

**Estimation of the Sun's rotation through
the tracking of Sunspots**

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Project unit: M301

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1 Abstract

There is still a lot that is unknown regarding the Sun, however we can calculate the solar period through the use of sunspots. Using a collection of images of the Sun over several days, we are able to see the progression and movement of sunspots. Through this movement we are then able to track them across the solar disk and therefore work out the Sun's rotational period for those latitudes. From this data we are able to calculate the time it takes for the sunspot to travel 360° and the amount of time it takes for the sunspot to return to the same position as observed from the Earth. These are known as the sidereal and synodic periods. These provide a good number to compare latitudes. After completing this, we then looked at the error that could be found and how confident we were in our results. By compiling a graph of the maximum and minimum values we could have obtained, we were then able to compare all three results to see if there was a large error. From there we started to question why the Sun rotated at different speeds at various latitudes. This led us to have a brief look into helioseismology, the study of the Sun's interior through the modelling of wave oscillations.

2 Acknowledgements

I would like to acknowledge and thank those who have been involved in this project. Thank you to Carol Bryan and Steve Knight for their support in our attempts at solar observations. Due to bad weather we were unable to observe anything but I thank them and the Hampshire Astronomical Society at Clanfield Observatory for the opportunity to do my own solar observations.

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3 Introduction

The Sun is a vital part of our survival and everyday life. It is the centre of our solar system and keeps our planet in orbit. As stars go, the sun is nothing special; its an average sized star that will continue to burn for another 5 billion years before eventually exploding into a red giant that will wipe out our entire solar system. It has therefore been a point of interest throughout human history. In this report I will be looking at Sunspots and what they can teach us about the Suns latitude, and sidereal and synodic periods. I will also be having a brief look into helioseismology, the study of the Suns interior through its oscillations and sound waves.

To look at sunspots to find the latitude of the Sun at that point, we must first understand the Suns structure. The Sun is comprised of a number of layers.

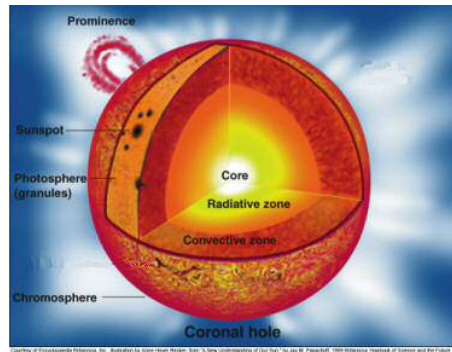


Figure 1: This shows the structure of the Sun.

First is the core; the core of the sun is where fusion takes place. This is where hydrogen is turned into helium and creates a temperature of around 15 million kelvin. This is where the light and heat we see is created.

Next we have the radiation zone and the convection zone. The radiation zone is where the energy created from the core attempts to leave the star in the form of photons. Due to this energy the radiation zone is very dense, meaning that a single photon takes around a million years to pass through. The convection zone is cooler than the other layers of the Sun. Due to this, some elements passing through keep their electrons causing this layer to be more opaque. This in turn stops radiation passing through the zone. This traps heat and makes the fluid convect. It is this convection that causes the Sun to oscillate and has lead, in part, to the study of helioseismology.

We then finally get on to the Suns atmosphere. There is the photosphere and chromosphere. The photosphere is the layer that gives visible light, it is the layer that we see and is significantly cooler than the core at around 5800 kelvin. The chromosphere is a dim layer on top that is even less dense than stellar gas. The Sun also has other characteristics such as granulation and sunspots.

Granulation is a blotchy pattern on the sun that forms and disappears over several minutes.

Sunspots are regions in the photosphere that appear dark. This is because they are cooler than the rest of the Sun's lower atmosphere. This is because the magnetic field of the sun disrupts the surface and slows down the energy flow thus creating the cooler area and the sunspots. Due to this, sunspots usually arise in clusters. They are almost always found just north and south of the equator. The number of spots vary over a period of 11 years and a single spot can last anywhere between a few hours and a few months. The structure of sunspots is broken down into two sections. The umbra, the dark central region and the penumbra, the brighter ring, seen below and are approximately 10,000 km across.

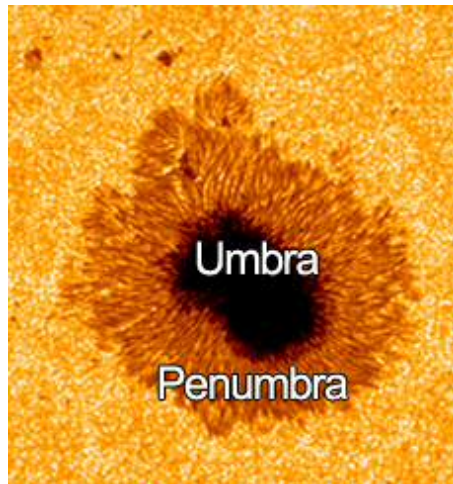


Figure 2: Showing the structure of a Sunspot.

Observing sunspots is relatively simple. Using special filters we can clearly see them and track them across the surface of the Sun over a period of days. It is this ability to track sunspots that allows us to find their longitude and latitude on the sun at that point. This ability to track sunspots also means we can find the synodic and sidereal periods of the sunspots. The sidereal period is the length of time the spot takes to travel 360° . The synodic period is the length of time the spot takes to complete a whole rotation as observed from Earth. This is different from the sidereal period because both the Sun and Earth are rotating meaning it takes longer for the spot to reach the same observed position.

4 Calculating Sunspot Rotation

To calculate a sunspots rotational period, they must be observed over a period of days. To do this I have collected images from spaceweather.com. This is a website that has access to pictures taken of the Sun from outside of the Earth's atmosphere. This means the pictures are not subject to the weather and are taken every day, all year round. Using spaceweather also means the sunspots are numbered, making it easier to track them. These images are taken from the 8th to 24th January 2013. It allows us to see the progression of the spots seemingly across the Sun's surface.

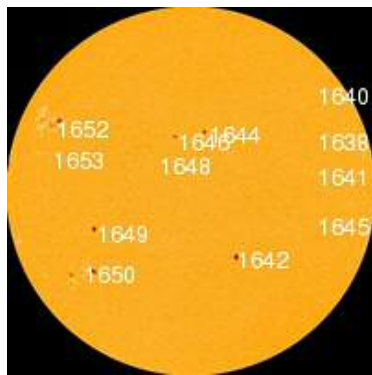


Figure 3: 8th January 2013

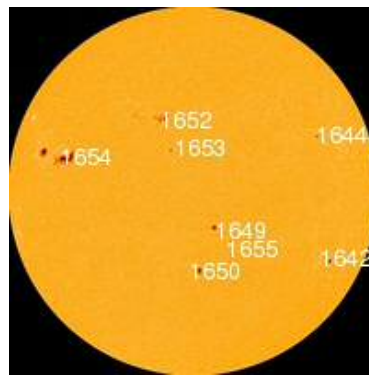


Figure 4: 11th January 2013

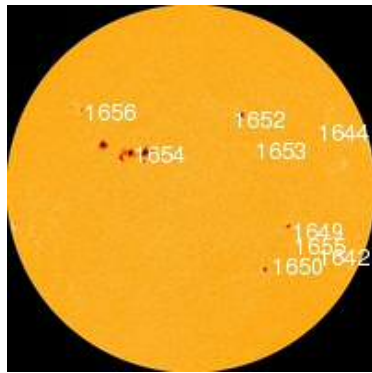


Figure 5: 13th January 2013

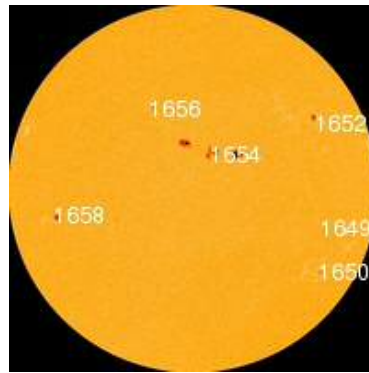


Figure 6: 15th January 2013

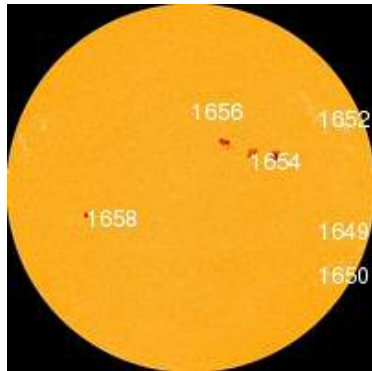


Figure 7: 16th January 2013

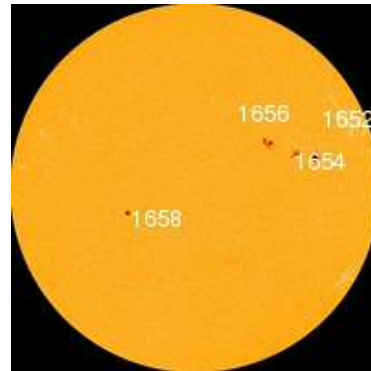


Figure 8: 17th January 2013

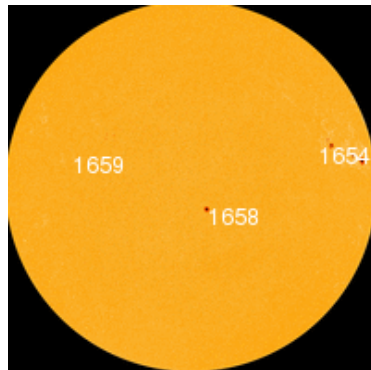


Figure 9: 19th January 2013

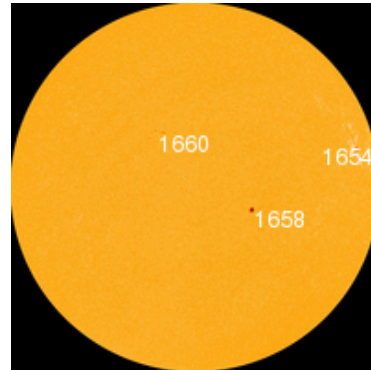


Figure 10: 20th January 2013

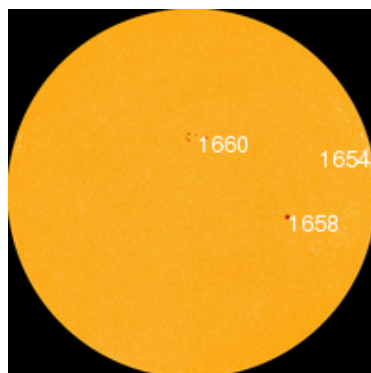


Figure 11: 21st January 2013

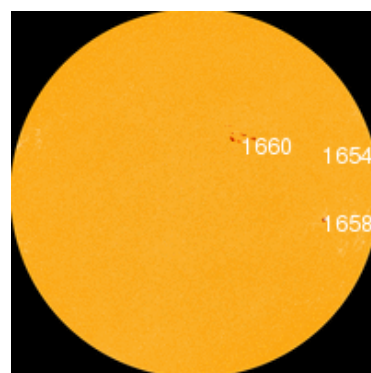


Figure 12: 22nd January 2013

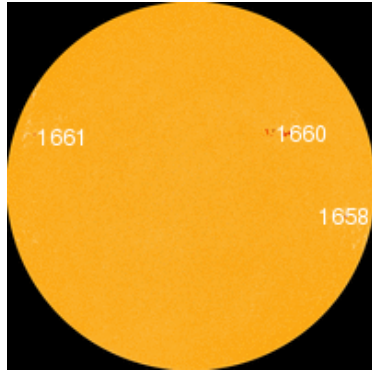


Figure 13: 23rd January 2013

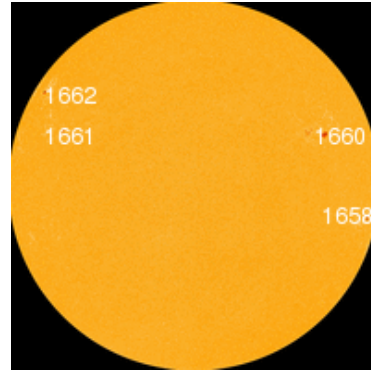


Figure 14: 24th January 2013

To find the sunspots latitude and longitude, you must track the sunspots movement across the Sun. Using Brück's Practical Exercises in Astronomy it says to draw a chord demonstrating the sunspots path. From this chord we create a perpendicular line through the centre, y . This then allows us to find the spots latitude, φ , by drawing a line from the intersect of the chord and the diameter to the centre. This can then be calculated using $\cos \varphi = r/R$, where r = the radius of the chord and R = the radius of the circle. From there we can start to work out the sunspots longitude, θ . To find this we need to find $\sin \theta$. This is found by measuring the length of the spot from y and is known as x . We then divide this by the r . We then use $\sin^{-1} \frac{x}{r}$ to find the longitude, θ .

4.1 Sunspot 1654

Sunspot 1654 can be observed from 11th to 22nd January. In this example $r = 38.5\text{mm}$ and $R = 39\text{mm}$. From this we can find the latitude, φ .

$$\begin{aligned} \cos \varphi &= \frac{r}{R} = 38.5/39 \\ \cos \varphi &= 0.987 \\ \varphi &= \cos^{-1} 0.987 = 9.18^\circ \end{aligned}$$

As the Sunspot is north of the equator its latitude is 9.18°N .

Table (1) shows the spots longitude over a number of days, with 8th January as Day 1, and allows us to see the variation.

Day	x	$\sin\theta$	θ (degrees)
3	-26mm	-0.675	-42
5	-9mm	-0.234	-13.52
7	10mm	0.260	15.05
9	18mm	0.468	27.87
11	25mm	0.649	40.49
12	37mm	0.961	73.95

Table 1: Sunspot 1654

From this information we can plot a graph showing the time in days and longitudes and can find the synodic and sidereal periods.

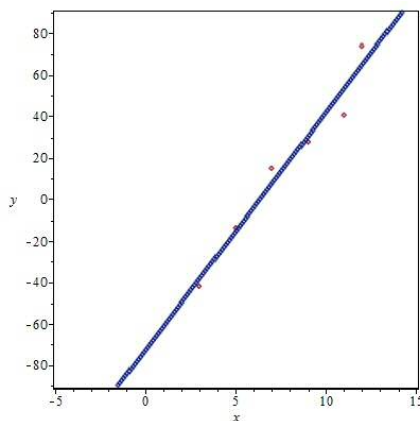


Figure 15: Plot of longitude over a number of days. 1654

4.2 Sunspot 1658

Now we can repeat this process with other sunspots to find the latitude and longitude of each one. Sunspot 1658 was observed from 15th January to the 24th January. As these sunspots are taken from the same pictures R remains constant at 39mm. Again r in this case is 38.5mm however the spot is below the equator. This means the latitude is now 9.18°S using the same formula:

$$\begin{aligned} \cos\varphi &= \frac{r}{R} = 38.5/39 \\ \cos\varphi &= 0.987 \\ \varphi &= \cos^{-1}0.987 = 9.18^\circ \end{aligned}$$

The longitude over this period is different.

Plotting the longitude against the days produces figure 16

Day	x	$\sin\theta$	θ (degrees)
7	-30mm	-0.779	-51.19
8	-22mm	-0.571	-34.85
9	-13mm	-0.338	-19.73
11	4mm	0.104	5.96
12	14mm	0.364	21.32
13	21mm	0.545	33.06
14	33mm	0.857	58.99
15	37mm	0.961	73.95

Table 2: Sunspot 1658

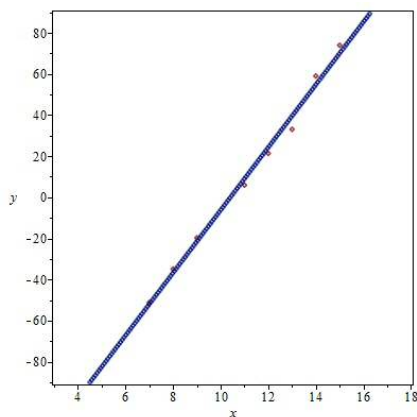


Figure 16: Plot of longitude over a number of days. 1658

4.3 Sunspot 1650

This particular sunspot is significantly further from the equator than the previous spots. In this spot $r = 35.5\text{mm}$, resulting in:

$$\begin{aligned} \cos\varphi &= \frac{r}{R} = 35.5/39 \\ \cos\varphi &= 0.91 \\ \varphi &= \cos^{-1}0.91 = 24.46^\circ \end{aligned}$$

Therefore Sunspot 1650 is at the latitude 24.46°S . The lowest spot observed on figures (3) to (14). The Sunspot itself was only observed on 5 occasions, resulting in Table (7).

These results give figure 17.

Day	x	$\sin\theta$	θ (degrees)
1	-19mm	-0.535	-32.36
3	3mm	0.085	4.85
5	17mm	0.479	28.61
7	29mm	0.817	54.78

Table 3: Sunspot 1650

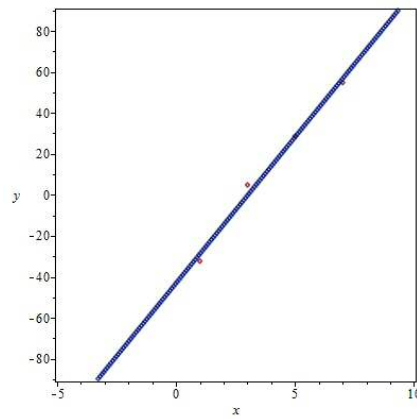


Figure 17: Plot of longitude over a number of days. 1650

5 Calculating the Sidereal and Synodic Periods

As seen above we calculate sunspot longitude by marking its path as a chord. However the spots actual motion is a circle with a radius less than that of the Sun. This is because the spot is not on the Sun's equator. After observing and calculating the spot's longitude the rate at which it increases is the synodic rotation and the time the spot takes to travel 360° is the synodic period.

However, this is not the true period of rotation. This is because the synodic period is the time the Sunspot takes to return to the same observed position. When you account for the Earth's rotation as well, it results in being longer than the sidereal period. The sidereal period is the time the sunspot takes to rotate 360° . This is calculated using the Sun's and Earth's rotations. Again looking at Brück we get:

w is the rate the Sun rotates in degrees per day. W is the rate the Earth goes round the Sun in degrees per day.

This means a point on the Sun's surface gain $w-W$ degrees per day on the Earth. After one synodic period it gains 360° . If the sidereal period of rotation is P days and the period of the Earth travelling around the Sun is Y days, where $Y = 365.24$ then

$$w = \frac{360}{P} \text{ and } W = \frac{360}{Y}$$

And if the synodic period is S days,

$$\begin{aligned} w - W &= \frac{360}{S} \text{ degrees per day} \\ \Rightarrow \frac{360}{P} - \frac{360}{Y} &= \frac{360}{S} \\ \Rightarrow \frac{1}{S} &= \frac{1}{P} - \frac{1}{Y} \end{aligned}$$

To find the synodic period we look at the graph created from finding the longitude. This means we can see how long it takes to travel -90° to $+90^\circ$ giving us half the synodic period. By doubling this value we obtain the synodic period and thus can find the sidereal period using the formula.

5.1 Sunspot 1654

To find the synodic period we look at figure 15. From seeing where the line is at -90° and $+90^\circ$, the time shown is the synodic period. Thus the period is from -1.5 days to 14 days, making the period 15.5 days. However this is only half the rotation and therefore only half the period. Hence by multiplying by 2 we get the entire synodic period of 31 days. From here we can work out the

sidereal period. Using the formula

$$\frac{1}{S} = \frac{1}{P} - \frac{1}{Y}$$

where $Y = 365.24$ and $S = 31$, we can find P

$$\begin{aligned}\frac{1}{P} &= \frac{1}{31} + \frac{1}{365.24} \\ \Rightarrow \frac{1}{P} &= 0.035 \\ \Rightarrow P &= 28.57 \text{ days}\end{aligned}$$

This gives a synodic period of 31 days and a sidereal period of 28.57 days.

5.2 Sunspot 1658

Looking at 16 we can find the sidereal and synodic periods at the latitude 9.18°S . This is done with the same method as before. Referring to figure 16, $\frac{1}{2}S = 16 - 4.5 = 11.5$. So $S = 23$ days. Thus

$$\begin{aligned}\frac{1}{P} &= \frac{1}{23} + \frac{1}{365.24} \\ \Rightarrow \frac{1}{P} &= \frac{372}{9131} \\ \Rightarrow P &= 24.56 \text{ days}\end{aligned}$$

Giving a synodic period at latitude 9.18°S of 23 days and a sidereal period of 21.64 days.

5.3 Sunspot 1650

We can also find the sidereal and synodic periods at the latitude 24.46°S using figure 17. From this graph we can see that $\frac{1}{2}S = 9 - (-3.5) = 12.5$. Therefore showing $S = 25$ days. Using this we calculate the sidereal period;

$$\begin{aligned}\frac{1}{P} &= \frac{1}{25} + \frac{1}{365.24} \\ \Rightarrow \frac{1}{P} &= 0.0373 \\ \Rightarrow P &= 26.84 \text{ days}\end{aligned}$$

Resulting in a sidereal period of 25 days and a synodic period of 23.4 days.

6 Calculating Errors in Sunspot Rotation

As my data was taken from spaceweather, my measurements for x was taken by hand using a ruler. This may have resulted in human error and have made my results less accurate. As such I will assume there is a difference of 0.5mm in my results. I have therefore revisited my tables assuming a correct latitude to look at the variation of the longitude.

6.1 Sunspot 1654

Day	$x + 0.5$	$\sin\theta$	θ	Original θ (degrees)
3	-26.5	-0.688	-43.47	-42
5	-9.5	-0.247	-14.3	-13.52
7	10.5	0.273	15.84	15.05
9	18.5	0.481	28.75	27.87
11	25.5	0.662	41.45	40.49
12	37.5	0.974	76.91	73.95

Table 4: Results with +0.5mm error

Day	$x + 0.5$	$\sin\theta$	θ	Original θ (degrees)
3	-25.5	-0.662	-41.45	-42
5	-8.5	-0.221	-12.76	-13.52
7	9.5	0.247	14.0	15.05
9	17.5	0.455	27.06	27.87
11	24.5	0.636	39.49	40.49
12	36.5	0.948	71.45	73.95

Table 5: Results with -0.5mm error

From tables 4 and 5 we can create another graph to see the error.

From graph 18 we can infer that the error is reasonably small as the regression lines are very close. From this it shows my results have a good level of accuracy.

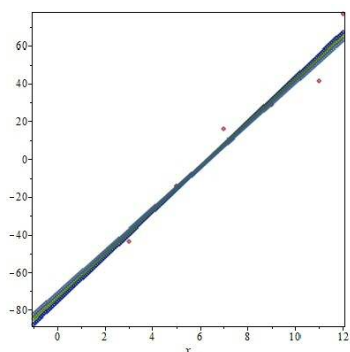


Figure 18: Maximum and Minimum error plot for 1654.

6.2 Sunspot 1658

Day	x	$\sin\theta$	θ	θ_+	θ_-
7	-30mm	-0.779	-51.19	-50.02	-52.39
8	-22mm	-0.571	-34.85	-33.95	-35.76
9	-13mm	-0.338	-19.73	-18.95	-20.53
11	4mm	0.104	5.96	6.72	5.22
12	14mm	0.364	21.32	22.13	20.53
13	21mm	0.545	33.06	33.95	
14	33mm	0.857	58.99		
15	37mm	0.961	73.95		

Table 6: Sunspot 1658

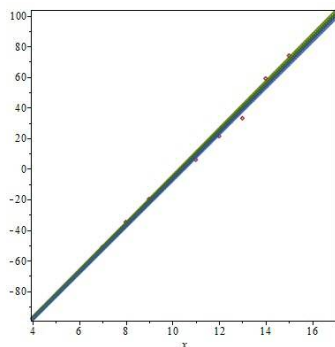


Figure 19: Maximum and Minimum error plot for 1658.

From graph 19 we can see there is a low error and therefore my results are fairly accurate.

6.3 Sunspot 1650

Day	x	$\sin\theta$	θ (degrees)	+theta	-theta
1	-19mm	-0.535	-32.36	-31.41	-33.32
3	3mm	0.085	4.85	5.66	4.04
5	17mm	0.479	28.61	29.54	27.69
7	29mm	0.817	54.78	56.2	53.4

Table 7: Sunspot 1650

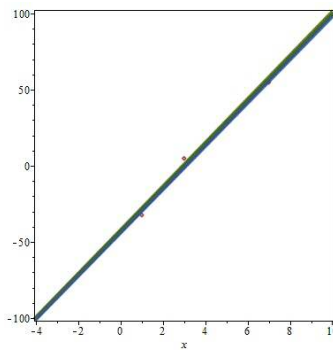


Figure 20: Maximum and Minimum error plot for 1650.

Graph 20 implies there is a low error rate and therefore means my results are quite accurate.

7 Conclusion

From my calculations it is clear to see that the Sun does not rotate as a singly body. Through the tracking of sunspots at various latitudes I could then work out the Sun's synodic and sidereal periods at those points. This showed me the time it took for the Sun to rotate at various points leading me to conclude the Sun rotates at different speeds. An interesting result is the fact I have two sunspots at the same latitude at either side of the equator that have very different rotational periods. Sunspots 1654 and 1658 are at 9.18° North and South respectively. They, however, have very different periods with 1654 having a synodic period of 31 days as opposed to sunspot 1658's 23 days. This is a big difference and something I was not expecting as I thought that the same latitudes may be similar. This is not the case as the Sun is not affected in that way.

However, my calculations may not be exact. My data was taken from spaceweather.com that captures images from outside the Earth's atmosphere. This means they are not subject to weather or any interference from the Earth. A big concern is human error. During the process of this project I have changed the size of the images. This could result in a distortion in my results that I am unaware of. Furthermore, I used a ruler to measure the length of x from the meridian which could further account for error, despite my calculations finding the error to be relatively small.

This project has also allowed me to question why the Sun rotates at different speeds. This is due to the composition of the Sun. The Sun is comprised of a gaseous plasma that flows and shifts according to the currents underneath the surface and the magnetic field produced. The study of this is known as helioseismology. As we cannot see into the Sun it is difficult to know exactly why these things, such as sunspots, happen. In the next section, I will take a brief look at helioseismology.

8 Helioseismology

Helioseismology is the study of the Sun's interior through wave oscillation. As we are unable to see into the Sun, these waves are the only way we can model the interior. It is a relatively new field with many advances being made in the last few decades, and more being made with new and better technology. There are millions of sound waves emitted from the Sun's surface (Helioseismology, 2013) and it is these sound waves that people are interested in. As the Sun is spherical, some of the sound waves resonate within the Sun and can be filtered to create a rich line spectrum. Helioseismology itself is broken down into two parts, global and local. Global helioseismology is the study of the oscillations as a whole, whereas local helioseismology focuses on specific parts, usually sunspots. One of the key purposes of Helioseismology is to find an explanation for sunspots.

Sunspots are under much debate regarding their formation, structure and stability and there is hope that Helioseismology will provide some of the answers. Gizon *et al.* (2010) looked at a case study of NOAA Region 9787 using a variety of methods of local helioseismology. They concluded that there is still too much unknown regarding the effects of strong magnetic fields on solar oscillations.

Global Helioseismology looks at the main waves found in the Sun. Figure 21 shows two different types of waves and where they originate. The g-modes, gravity waves, are found in the radiative zone and are internal gravity waves. The p-modes are pressure waves in the convection zone. There are also f-modes, fundamental modes that are surface gravity waves. These modes are driven by turbulent convection in shallow subsurface layers and causes granulation (Advances in Global and Local Helioseismology: an Introductory Review, 2011). Kosovichev (2011, p.23) shows the basic equations for calculating the p and g modes and can be solved numerically for any solar or stellar model. These equations show the typical behaviour of the modes, i.e. the p-modes are concentrated on the outer layers of the Sun and the g-modes are concentrated on the inner layers of the Sun. From these equations you can then find the dispersion and frequencies of the modes.

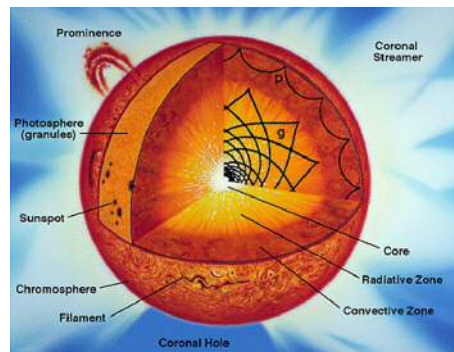


Figure 21: Image showing the propagation of p and g waves

Within Helioseismology there is still a lot that is unknown and there are various models that attempt to solve these. However it is difficult to prove any of these results as we are unable to see into the Sun.

9 References

Brück, M.T. (1990). *Exercises in Practical Astronomy using Photographs: with solutions*. Publisher: Taylor and Francis.

Armet, D. (2010). Helioseismology. Retrieved March 27, 2013, from <http://gong.nso.edu/info/helioseismology.html>.

Gizon, L. Schunker, H. Baldner, C.S. Basu, S. Birch, A.C. Bogart, R.S. Braun, D.C. Cameron, R. Duvall Jr. T.L. Hanasoge, S.M. Jackiewicz, J. Roth, M. Stahn, T. Thompson, M.J. Zharko, S. (2010) Helioseismology of Sunspots: A Case Study of NOAA Region 9787 [Electronic Version]. *Space Science Reviews*, Volume 144, Issue 1-4, page 249.

Kosovichev, A.G. (2011) Advances in Global and Local Helioseismology: an Introductory Review [Electronic Version].

Solar Physics Summer School, Retrieved March 27, 2013, from <http://www.google.co.uk/url?sa=trct=jq=esrc=ssource=webcd=1ved=0CC8QF-jAAurl=http3A>

Retrieved January 8-24, 2013 from <http://www.spaceweather.com/>

Comins, N.F. Kaufmann, W.J. (2009). *Discovering the Universe*. Freeman Pub.

Pasachoff. (1997). *Astronomy: From the Earth to the Universe*. Brooks Cole.

10 Appendix A

Final Year Project Plan

Date: 2012/2013

Student: Kelly Stark

Supervisor: Michael McCabe

Provisional Title:

Estimation of the Sun's Rotation through the Observation and tracking of Sunspots.

Project Brief:

The aim of this project is to be able to calculate the sun's rotation at various latitudes with the use of sunspots. I will be observing my own sunspots at Clanfield Observatory however due to weather and the limited amount of time I will also be using images from various resources to ensure I have enough data. Using these I will be able to use a mathematical equation to find the rotation at that point. I will then evaluate all my answers and assess the error margins. I am also hoping to include a section on helioseismology. This is the study of the interior of the sun and the waves and how they are produced using the convection currents.

Plan:

- o September - November: Background reading and getting used to the equipment used to observe the sunspots.
- o November - February: Observations and collecting data.
- o December - Begin writing up project while continuing to collect data.
- o January - Look more depth into helioseismology. Write up helioseismology section.
- o February - Finish going to observatory. Write up all sunspot data and start analysing and comparing results.
- o March - Finish writing up the project, including the abstract, contents page and appendices etc.

Project Report Outline:

Abstract

Contents

Basic Introduction:

Explanation of the project and its aims;

Explaining terms, etc.

Technical Introduction:

Explanation of the Sun and Sunspots.

Methods of Data collection:

My own observation - Clanfield Observatory;

Space weather, etc.

Calculations of the collected data

Look at each sunspot individually;

Calculate the solar rotation at each spot.

Analysis of all data

Compile all sunspot data;

Look for errors in the data.
Conclusions and Suggestions for Further Work.
References/ Bibliography.
Appendices

Resources:

Universe; Freedman and Kaufmann
The Sun and How to observe it; Jenkins, J.L.
Observing the Sun; Taylor, P.
<http://www.spaceweather.com/>
<http://stereo.gsfc.nasa.gov/>
<http://sohowww.nascom.nasa.gov/>