LIP-STUDENTS-22-16

Unravelling time variability in solar activity

Rafael Parente[1,a]

[1] *Instituto Superior Técnico, Lisboa, Portugal*

Project supervisors: F. Barão and M. Orcinha *November 1, 2022*

Abstract. In this paper, we studied the time variability of solar activity through various solar observables to better understand the Sun's behaviour and the means by which it affects us, allowing for a better prediction of solar events. We began by making predictions about the existence of the 13.5 days and 27 days solar cycles based on Parker's spiral magnetic field model, which will be discussed. Then, we explored data collected by the Advanced Composition Explorer (ACE) satellite, using the Continuous Wavelet Transform (CWT), to find the frequencies present in sampled signals and their variations over time. We found several periodicities associated with the solar activity cycle and the predicted cycles on various solar observables.

Keywords: Parker, ACE, CWT

1 Introduction

1.1 Sun

The Sun is the star at the center of the Solar System. It is a huge ball of hot plasma, about 1.3 million times larger than the Earth and is heated by nuclear fusion in it's core, being the main source of energy in the Solar System.

The solar corona consists of highly conductive plasma with a high temperature of around 1-2 million Kelvin. The hot coronal temperature causes a steady outflow of plasma which we denominate as solar wind, that drags the coronal magnetic field out into the solar system. Solar wind can travel with speeds ranging from ~ 300 km/s to ~ 750km/s depending on their latitude relative to the solar magnetic equator ([1]).

Solar activity

One of the most important features of the Sun is its variability. It was discovered nearly 4 centuries ago as variations of sunspots by early telescopic observations, nowadays we know that all of the Sun's properties change with time.

Solar activity is measured primarily by the number of sunspots on the photosphere and it follows a 11 years activity cycle also known as the Schwabe cycle, named after its discoverer. During the solar activity cycle, the Sun's magnetic dipole tilts from the rotation axis towards the equator leading to an inversion of the magnetic dipole. Solar activity is at its minimum when the magnetic dipole is aligned with the Sun's rotation axis, which then evolves over time into a solar maximum when the magnetic dipole approaches the equator where the dipole's polarity is about to switch, and so on. The Schwabe cycle is part of a 22 years cycle known as the Hale cycle, that corresponds to the periodic reversal of the solar magnetic dipole.

It is important to monitor and predict solar activity because solar flares and coronal mass ejections (CME) are more likely to occur in periods of high solar activity, both of which can damage electrical systems in satellites and even overload power grids on land depending on their intensity ([2]). A famous example of the effects caused by CMEs is the Carrington Event ([3]) which was the most intense geomagnetic storm in recorded history. It has also been seen ([4]) that the extension of solar activity into the heliosphere results in a periodic modulation of the flux intensities of high energy cosmic rays that is inversely related to the number of sunspots in the solar activity cycle.

1.2 Solar Magnetic Field

The Sun has a highly variable magnetic field, which is responsible for all of the solar activity. It is formed by the flow of the highly conductive plasma in the Sun's convection zone, which generates an electrical current that acts as a magnetic dynamo ([5]).

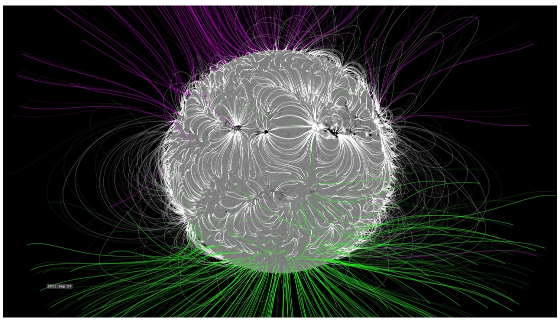

Figure 1: View of the magnetic field lines in the solar corona. The purple and green field lines represent the magnetic dipole field and the white field lines are closed loops formed by sunspot pairs

Interplanetary Magnetic Field

The Interplanetary Magnetic Field (IMF) is the extension of the Sun's magnetic field from the solar corona throughout the heliosphere and is the main focus of our study. With a few assumptions, the IMF can be modelled by Parker's spiral magnetic field model.

[a] e-mail: rafael.parente@tecnico.ulisboa.pt

Parker Model

Assumptions:

- Solar wind with infinite electrical conductivity and a radial outflow at a constant speed throughout the photosphere
- Solar magnetic field is dipolar
- The footpoints of the magnetic field are fixed in the photosphere (they rotate with the Sun)
- Solar magnetic field is frozen[1] in the solar wind (the magnetic field is transported by the solar wind)

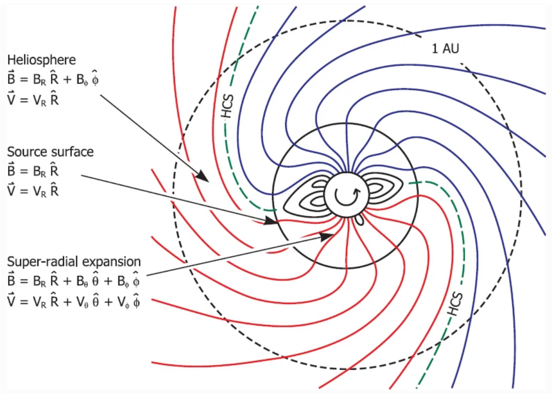

Figure 2: Parker's spiral magnetic field seen from above

The region of the Parker model we will be studying is the Heliosphere, which starts at the Source surface located at about 10-20 solar radii from the Sun, where the solar wind becomes super-Alfvénic ([1]).

$$B_R(R,\theta,\phi) = B_R(R_0,\theta,\phi_0)\left(\frac{R_0}{R}\right)^2 \quad (1)$$

$$B_\theta(R,\theta,\phi) = 0 \quad (2)$$

$$B_\phi(R,\theta,\phi) = -B_R(R_0,\theta,\phi_0)\frac{\Omega R_0^2 sin(\theta)}{V_R R} \quad (3)$$

where R_0 is the distance between the sun and the source surface [AU], V_R is the radial solar wind speed [km/s] and Ω is the mean solar rotation speed [rad/s].

Heliospheric Current Sheet

The Heliospheric Current Sheet (HCS) is a surface that separates IMF lines of different polarities. It has a low electrical current density of around 10^{-10} Am^{-2} and is about 10,000 km thick at 1 AU[2] from the Sun. The HCS' waviness is due to solar rotation and the tilt of the magnetic axis in relation to the rotation axis of the Sun ([6]).

The HCS expression can be derived with a simple trigonometrical exercise as done in ([7])

$$\theta_{HCS} = \frac{\pi}{2} - tan^{-1}\left[tan(\alpha)sin\left(\phi - \frac{\Omega(R-R_0)}{V_R}\right)\right] \quad (4)$$

where α is the magnetic dipole tilt angle with respect to the rotation axis of the Sun.

[1] Alfvén's theorem states that in a fluid with infinite conductivity, the magnetic field is frozen into the fluid

[2] Astronomical Unit (1 AU = 149 597 871 km)

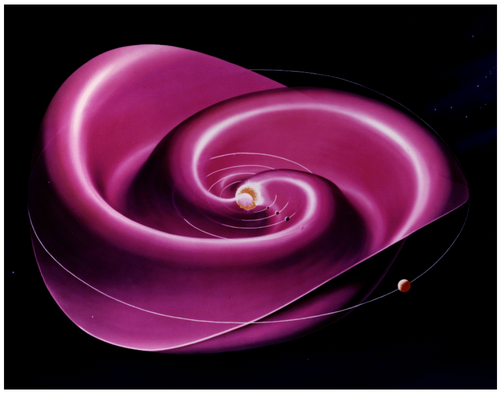

Figure 3: Visualisation of the Heliospheric Current Sheet

Coordinate System

In this project we use the Geocentric Solar Ecliptic (GSE) coordinate system as seen in Figure 4

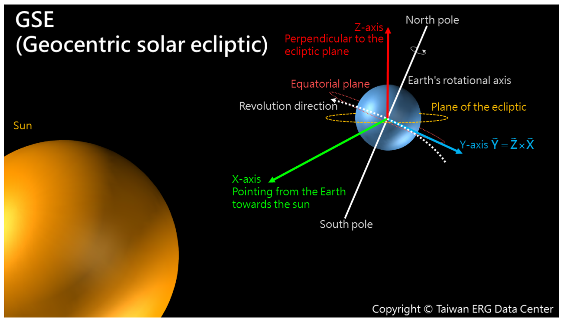

Figure 4: Diagram of the GSE system

2 IMF Visual Representations

Using Parker's model, some visual representations of the IMF were made to help us understand it's structure and how it evolves with time.

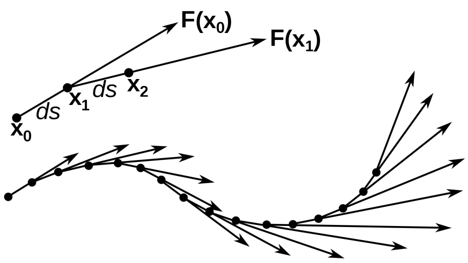

Figure 5: Algorithm for field line computation

To do so, we chose multiple points on the photosphere to set as the magnetic field's footpoints, then for every field line we computed the points it goes through by taking small steps in the magnetic field's direction and joined them all with straight lines to form the field lines.

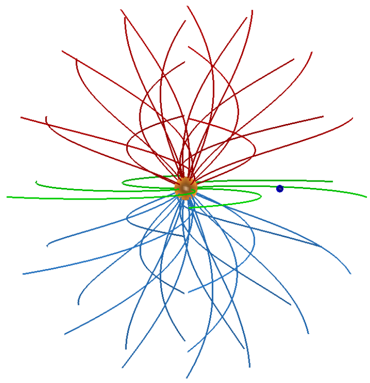

Figure 6: IMF visualisation ($\alpha = 0°$), the red and blue lines represent positive and negative field lines respectively and the green lines represent the HCS. The orange and blue balls are the Sun and the Earth

The magnetic dipole tilt was done by rotating all the magnetic field's footpoints by α degrees around the x-axis, then the field lines were computed with the magnetic field equations.

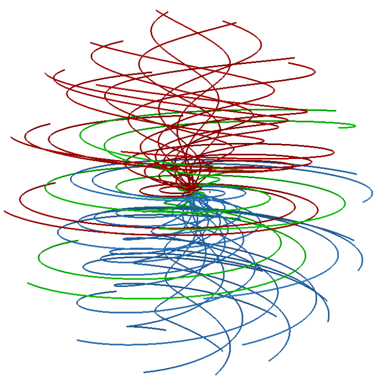

Figure 7: IMF visualisation ($\alpha = 30°$) with a further away view

From Figure 7, it can be seen that the HCS oscillates as the IMF spreads throughout the heliosphere. To see how the IMF polarity changes around Earth as the Sun rotates, we plotted intersections of the magnetic field with the x-z plane at different instants of a solar rotation period.

Since the orientation of the IMF lines depends on their polarity we will be using IMF y-component to represent the polarity of magnetic field lines. From Figure 8, we can predict that in a period of 27 days (mean solar rotation period) the IMF near Earth goes through a polarity change

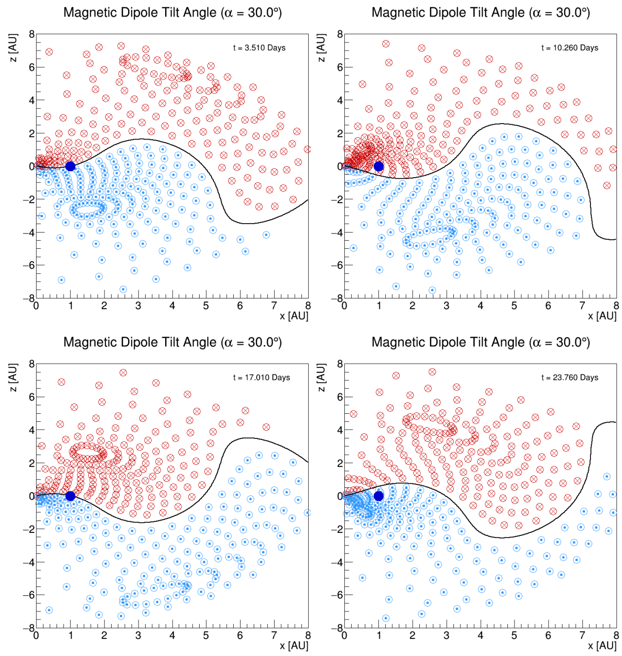

Figure 8: The red symbols are positive field lines going into the plane and the blue symbols are the negative field lines going out of the plane. The dark blue circle is the Earth and the black curve is the HCS

cycle, and consequently that the y-component of the IMF follows that 27 days cycle.

Predictions

Taking into consideration the properties of each cycle, below is a table of which periodicities we expect to find in the data analysis of various solar observables.

	Solar Cycles			
	22 years	11 years	27 days	13.5 days
SSN	✗	✓	✗	✗
IMF mag.	✗	✓	✗	✗
IMF y	✓	✓	✓	✓

Table 1: Predictions for the cycles present in different solar observables, Sunspots Number (SSN), IMF magnitude and IMF y-component

3 Time Variability Analysis

To search for periodicities on solar observables, we use data taken from the ACE satellite that orbits the Sun at L1[3] ([8]). The observables we will be analysing are the IMF magnitude, IMF y-component and Sunspots Number (SSN).

[3]Lagrange Point 1

3.1 Continuous Wavelet Transform

The CWT is a tool that decomposes time series into time-frequency spaces ([9]). It does so by "scanning" the signal with wavelets of variable scale centered at different points in time. In this project we use the Morlet wavelet, because it is the most suitable for analysing oscillating signals ([10]). For a sampled signal, the CWT is given by:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s} \right] \tag{5}$$

where x_n is the sampled signal, ψ is the wavelet, δt is the time step of the signal and s is the scale of the wavelet.

Morlet Wavelet

$$\psi(\eta) = \pi^{-\frac{1}{4}} e^{-i\omega_0 \eta} e^{-\frac{\eta^2}{2}}, \quad \eta = \frac{(n'-n)\delta t}{s} \tag{6}$$

$$T = \frac{4\pi s}{\omega_0 + \sqrt{2+\omega_0^2}} \tag{7}$$

The Morlet wavelet is a complex exponential with gaussian amplitude modulation. It oscillates with a period that is directly related to the wavelet's scale by (Equation 7). The parameter ω_0 defines how many oscillations are contained in the wavelet's envelope[4]. We set $\omega_0 = 6$ so the proportionality constant between period and scale is close to 1. (T ≈ 1.03s)

3.2 Data Analysis

IMF Magnitude

Applying the CWT to the IMF magnitude time series in a time period of 52 years, we can see that the observable appears to mostly depend on the 11 years activity cycle.

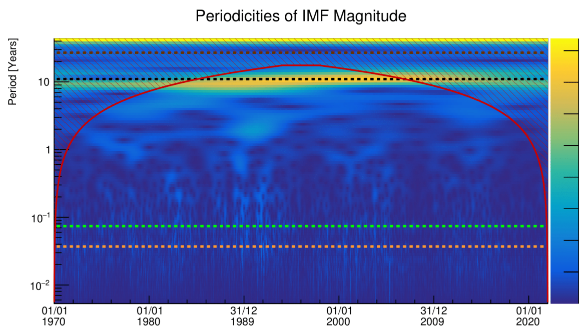

Figure 9: Periodogram of CWT to IMF Magnitude data, the dashed lines correspond to the following periodicities: 13.5 days (orange), 27 days (green), 11 years (black), 22 years (brown). Data covers the period of 01/10/1970-01/01/2022.

Additionally, we looked into a time interval of 2 years trying to find evidence for the dependence on cycles with

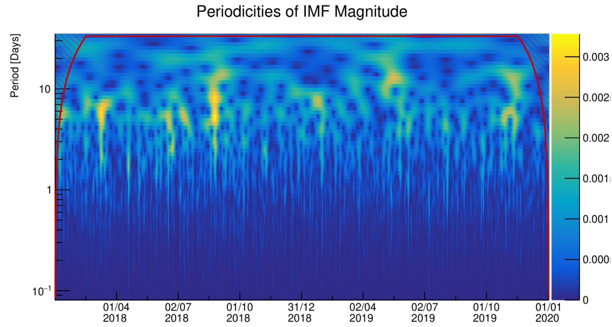

Figure 10: Periodogram of CWT to IMF Magnitude data. Data covers the period of 01/10/2018-01/01/2020.

lower periods with no success. However we can see a few events along that time interval.

Focusing on one of those events, we can see that there was a disturbance in the IMF that lasted for a few days. It corresponds to a CME on the Sun in August 20, 2018 which that took 6 days to reach Earth. This CME was an unusual one which occured during a solar minimum and was intense enough to form auroras that could be seen in Alaska ([11]).

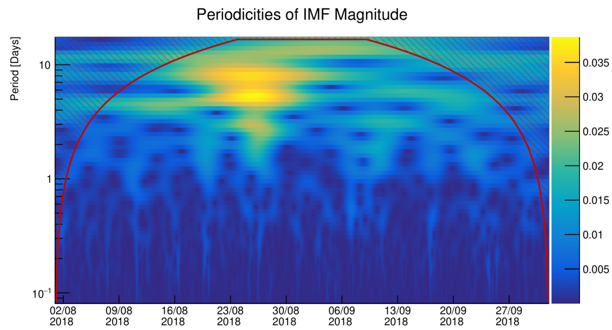

Figure 11: Periodogram of CWT to IMF Magnitude data. Data covers the period of 01/08/2018-01/10/2018.

IMF y-Component

Motivated by Figure 8, we analysed the IMF y-component in a time interval of 52 years (see Figure 12). We could not find the 11 years periodicity, however the 22 years cycle was present, although with a fading wavelet power, caused by boundary effects.

The wavelet transform power at a given time *t* and period (or equivalent scale - *s*) involves estimating the correlation between the wavelet centred in time *t* and requires that this wavelet is fully contained within the time series as it spreads outwards. The spread of the wavelet (region of influence) is dependent on the period. For larger periods the wavelet is wider and thus spreads over a larger time interval over our time series. As the wavelet moves

[4]The envelope is the time interval in which the wavelet isn't cancelled by the gaussian amplitude modulation

towards the boundaries it is not fully covered within our time range, influencing the general power of the wavelet transform artificially.

We can then define a region dependent on the period within which we consider our transform result meaningful. This region is called the Cone of Influence (COI) and is estimated by calculating the amplitude decay of a wavelet centred at the edges of our time series and estimating the time at which the amplitude decays by e^{-2}, the e-folding time. The result within the COI is considered to be accurate and significant while outside this region we will need to take into account boundary effects.

Additionally we found a 5.5 years cycle and a 17 years also known as the global solar cycle ([4]). However, just like the Parker Model predicted, we were able to find both 27 days and 13.5 days periods.

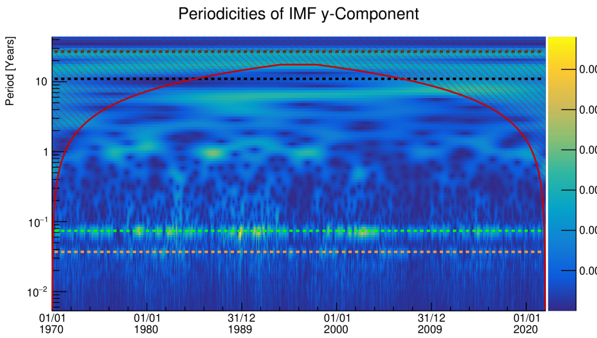

Figure 12: Periodogram of CWT to IMF y-Component measured by the ACE satellite. The dashed lines correspond to the following periodicities: 13.5 days (orange), 27 days (green), 11 years (black), 22 years (brown). Data covers the period of 01/01/1970-01/01/2022.

Number of Sunspots

As expected, the number of sunspots on the photosphere follows the 11 years activity cycle.

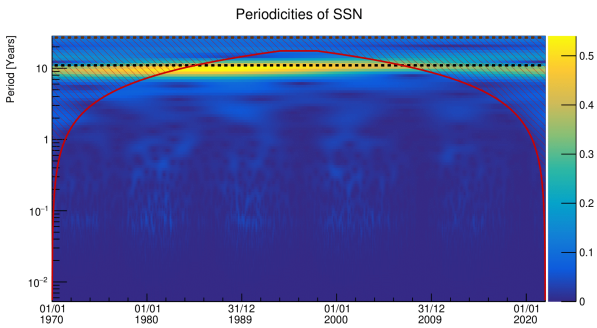

Figure 13: Periodogram of CWT to IMF y-Component measured by the ACE satellite, the dashed lines correspond to the following periodicities: 11 years (black), 22 years (brown). Data covers the period of 01/01/1970-01/01/2022.

4 Conclusions

Using Parker's spiral magnetic field model, we were able to construct visual representations of the solar magnetic field, which granted us foresight in regards o the existence of the 13.5 and 27 days periodicities.

The CWT is not only able to detect various solar cycles, but also solar events, such as CMEs. Using the CWT to analyse the periodicities of the IMF y-Component, we were able to detect both the 13.5 and 27 days periodicities, confirming our predictions.

The 11 years activity cycle was found in both the IMF magnitude and SSN data samples, confirming that the number of sunspots is a good proxy of solar activity and allows us to characterize the activity cycle.

The Sun has been object of study for centuries and the availability of solar observables, as well as the rich ensemble of periodic signals they contain, makes it a great object of study using the Continuous Wavelet Transform. We were able to identify periodic signals as they evolve with time in both SSN and IMF time series.

References

[1] M.J. Owens, R.J. Forsyth, Living Reviews in Solar Physics **10**, 5 (2013)

[2] K.H. Bryan Mendez, Laura Peticolas, *Solar flares and coronal mass ejections*, https://www.nasa.gov/audience/foreducators/9-12/features/F_Dangers_of_Solar_Flares_and_CME.html

[3] S. Silverman, Advances in Space Research **38**, 136 (2006)

[4] A. Balogh, H.S. Hudson, K. Petrovay, R. von Steiger, Space Science Reviews **186**, 1 (2014)

[5] *The sun and magnetism*, https://www.nasa.gov/mission_pages/sdo/science/sun-magnetism.html

[6] *The heliospheric current sheet*, https://www.nasa.gov/content/goddard/heliospheric-current-sheet

[7] L. Batalha, Master's thesis, Instituto Superior Técnico (2012)

[8] R. Candey, *Omniweb*, https://omniweb.gsfc.nasa.gov/

[9] C. Torrence, G.P. Compo, Bulletin of the American Meteorological Society **79**, 61 (1998)

[10] M.S. Tiscareno, M.M. Hedman, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **376**, 20180046 (2018)

[11] M. Hatfield, *Here's a coronal mass ejection right before it hit earth*, https://blogs.nasa.gov/sunspot/2018/10/18/heres-a-coronal-mass-ejection-right-before-it-hit-earth/