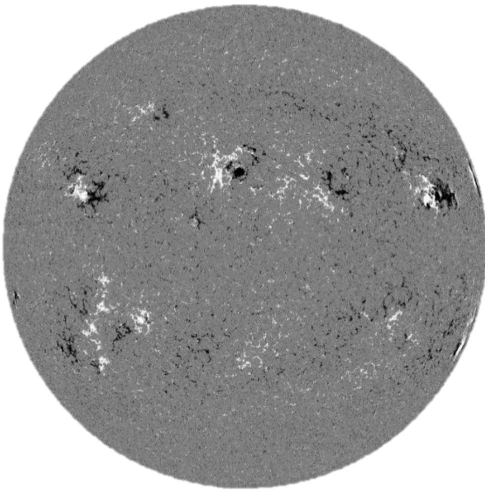
TRACKING A SUNSPOT



Full-Disk magnetogram from SDO/HMI

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ABSTRACT:

This literature review gives a background on the underlying physics and life cycle of sunspots, giving insight into their origins and correlations between their properties. In due course, we present the speculated contribution sunspots bear with solar atmospheric events, by investigating the observable properties of sunspots through the analysis of SDO/HMI data.

CONTENTS

1 INTRODUCTION

The focus of this project is to investigate characteristics of sunspots, in hopes of correlating solar properties and phenomena, by tracking them over some time period. As such, a number of fundamental questions are to be resolved 'How do sunspots manifest solar magnetic activity', 'what are the processes involved in the formation of sunspots', 'what properties are connected within a sunspot' and finally 'How do sunspots correlate to solar atmospheric events'.

In this review, basic questions are to be answered and some insight into previous and current research on sunspots is to be given, along with a preliminary overview of the foreseen methodology to our project.

The premise for completing the project is entirely based on acquiring, processing, and analysing data. Such a practice requires a streamlined approach, establishing a database of images from SDO/HMI in the first place, then processing and plotting the data using SSWIDL. A quasi-automated approach is vital for generating large unbiased samples of sunspots in order to understand their contribution to solar activity.

2 SUNSPOTS

INTRODUCTION

Sunspots are the most obvious feature on the disturbed photosphere and appear to play a key role in major solar events. They manifest the complexity of magnetic activity of the solar interior, witness the operation of solar dynamo deep in the convection layer, and define the frequency of solar cycles.[1, 2]

LIFECYCLE

The differential rotation of the Sun is its rotation around its axis. At the poles, the rotational period is approximately 40 days, and at the equator, 27 days (which indicates a rotational speed of 2 km s-1).

After a solar minimum, sunspots suddenly appear at ~40° latitudes (rotational period of this location is 31 days). As the solar cycle progresses, they appear to drift towards the equator. At the next solar minimum, the sunspots (which will have reached the equator) disappear. Latitude migration of sunspots has no statistical difference between hemispheres. [3]

UNDERLYING PHYSICS

The coalescence of 3 or 4 small scale magnetic flux tubes proves to be sufficient in producing a cool area on the surface of the photosphere, described as a pore. These are distinguished from sunspots by their lack of a penumbra. In some cases, the magnetic knots move up towards the surface along field lines and merge with the pore. A penumbra (Fig 2.1) is formed when the magnetic configuration becomes unstable and the strongly inclined field interacts with the surrounding convective motions. [4]

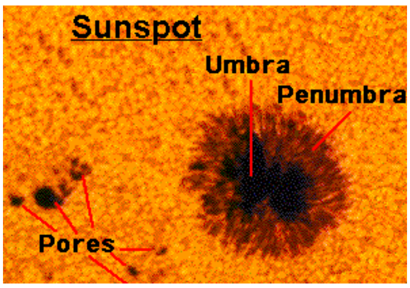

Fig. 2.1

Observations have shown in the past [5] that sunspots are formed from the accumulation of small magnetic flux tubes (Fig. 2.2) at distances of general order of 10^3 km beneath the surface into a single magnetic flux tube. The motions of which are postulated to be driven by subsurface downdraft, depicted as dotted lines in Fig. 2.2, fed by inward horizontal flow from the surrounding region, dragging separate flux tubes into the sunspot. Once established, the convective force is thought to maintain the downdraft. [4]

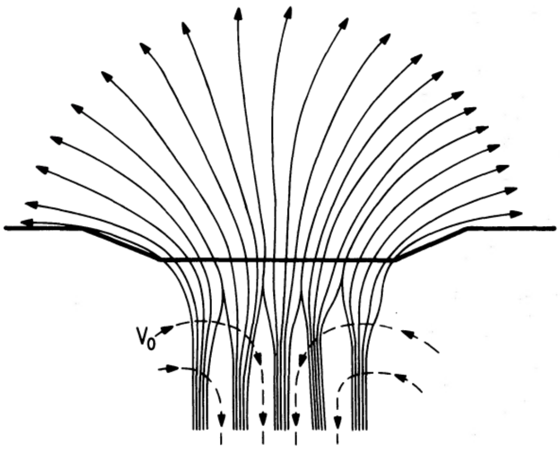

Fig. 2.2

From the centre umbra, the magnetic field strength systematically decreases from 0.3 T to about 0.1 T at the boundary of the penumbra, and then rapidly dies off. [6] Within the boundaries of the umbra, the field lines are vertical, with an increasing inclination outward. At the outer edge of the penumbra, the field lines flare outwards with an angle to the vertical of about 60° or more. Sunspots however are long-living magnetic structures, and hence they are stable for some extent of time. These flaring magnetic field lines at the surface are compressed by magneto-hydrostatic forces, its energy is enhanced, which would lead to instability. The question of how magnetic structures are made stable within a sunspot has been a long running puzzle in solar physics.

Meyer and Schmidt [7] suggest a formal criterion of the required conditions for stability: The surface of the flux tube is stable when confronted with the hydromagnetic exchange instability providing the flux tube diverges from the vertical by an angle θ larger than $\Theta_0 \approx 20°$ for a common sunspot spanning 4 Mm across the umbra. Hence the usual observed 60° is rather larger than the Θ_0 criterion, indicating that the visible portion of the sunspot is stable.

These intense vertical magnetic fields within a sunspot are generally accepted to inhibit the surrounding subsurface convective motions that transfer heat up to the photosphere. The resulting reduced temperature is observed as a dip in energy flux within the bounds of a sunspot. *Parker[4]* points out the amount of magnetic flux within a sunspot isn't sufficient to explain the extent of the observed 1/5th of the normal photospheric energy flux value. Measurements have shown sunspots to still be relatively hot, with an effective temperature in umbrae of about 4500 K and 5500K for the penumbrae. These observations lead to the assumption that convective energy transport is not completely suppressed. It is worth saying that the intensity contrast of sunspots with respect to the standard brightness of the photosphere is strongly wavelength-dependent. [1]

There are many characteristics of a sunspot to be understood and correlations to be made between each of their properties, but also to some of the sun's most fundamental mechanisms. Due to the magnetic nature of sunspots, it is clear that magnetogram observations will be one of the main focuses of this study. Also, due to the brightness and area of a sunspot being tightly kindred to the intensity of the magnetic structure, it would be wise to study the evolution of such properties. We shall also consider investigating the effects of sunspots on major solar events.

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3 SUNSPOT & SOLAR ACTIVITY

INTRODUCTION

A general consensus has been established, ever since the discovery of the existence of magnetic fields in sunspots [8], that they have an important role in solar activity. [9] The extensive investigation of the structure and polarity of magnetic fields in solar active regions in later years have led to the understanding that at large scales, the evolution of magnetic fields are crucial to the solar activity cycle. The level of complexity of magnetic fields can be linked to energetic solar events such as flares and CMEs to solar flares; it is of general belief that the transport of magnetic energy from the solar interior and its storage in the corona seem to be the product of complex dynamics of active regions. [10] However, the understanding of how energy is stored and released is limited and the connections are purely empirical.

CAUSALITY BETWEEN SUNSPOT ROTATION AND SOLAR FLARES, CORONAL LOOPS, CMES

From numerous studies [11-13], it is widely accepted that flares derive their power from excess energy stored in stressed magnetic fields in active regions, such as sunspots. The details of the process of how the magnetic energy is explosively transformed into kinetic energy of coronal matter, however, requires more observational evidence, and remains an important issue in solar physics.

There seems to be several characteristics which favour the occurrence of flares, such as highly sheared magnetic fields [14] and the sudden change in the separation of two opposing polarities of active regions. [15] In this project, however, our attention will be turned towards the suggested complicity of sunspot rotation with the energy build-up and release prior to flares.

Brown et al. [16] identified sunspot rotations in active regions using white light imagery from *TRACE*. Later *Tian et al.* [17] theorised the rotation of a sunspot twisted the corona, resulting in the generation of vertical helical currents within the solar atmosphere. More recently, *Xiao-Li Yan et al.* [18] emphasised the possible causality with flares by tracing the rapid rotation of a sunspot seemingly related to the X3.4 flare of 2006. By observing the evolution of NOAA 10930, a grouping of sunspots of negative polarity, the evidence was significant: There's an apparent correlation between the spatio-temporal characteristics of rotating sunspots and solar flares. Thus, the X3.4 flare was reasonably regarded as a result of the sunspot motions.

Xiao-Li Yan et al. [19] identified and classified rotating sunspots using *TRACE* and SOHO/MDI data. They found that there were some 60 possible different rotational patterns and found a strong relationship between these sunspots and flares. For sake of brevity, we will not be studying these different rotational patterns, however the data and relationships drawn in their study will prove to be invaluable to our project.

CORONAL MASS EJECTIONS

Solar eruptions are thought to be triggered by the magnetic shear stress exceeding a critical value, usually along a Polarity Inversion Line.

Observed sunspot rotation may be caused by photospheric flow or twisted flux tube emergence. The rotational motion can be the most dominant contributor to the magnetic field's twist and energy, which may contribute to how a flux rope system develops (which erupts as a CME).

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Sunspot rotation may shear the footpoints of coronal magnetic field structures, causing magnetic reconnection between the low-lying flux rope and the overlying loop, which is thought to result in solar flares and coronal mass ejections. This process is theoretical, based on observations made on a major solar eruption in 2012. [20]

The area of the sun covered by sunspots has a correlation with the rate at which solar flares occur. The correlation between sunspot activity and coronal mass ejection rate is strongest with CMEs with speeds greater than the average speed. This suggests that sunspot associated CMEs are more energetic than those which originate elsewhere.

CMEs with speeds slower than average occur in all phases of the solar cycle. [21]

It was found that the activity cycle of CME slightly leads the sunspot area cycle close to the equator, but begins to significantly lag behind the sunspot area cycle as latitude increases. The cyclical behaviour of CMEs (where solar activity at low latitudes is in anti-phase to activity in high latitudes) supported existing ideas that CMEs are intrinsically associated with the magnetic structure. [22]

4 OBSERVATIONAL DATA

Data used in this project will be sourced from instruments on board the Solar Dynamics Observatory (SDO), specifically the Helioseismic and Magnetic Imager (HMI) as a means of capturing the complexities and evolution of active regions along the solar disk. The instrument is designed to produce four main types of data: Dopplegrams, continuum filtergrams, line-of-sight and vector magnetograms. [23]

In the first place, the continuum filtergrams (Fig. 4.1) will be used to track the visible properties of sunspots, such as their motions along the solar disk, the progression of their size, brightness, and rotation.

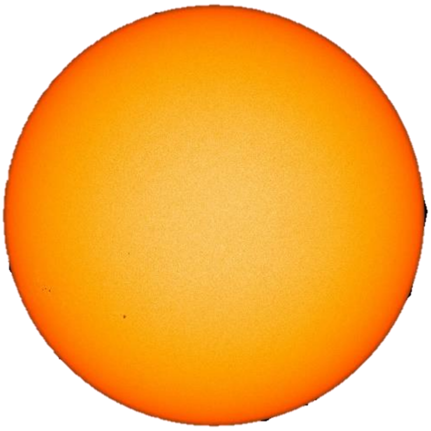

Fig. 4.1

In second place, the magnetograms (Fig. 4.2) will be used to investigate the complex magnetic structures that arise from sunspots, to study their polarity and to quantify the change in magnetic fields prior to solar atmospheric events.

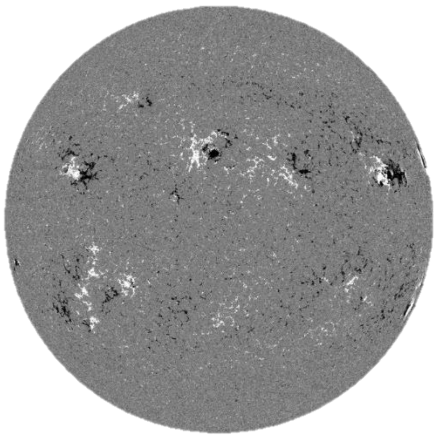

Fig. 4.2

Eventually, the HMI data could be used in conjunction with the Atmospheric Imaging Assembly (AIA), which provides continuous observations (Fig. 4.3) of the solar chromosphere and corona under 10 different wavelengths, to identify plausible

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connections between the magnetic features of sunspots and their effects on the sun's atmosphere.

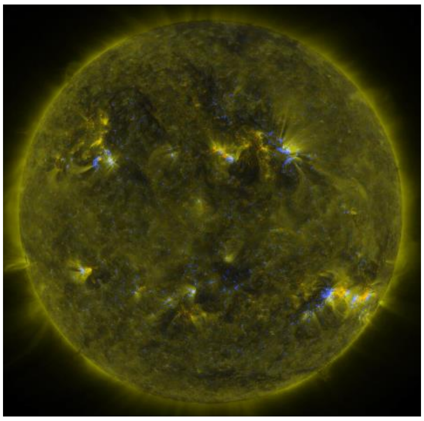

Fig. 4.3

5 AUTOMATED TRACKING AND PROCESSING METHODS

PROCESSING DATA

Our SDO data will first be read and processed using SSWIDL, following the guidelines described in *Daniel Brown's* SDO primer. [24]

TRACKING SUNSPOT GROUPS

L. Győri [25, 26] developed a method to track entities related to sunspot groups, based on graph operations. The pixels of the first image in sequence are transformed into the pixels of the next image (Fig. 5.1.a/b), using heliographic coordinates to account for differing scales and orientations.

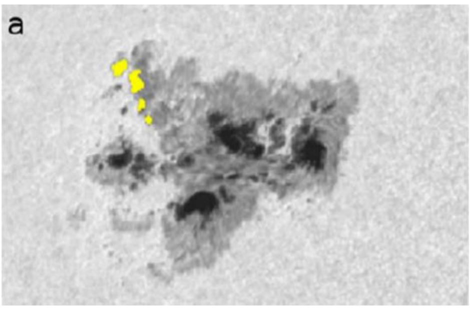

Fig. 5.1 a

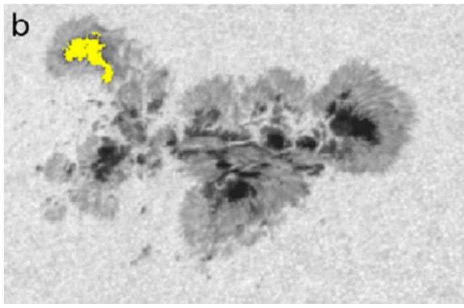

Fig. 5.1 b

Relations are defined between entities in the images. Once completed for an image series, a chart is produced for each entity pair. Vertices represent entities in the images and the edges link to related entities in future images. Iterating through families, the entities can be studied for merge and fragmentation events.

TRACKING SUNSPOT ROTATION

Another method was used by *B. Daniel and Walker A.* SDO continuum data is analysed by comparing numerous observations in a sequence. The centre of the sunspot in each image is identified (Fig. 5.2) and uncurled from cartesian coordinates to polar coordinates (Fig. 5.3).

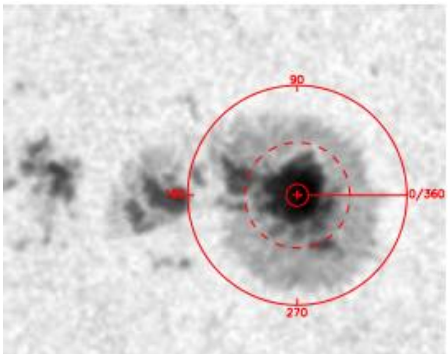

Fig. 5.2

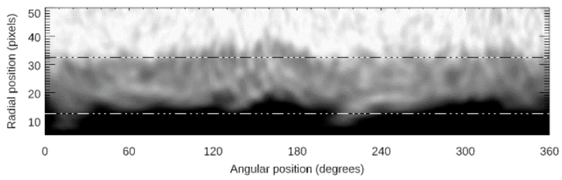

Fig. 5.3

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The intensity profile of each radial band in the sunspot is investigated. Turning points are found, which will track rotational motion in the penumbra. Turning points are matched to equivalent ones in the previous observation, allowing for the change in rotation to be calculated between the two images, which can be divided by time to get rotational speed. [27]

The time-slice method can be used to determine the rotation rate of a sunspot as a function of time. Active regions are selected, with the image closest to the solar disk's centre chosen to minimise the projection effect.
To derive the rotational parameters of the sunspots, the centre of the umbra is followed. Determining the centre of the sunspot can either be determined by the maximum point on the magnetogram or the point of minimum intensity on a white-light image.
The sunspot image is uncurled by transforming from a cartesian frame of reference to a polar frame. This is to get the intensitygram of the sunspot in polar coordinates. Repeating for all images provides the θ variation as a function of time. [28]

TRACKING MOVEMENT AND AREA

With a suitable image of a sunspot *ImageJ* can be used to determine the coordinates and area of a sunspot, and *Helioviewer* can be used to determine centre disk heliographic coordinates, position angle, and semi-diameter of the Sun. These parameters are then used to convert the pixel coordinates into heliographic coordinates.

By using linear regression, the equation of differential rotation can be found as a function of a sunspots age T, its longitudinal drift velocity dL and V_c the Carrington velocity:

$$\omega(\mathrm{B}) = \frac{(V_c\ \mathrm{T}) + \mathrm{dL}}{T}$$

It has been shown that the rotational velocity of a sunspot increases as it approaches the equator. [29]

6 FUTURE DIRECTIONS

ATMOSPHERIC COUPLING

In the 1960's, *Leighton* and his team discovered that the photosphere oscillates, their explanation was that sound waves exist within the solar interior. [30] Studying these oscillations would bring forth properties of these waves, along with an understanding of the solar centre. It has been found that there are systematic variations in the frequency of different oscillation modes in time.[31] The time period of these shifts of frequencies is about 11 years, indicating that there is some correlation with magnetic effects going on. During the periods where the sun is more active, presenting more sunspots on the surface, the frequencies of global oscillations increase likewise. [32] The question is worth asking, how could the magnetic field present in the atmosphere interact with the global oscillations which are thought to exclusively exist in the solar interior?

Since these ground-breaking studies, there have been great improvements over the resolution of spatial and temporal data, allowing more detailed study of these oscillations present within the solar atmosphere. Sunspots might prove to be windows for studying helioseismology. [33]

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7 CONCLUSION

The aim of this project is to closely investigate the motions and evolution of sunspot groups using SDO/HMI data, in the hopes of establishing our own correlations between their properties and relate them to some of the most intriguing solar atmospheric events. Following the processing and automatic tracking methods of both *L. Győri [25]* and *B. Daniel* [27] will provide observational results which may offer answers to our projects focus. The literature on the motion and properties of sunspots was widely regarded as factual, however the same cannot be said for the literature concerning sunspot effects on events such as solar flares or CMEs. Most studies have been correlating magnetic properties and solar phenomena purely on an empirical basis.

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8 BIBLIOGRAPHY

1. Schmidt, W., *Magnetic field and dynamics of sunspots.* Solmag 2002: Proceedings of the Magnetic Coupling of the Solar Atmosphere Euroconference and Iau Colloquium 188, 2002. **505**: p. 167-174.
2. Kosovichev, A.G., *Subsurface characteristics of sunspots.* Solar Activity Cycle and Particle Acceleration, 2006. **38**(5): p. 876-885.
3. Hoppner, K. and M. Bittner, *Detection of solar activity signatures in OH* temperature fluctuations possibly related to the differential rotation of the Sun.* Journal of Atmospheric and Solar-Terrestrial Physics, 2009. **71**(12): p. 1287-1292.
4. Parker, E.N., *SUNSPOTS AND THE PHYSICS OF MAGNETIC-FLUX TUBES .1. GENERAL NATURE OF THE SUNSPOT.* Astrophysical Journal, 1979. **230**(3): p. 905-913.
5. Wang, H.M. and H. Zirin, *FLOWS AROUND SUNSPOTS AND PORES.* Solar Physics, 1992. **140**(1): p. 41-54.
6. Beckers, J.M. and E.H. Schröter, *The intensity, velocity and magnetic structure of a sunspot region.* Solar Physics, 1969. **10**(2): p. 384-403.
7. Meyer, F., H.U. Schmidt, and N.O. Weiss, *The stability of sunspots.* Monthly Notices of the Royal Astronomical Society, 1977. **179**(4): p. 741-761.
8. Hale, G.E., *On the Probable Existence of a Magnetic Field in Sun-Spots.* The Astrophysical Journal, 1908. **28**: p. 315.
9. Wang, H.M. and C. Liu, *Structure and evolution of magnetic fields associated with solar eruptions.* Research in Astronomy and Astrophysics, 2015. **15**(2): p. 145-174.
10. Zhang, M. and B.C. Low, *The Hydromagnetic Nature of Solar Coronal Mass Ejections.* Annual Review of Astronomy and Astrophysics, 2005. **43**(1): p. 103-137.
11. Kosovichev, A.G. and V.V. Zharkova, *Magnetic Energy Release and Transients in the Solar Flare of 2000 July 14.* The Astrophysical Journal, 2001. **550**(1): p. L105-L108.
12. Wang, H., et al., *Rapid Changes of Magnetic Fields Associated with Six X-Class Flares.* The Astrophysical Journal, 2002. **576**(1): p. 497-504.
13. Patterson, A. and H. Zirin, *Transient magnetic field changes in flares.* The Astrophysical Journal, 1981. **243**: p. L99.
14. Rausaria, R.R., et al., *THE VARIATION OF FILAMENT DIRECTION IN A FLARING REGION.* Solar Physics, 1993. **146**(1): p. 137-145.
15. Wang, S., C. Liu, and H.M. Wang. *Study of sunspot motion and flow fields associated with solar flares*. in *273th Symposium of the International-Astronomical-Union*. 2010. Ventura, CA.
16. Brown, D., Nightingale, R., Alexander, D. . and et al., *Observations of Rotating Sunspots from TRACE*. 2003.
17. Tian, L. and D. Alexander, *Role of sunspot and sunspot-group rotation in driving sigmoidal active region eruptions.* Solar Physics, 2006. **233**(1): p. 29-43.
18. Yan, X.L., et al., *The causality between the rapid rotation of a sunspot and an X3.4 flare.* Research in Astronomy and Astrophysics, 2009. **9**(5): p. 596-602.
19. Yan, X.L., Z.Q. Qu, and D.F. Kong, *Relationship between rotating sunspots and flare productivity.* Monthly Notices of the Royal Astronomical Society, 2008. **391**(4): p. 1887-1892.
20. Wang, R., et al., *Relationship Between Sunspot Rotation and a Major Solar Eruption on 12 July 2012.* Solar Physics, 2016. **291**(4): p. 1159-1171.
21. Ramesh, K.B., *CORONAL MASS EJECTIONS AND SUNSPOTS-SOLAR CYCLE PERSPECTIVE.* Astrophysical Journal Letters, 2010. **712**(1): p. L77-L80.
22. Gao, P.X., J.L. Xie, and J. Zhong, *Phase Relationships Between the CME-Energy Cycle, the Sunspot-Area Cycle and the Flare-Index Cycle.* Solar Physics, 2014. **289**: p. 1831.

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23. Scherrer, P.H., et al., *The Helioseismic and Magnetic Imager (HMI) Investigation for the Solar Dynamics Observatory (SDO).* Solar Physics, 2012. **275**(1-2): p. 207-227.
24. Brown, D., *SDO primer.* 2010.
25. Gyori, L., *Automation of Tracking Various Sunspot Group Entities and Demonstrating Its Usage on the Flaring NOAA AR 11429.* Solar Physics, 2015. **290**(6): p. 1627-1645.
26. Györi, L., *Automation of Area Measurement of Sunspots.* Solar Physics, 1998. **180**(1): p. 109-130.
27. Brown, D. and A. Walker, *A Semi-Automatic Method to Measure the Rotation of Sunspots.* Solar Physics, 2021. **296**(3): p. 32.
28. Zheng, J.C., et al., *ON THE ROTATION OF SUNSPOTS AND THEIR MAGNETIC POLARITY.* Astrophysical Journal, 2016. **826**(1).
29. Permata, K. and D. Herdiwijaya. *The Measurement of Solar Differential Rotation from Proper Motion of Individual Sunspots*. in *10th Southeast-Asia-Astronomical-Network (SEAAN) Meeting*. 2018. Indonesia: Iop Publishing Ltd.
30. Leighton, R.B., R.W. Noyes, and G.W. Simon, *Velocity Fields in the Solar Atmosphere. I. Preliminary Report.* The Astrophysical Journal, 1962. **135**: p. 474.
31. Chaplin, W.J., et al., *The solar cycle as seen by low-ℓ p-mode frequencies: comparison with global and decomposed activity proxies.* Monthly Notices of the Royal Astronomical Society, 2004. **352**(4): p. 1102-1108.
32. Dziembowski, W.A. and P.R. Goode, *Sources of Oscillation Frequency Increase with Rising Solar Activity.* The Astrophysical Journal, 2005. **625**(1): p. 548-555.
33. Schunker, H., D.C. Braun, and P.S. Cally, *Surface magnetic field effects in local helioseismology.* Astronomische Nachrichten, 2007. **328**(3-4): p. 292-297.