Tracking a Sunspot

A picture containing black, echinoderm

Description automatically generated  
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.

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# Introduction

The focus of this project is to investigate properties/characteristics of sunspots, in hopes of correlating solar properties and phenomena, by tracking them over some period. As such, a number of fundamental questions are to be resolved. ‘what+how’ ‘how are they related’[…]

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 collection + data analysis. Such a practice requires a streamlined approach, establishing/obtaining a database of images from SDO/HMI in the first place, plotting + read/analyse it. Large data sets require being clever about data acquisition processing and analysis, filtering is needed. Mention usage of SSWIDL for plotting and analysis[…] A quasi-automated approach is vital for generating large unbiased samples of sunspots in order to understand their contribution to solar activity.

# 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. [Wolfgang schmidt 2002]

[Sunspots are significantly hotter than the surrounding plasma (by three orders of magnitude).The relative contribution of magnetic field to a sound-speed signal rapidly decreases as depth increases due to the conservation of magnetic flux in the flux tubes that form sunspots.

At a depth of 4 Mm, most of the observed signal is implied to be caused by variations in temperature. In addition, at this depth, there are connections to pores which have the same polarity as the main sunspot. This suggests the sunspots represent a tree-like structure located in the upper convection zone. Source: Subsurface characteristics of sunspots]

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. (Hoppner, K & Bittner, M, 2009)

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 is formed when the magnetic configuration becomes unstable and the strongly inclined field interacts with the surrounding convective motions. [EN Parker]

Observations have shown in the past (Wang & Zirin 1992, Keil et al. 1999) that sunspots are formed from the accumulation of small magnetic flux tubes 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, 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 (E.N parker).

From the center 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. (jm becker 1969). Within the boundaries of the umbra, the field lines are vertical, with an increasing inclination outwards. 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, Schmidt (1997) 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 𝚹0≈ 20° for a common sunspot spanning 4 Mm across the umbra. Hence the usual observed 60° is rather larger than the 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. (E.N Parker 1979) 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, in order to explain the temperatures of sunspots. It is worth saying that the intensity contrast of sunspots with respect to the standard brightness of the photosphere is strongly wavelength-dependent. (Wolfgang S. 2002)

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 HMI observations will be one of the main focuses of this study. Also, due to the fact that brightness and area of a sunspot are 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.

# Sunspot & solar activity

Introduction

A general consensus has been established, ever since the discovery of the existence of magnetic fields in sunspots (Hale 1908), that they have an important role in solar activity (Haimin Wang and Chang Liu 2015). 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 complex dynamics of active regions (Zhang & Low 2005). 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 […], 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 (Rausaria et al. 1993) and the sudden change in the separation of two opposing polarities of active regions(Wang et al. 1994, 2006). In this project, however, our attention will be turned towards the suggested complicity of sunspot rotation with the energy buildup and release prior to flares.

Brown et al. (2003) identified sunspot rotations in active regions using white light imagery from TRACE. Later Tian et al. (2006) 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 (2009) 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.

Yan X.L. et al (2008) 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 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).

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.

[Source: Relationship Between Sunspot Rotation and a Major Solar Eruption on 12 July 2012]

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. (Ramesh, K. B., 2010)

[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 behavior 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

SOURCE: Phase Relationships Between the CME-Energy Cycle, the Sunspot-Area Cycle and the Flare-Index Cycle]

# 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. [The HMI investigation for the SDO]

In the first place, the continuum filtergrams 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.

In second place, the magnetograms 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.

Eventually, the HMI data could be used in conjunction with the Atmospheric Imaging Assembly (AIA), which provides continuous observations of the solar chromosphere and corona under 10 different wavelengths, to identify plausible connections between the magnetic features of sunspots and their effects on the sun’s atmosphere.

# Automated tracking and processing methods

Processing data

Our SDO date will first be read and processed using SSWIDL, following the guidelines described in Daniel Brown’s SDO primer [http://helio.cfa.harvard.edu/trace/SSXG/ynsu/Ji/sdo\_primer\_V1.1.pdf]

Tracking sunspot groups

[L. Győri (2015) 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, using heliographic coordinates to account for differing scales and orientations.  
Relations are defined between entities in the image. 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. [Source: Automation of Tracking Various Sunspot Group Entities and Demonstrating Its Usage on the Flaring NOAA AR 11429]

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 and uncurled from cartesian coordinates to polar.  
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. [Source: A Semi-Automatic Method to Measure the Rotation of Sunspots]  
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.[Source: ON THE ROTATION OF SUNSPOTS AND THEIR MAGNETIC POLARITY]

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 the Carrington velocity:

It has been shown that the rotational velocity of a sunspot increases as it approaches the equator.[Source: The Measurement of Solar Differential Rotation from Proper Motion of Individual Sunspots]

# 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 (Leighton, Noyes, & Simon 1962). Studying these oscillations would bring forth properties of these waves, along with an understanding of the solar interior. It has been found that there are systematic variations in the frequency of different oscillation modes in time (chaplin et al. 2004). 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 (dziembowski & Goode, 2005). The question is worth asking, how could the magnetic field present in the atmosphere of the sun 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. [Surface magnetic field effects in local helioseismology]