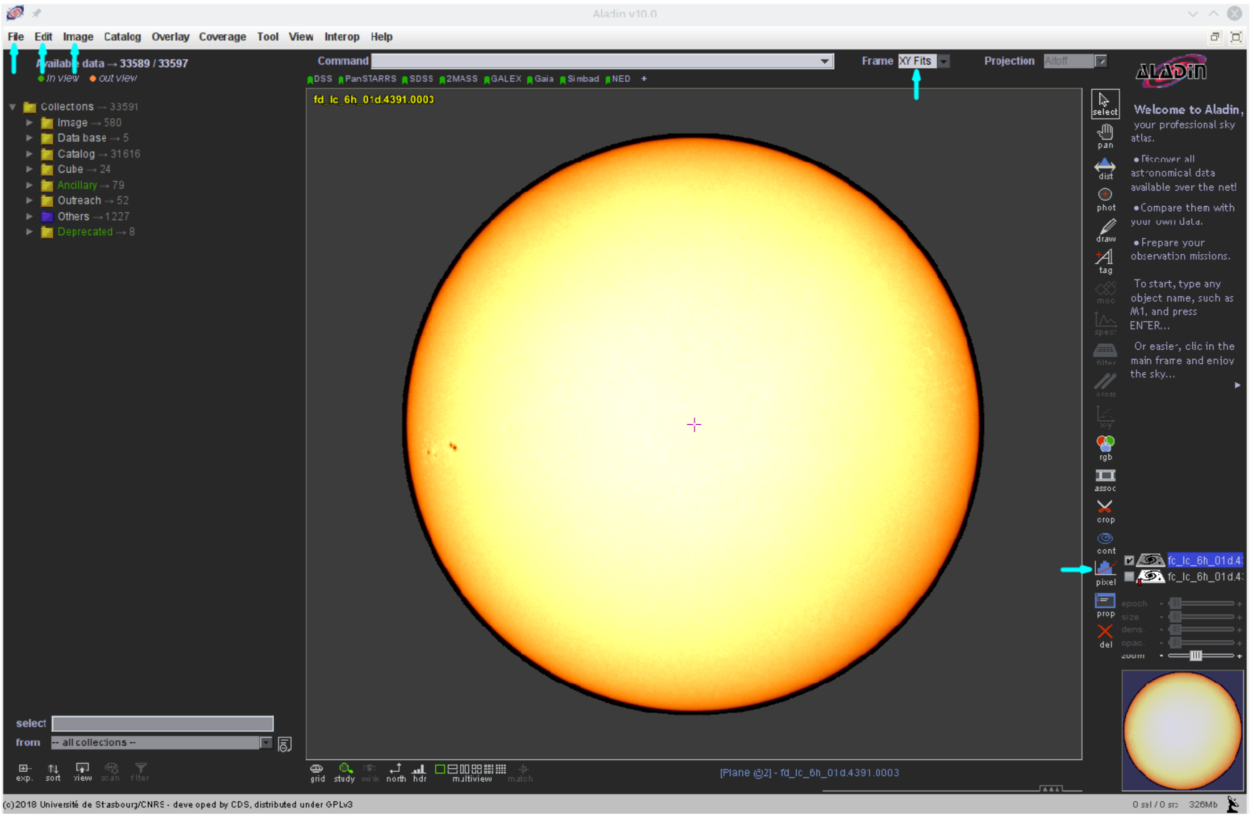
- To change the color, clock on the *pixel* icon on the right side. A window pops up where you should click on *All values* and set the color-scale from *gray* to *BB*. Now the image should look as the thumbnail image on the SOHO page.

- Redo the same for the other image of the pairs of images.

- Now you should determine the position of the sunspot in pixel coordinates. To do so, you need to first set the coordinate system from *ICRS* to *XY fits* in the *Frame tab* in the upper right for both images. To measure the position of the sunspot click on it and a crosshair will appear. This will now be the new center of the frame in Aladin. With the center mouse you can now zoom in and out and determine the position. You can read the numbers in the *command* section on top.

- The last thing is to determine the position of the center and radius of the sun. This is tricky using the image by itself. It is much better and more accurate to use the relevant information from the image headers. To open the image header go to *edit* on the top left and scroll down to *Fits header*. A window will pop-up, from where you should search for the keywords CENTER_X, CENTER_Y and R_SUN to find these numbers.

- For each images you should have now the x,y-coordinates of the sunspot, the x,y-coordinates of the center of the sun and its radius (all in pixel coordinates).



Welcome to Aladin, your professional sky atlas.

- Discover all astronomical data available over the net!
- Compare them with your own data.
- Prepare your observation missions.

To start, type any object name, such as M1, and press ENTER...

Or easier, clic in the main frame and enjoy the sky...

Figure 3: *Screenshot of the Aladin tool, the features to be used are labeled in red.*

The final step is now to calculate the latitude and longitude for the spots on each frame using some trigonometry (think about it) and to derive the rotational period as a function of latitude by using the difference in longitude and time between two images. Make a simple *Ansatz* by assuming small latitudes. To do it right, you would need to use spherical trigonometry to solve the problem. Ask your tutor in case you need more details. Remember that 0 degrees is in the center of the image, negative to the left and positive to the right.

Final questions:

- Which rotational periods and latitudes did you find and how do they compare to each other?
- The Earth is moving around the Sun in the same direction at about 1 degree per day (almost 365 days to circle the Sun in a year). Therefore, the rotation you have just calculated will be larger than the actual solar rotation (we can assume that the SOHO satellite is at approximately the same distance from the Sun as the Earth). This is called *synodic rotation*. Calculate now the *sidereal rotation* by correcting for this effect. How large is this?