Magnetic Helicity as a Predictor of the Solar Cycle

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Abstract. It is known that the poloidal field is at its maximum during solar minima, and that the behaviour during this time acts as a strong predictor of the strength of the following solar cycle. This relationship relies on the action of differential rotation (the Omega effect) on the poloidal field, which generates the toroidal flux observed in sunspots and active regions.

We measure the helicity flux into both the northern and southern hemispheres using a model that takes account of the omega effect, which we find offers a strong quantification of the above relationship. We find that said helicity flux offers a strong prediction of solar activity up to 5 years in advance of the next solar cycle.

Keywords. Magnetic Fields, MHD, Sun: Activity, Sun: Magnetic Fields

1. Introduction

Solar activity and its associated phenomena and drivers are known to have wide ranging effects on the heliosphere, and (for example) how cosmic rays pass through said regions, a process described in (for example) Ferreira & Potgieter (2004).

There have been many attempts to model predictions of the solar activity cycle, which itself tends to be quantified by either sunspot/active region number or area. Prediction methodologies can be split into three subsets, extrapolation methods, precursor methods and model based predictions, see Munoz-Jaramillo, Balmaceda & Deluca (2013).

Magnetic helicity has even recently been used as a proxy for solar eruptions, see Pariat et al. (2016), although this is admittedly restricted to singular events, rather than over the whole solar body.

2. Overview

Considering only helicity flow across a boundary, Berger and Ruzmaiken (2000) gives the rate of change of helicity with respect to time as,

$$\frac{dH_{\mathcal{V}}}{dt} = 2\oint_{\mathcal{V}} (\mathbf{A}_P \cdot \mathbf{v}) B_n d^2x, \tag{2.1}$$

where B_n is the component of the magnetic field normal to the sun's surface, $\mathbf{A}_P$ is the potential field and $\mathbf{v}$ is the plasma surface velocity. The expressions for B_r and $\mathbf{A}_P$ are expanded using a spherical harmonic model (see Berger and Ruzmaiken (2000)) . The time variability of the model comes from the spherical harmonic co-efficients, which we use to calculate helicity flux from 1976 onwards.

Our model for helicity generation is based upon differential rotation alone (the Ω effect) - the zonal velocity of the solar body decreases as we move away from the equatorial slice towards the polar regions. The velocity field $\mathbf{v}$ is an analytical expression, which can be also be found in Berger and Ruzmaiken (2000).

Helicity flow for the solar body is modelled as shown in the aforementioned paper, with positive helicity flowing out from the northern corona, through the northern and southern hemispheres (in that order) and out into the southern corona.

Sunspot number has frequently been used as a solar activity proxy, indicating regions of increased magnetic activity. Sunspots will often appear in pairs, of opposing polarity (sometimes split by the equatorial plane).

Data and Analysis

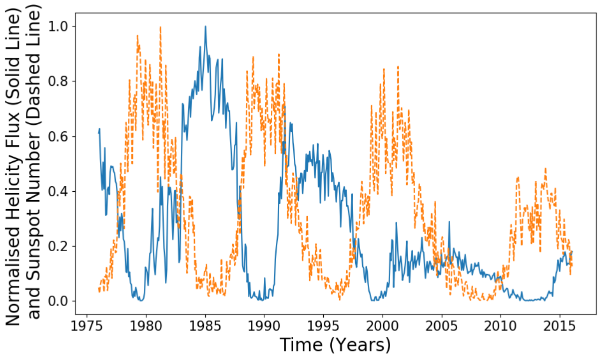

Figure 1. Normalised Helicity Flux plotted against Normalised Sunspot Number for the period of 1976 to 2017

In figure 1 we see Normalised helicity flux through the northern hemisphere plotted against monthly sunspot number over a period of $\sim 1976 - 2017$. Both data sets are averaged over a Carrington Rotation - see Acknowledgements for data sources. During this period we observe 3 complete helicity cycles, and nearly 4 complete sunspot number cycles. Disregarding incomplete cycles, and the first sunspot cycle, we see clear similarities between each helicity cycle and the sunspot cycle that follows. We see the sunspot peaks decreasing approximately in line with the trend of the helicity flow peaks, with some phase shift (which is approximated below). Two phase shifts were calculated, using a

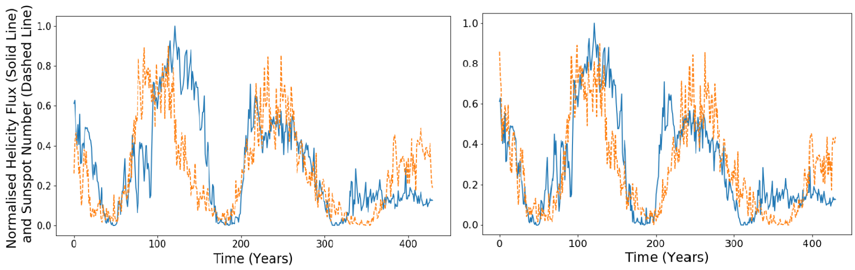

Figure 2. Normalised Helicity Flux plotted against Normalised Sunspot Number for the period of 1976 to 2017

function which maximises corelation - we maximised the correllation of the second pair of peaks for the left hand side of the figure, and maximisation of the first peaks gave the figure on the right. The phase shift of the second pair of peaks was found to be longer.

This change in lag time could be due to a number of factors, the most obvious of which is the amplitude of the cycles.

In figure 2 we attempt to optimise the phase shift of the two underlying cyclic behaviours. On the left of we have plotted the two data sets, with an ~ 6.75 year phase shift on the left, whilst on the right we have an ~ 5.6 year phase shift. Both have their strong and weak points. For the former, we see a good correlation of foot points, and excellent correlation for the second pair of peaks. The first pair of peaks is less well aligned (in the region between the footpoints). This is could be due to the sudden drop observed in the helicity flux around the year 1990, which is not reflected in the sunspot relation. The 5.6 year phase shift gives a stronger correlation for the first pair of peaks, although the footpoints are no longer as well aligned. In the right figure, the second pair of peaks is less well aligned between the footpoints.

The maximisation of the first pair of peaks offered a Pearson Correlation Co-efficient of $\mathbf{r = 0.79}$. Similarly, the second pair of peaks offered $\mathbf{r = 0.89}$, both of which indicate strong positive correlation.

Peak No	Integrated Helicity Flow	Integrated Sunspot Number	Ratio
1	59.5	44.17	70%
2	42.39	42.66	99%
3	17.5	21.4	82%

To take account of the differences in structure, particularly notable for the third pair of peaks, we attempt a different form of data analysis. We note that whilst the third helicity flux cycle is quite long, its sunspot twin is shorter, but taller. We thus reduce these cycles to singular data points by integration. The results of this are shown in the table above.

3. Conclusions

We have provided strong indication of a relationship between the solar cycles of helicity flux and the corresponding sunspot number cycle. Our analysis indicates that there is a phase shift between the two mechanisms of approximately $5 - 7$ years. We aim to collect more data to further verify our hypothesis, and make direct comparisons with the predictive capability of the polar field alone (given the presence of B_n in our flux equation).

4. Acknowledgements

The Wilcox Solar Observatory data used in this study to calculate Magnetic Helicity Flux was obtained via the web site http://wso.stanford.edu, courtesy of J.T. Hoeksema. Sunspot Number Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

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