Solar activity characterization

time variability of its observables

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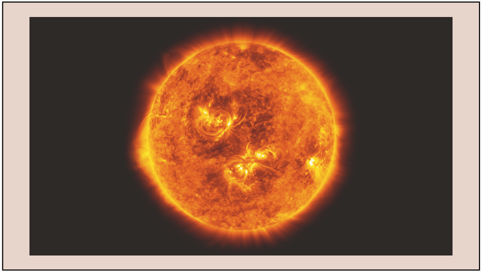
LIP/IST



Talk Overview

- **Solar activity**
  - Solar cycles
  - Observables: sunspots, magnetic field,
  - Parker model
- **Mathematical tool**
  - Wavelet transform
- **Characterization of solar activity in time and frequency**
  - Data collection
  - Magnetic field
  - Sunspots number
- **Final remarks**

Solar Cycles

- 27 days cycle, which is the average rotation period of the Sun

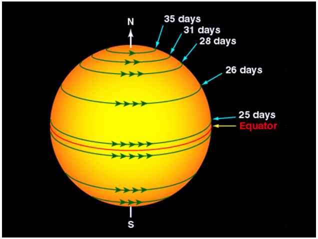


Figure 1: Differential rotation of the sun

- 11 years activity cycle, during which the magnetic dipole tilts from the Sun's rotation axis to the equator and switches polarity

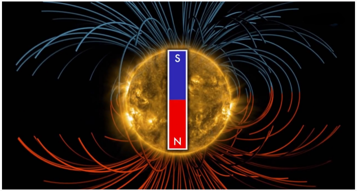


Figure 2: Sun's magnetic dipole

Solar Activity

- **Solar Activity is characterized by:**
  - Sunspots number
  - Solar flares
  - Solar Prominences
  - Coronal mass ejections
- All of these phenomena are correlated with the 11 years solar activity cycle

Sunspot

- Consists of a dark region (umbra) and lighter region (penumbra)
- Colder than the rest of the photosphere [1]
- The magnetic field is more intense near the sunspots
- Sunspots are usually about the size of the Earth

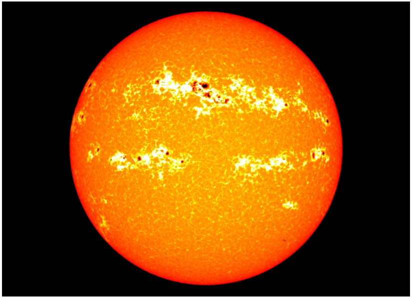


Figure 3: Sunspots on the photosphere

[1] Outer shell of stars, from which radiation is emitted

Solar Magnetic Field

- It's formed by the movement of highly conductive plasma inside the Sun
- The magnetic field is spread around the solar system by the solar wind[2]
- The Sun's magnetic field causes all solar activity

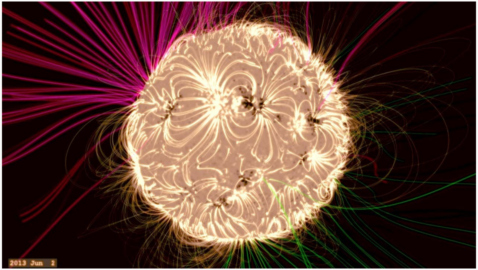


Figure 4: Solar magnetic field

[2] Solar wind is a a stream of charged plasma released from the photosphere

Interplanetary Magnetic Field

- The interplanetary magnetic field (IMF) is an extension of the Sun's magnetic field beyond the solar corona and spreads throughout the Heliosphere
- IMF is the field that interacts with the rest of the solar system
- Making a few assumptions about solar behaviour, the IMF can be modelled by Parker's model

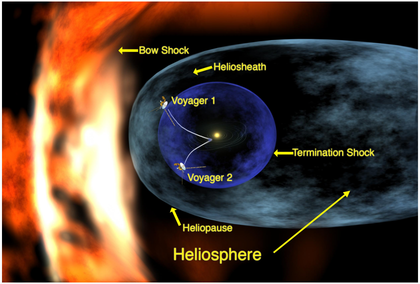


Figure 5: Visualization of the heliosphere

Parker Model

- **Assumptions:**
  - Solar wind with infinite conductivity and a radial outflow at constant speed all over the photosphere
  - The magnetic field is dipolar
  - The magnetic field is frozen[3] in the solar wind, meaning the magnetic field has a radial outflow

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

Parker Model

- Beyond the source surface, the expansion of the solar wind dominates over the magnetic field
- The solar wind flow becomes purely radial

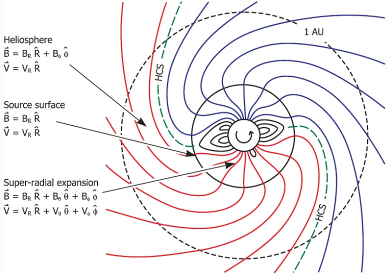


Figure 6: Solar magnetic field seen from above

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

$$B_\theta = 0 \quad (2)$$

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

- R_0: distance from the sun to the source surface [AU]
- V_R: radial solar wind speed [km/s]
- Ω: mean solar rotation speed [rad/s]

IMF Visual Representation

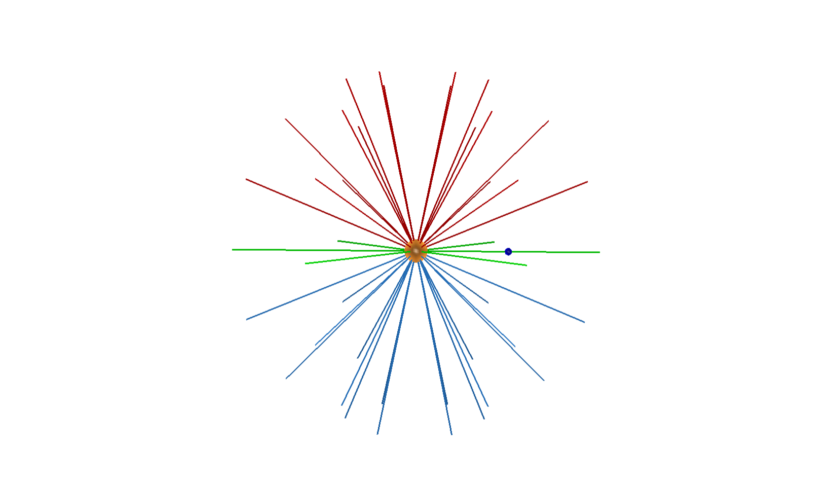


Figure 7: Purely radial IMF

IMF Visual Representation

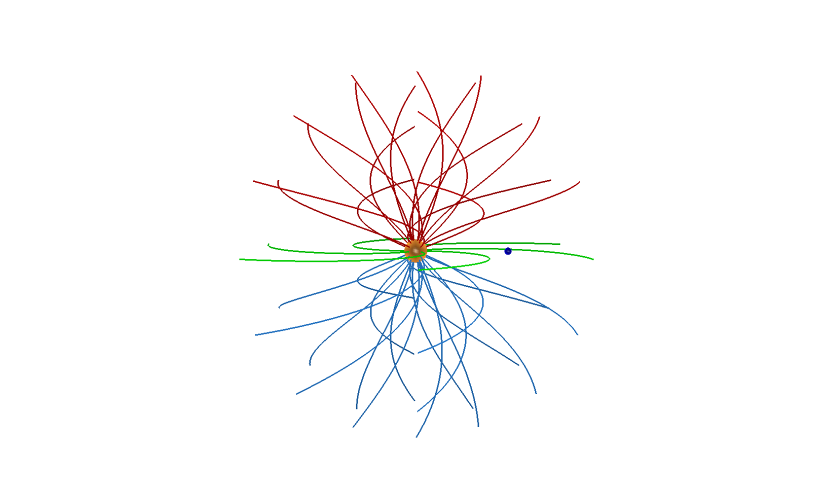


Figure 8: Radial IMF with solar rotation ($\alpha = 0°$)

IMF Visual Representation

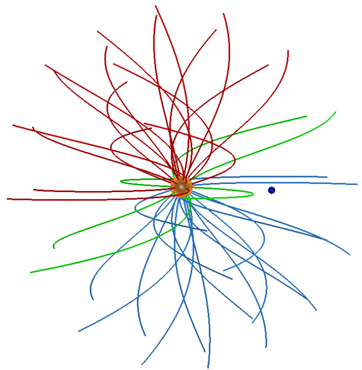


Figure 9: Radial IMF with solar rotation and magnetic dipole tilt ($\alpha = 30^\circ$)

IMF Visual Representation

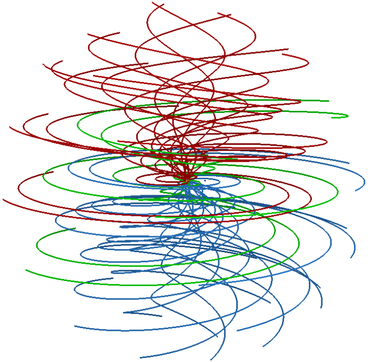


Figure 10: Radial IMF with solar rotation and magnetic dipole tilt ($\alpha = 30^\circ$)

Heliospheric Current Sheet

- The Heliospheric Current Sheet (HCS) is the surface separating heliospheric magnetic field lines of opposite polarities

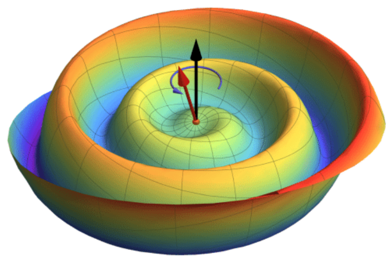


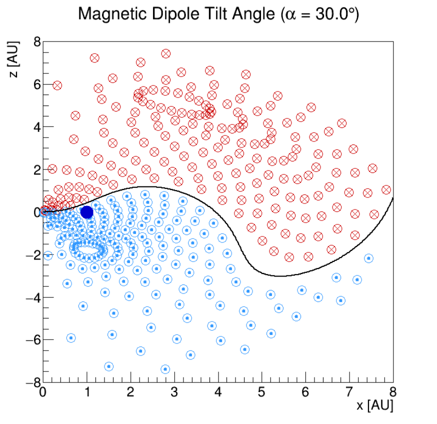
Figure 11: Visualization of the HCS surface

- It has low electric current density of around 10^{-10} Am^{-2} and is about 10,000 km thick at 1 AU[4] from the Sun

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

Heliospheric Current Sheet

➔ The animation below is the cross-sectional view of the magnetic field on the x-z plane of the GSE coordinate system over the period of a solar rotation



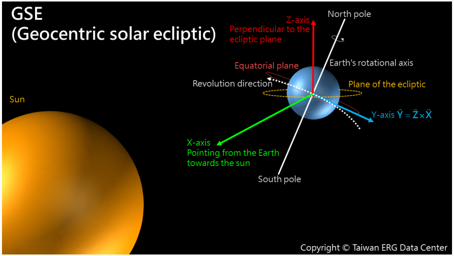


Figure 12: Coordinate system used in this project

Mathematical tool

- ➔ To analyse the correlations of various observables with the solar cycles we need to use tools that can detect the frequencies in a signal
- ➔ **Tool used for data analysis:**
  - ➔ Continuous wavelet transform

Continuous Wavelet Transform

- Continuous Wavelet Transform (CWT) is a tool that decomposes time series into time-frequency spaces
- It works by "scanning" the signal with wavelets of different scales shifted along the time domain
- We will be using the Morlet wavelet, because it is the most suitable for scanning oscillating signals

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n' - n)\delta t}{s} \right] \quad (4)$$

$$s = s_0 2^{j\delta j}, \; j = 0, 1, ..., J \quad (5)$$

Continuous Wavelet Transform

- The Morlet wavelet is a complex exponential with a gaussian amplitude modulation

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

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

- It oscillates with a period that is directly related to the scale, given by eq. (9)

- ω_0 defines how many sinusoidal oscillations are contained in the envelope (usually $\omega_0 = 6$ so that $T \approx 1.03s$)

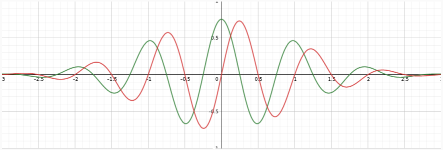


Figure 13: $\omega_0 = 1, \ s = 1$

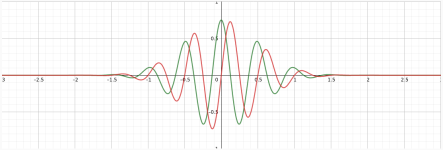
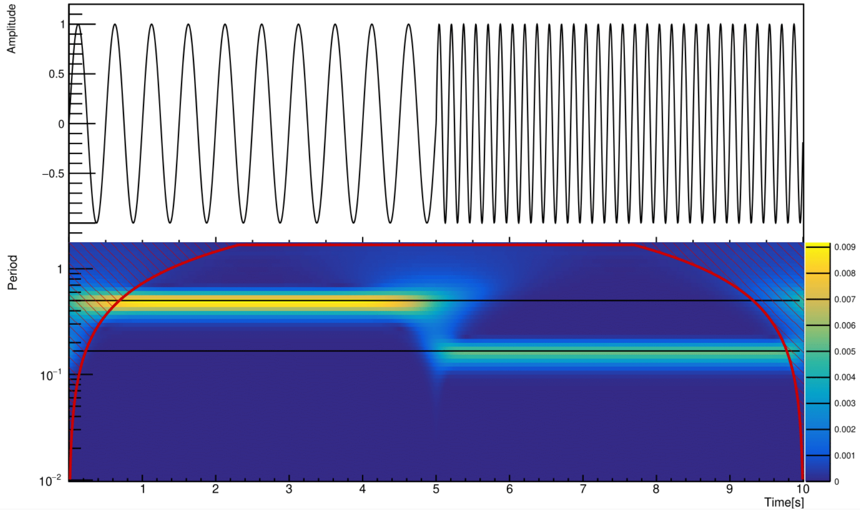


Figure 14: $\omega_0 = 1, \ s = 0.5$

CWT Example



Amplitude
1
0.5
0
−0.5
Period
1
10^{-1}
10^{-2}
1
2
3
4
5
6
7
8
9
10
Time[s]
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0

Characterization of solar activity in time and frequency

- **Data analysis:**
  - Data collection
  - Magnetic field
  - Sunspots number

Data Collection

→ All the data used in this project was taken from OMNIWeb, which was measured by the ACE satellite, orbiting the Sun at L1

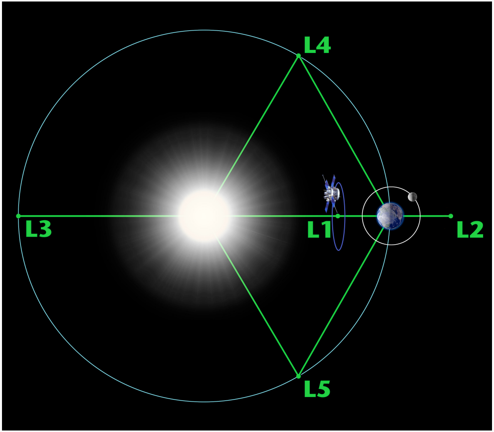
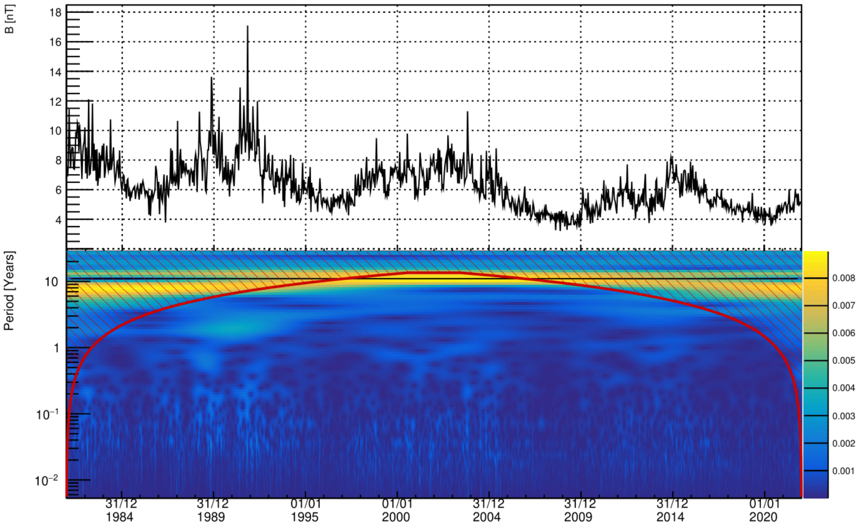
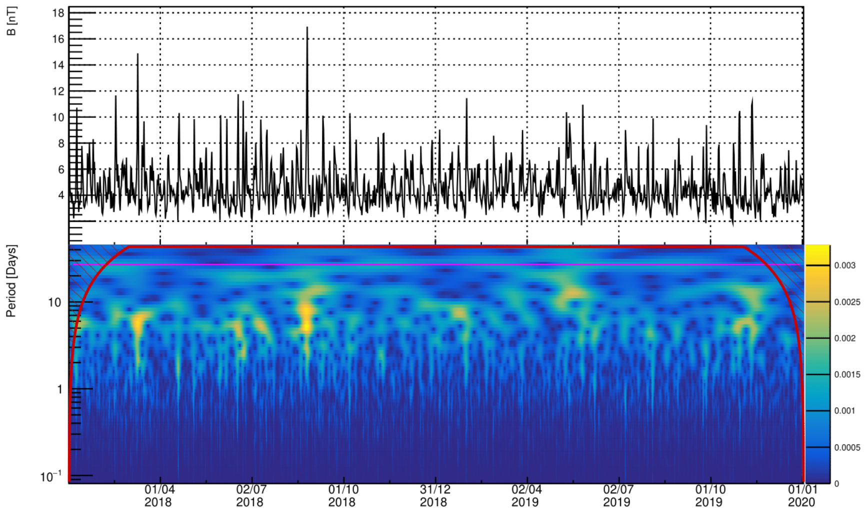


Figure 15: Orbit of the ACE satellite

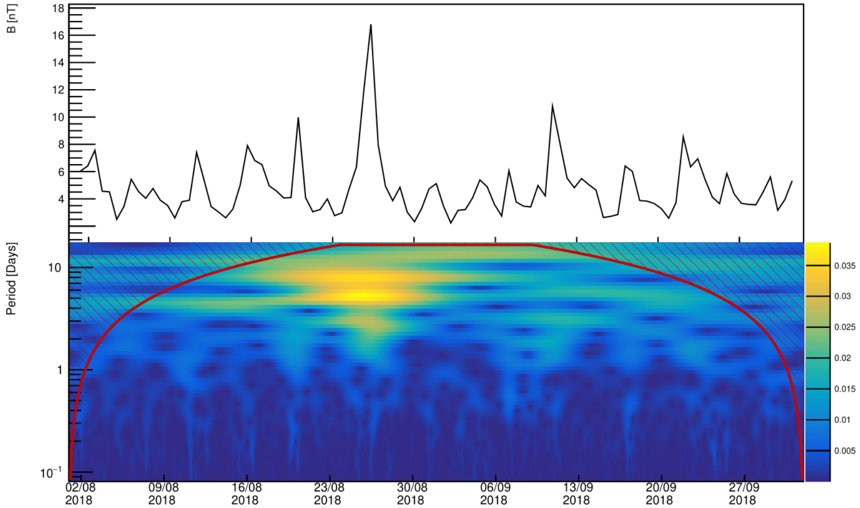
IMF Magnitude



IMF Magnitude



IMF Magnitude



Coronal Mass Ejection (CME)

- In August 20, 2018 there was a CME in the Sun which made its way towards the Earth

- It took 6 days to reach us and it's effects on IMF lasted for about 5-6 days

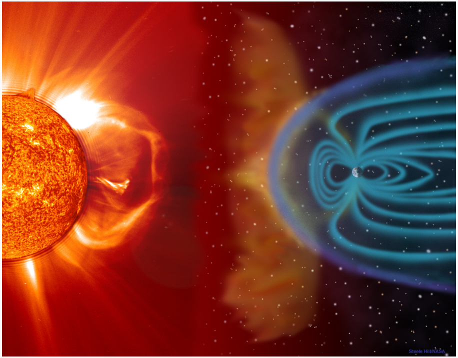
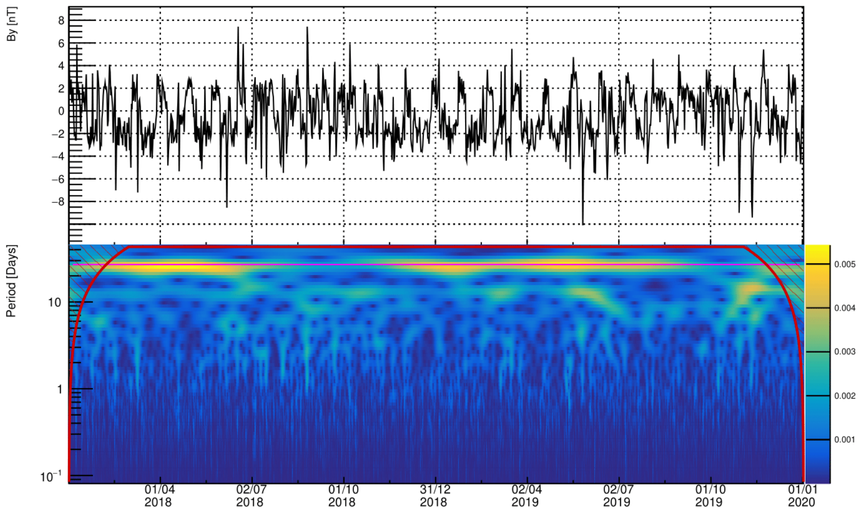
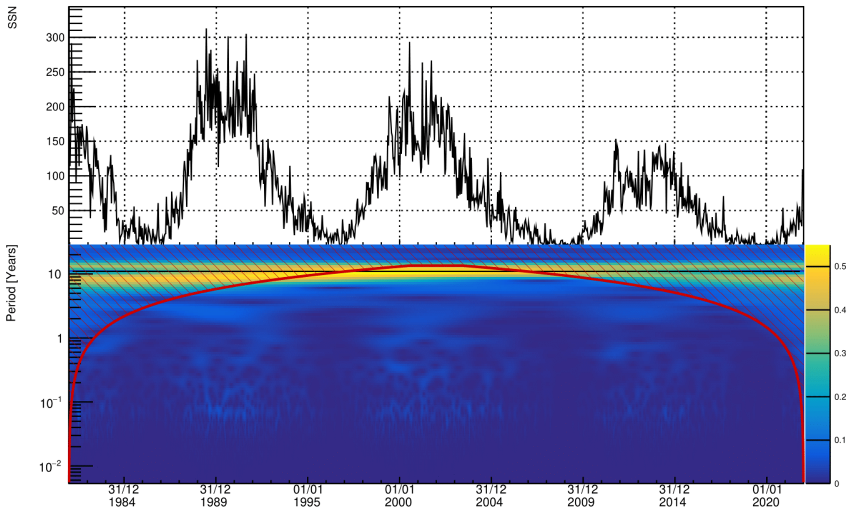


Figure 16: Visualization of a Coronal Mass Ejection

IMF y-Component

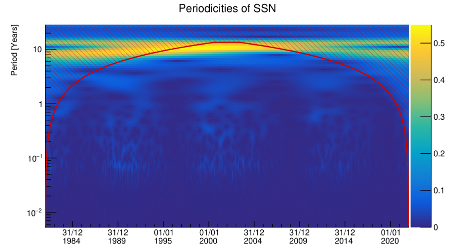


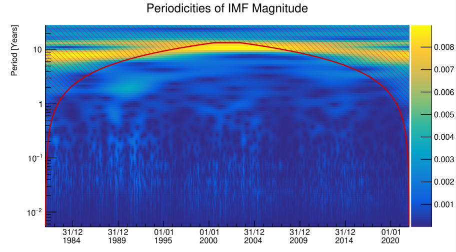
Sunspots Number



SSN vs. IMF Magnitude

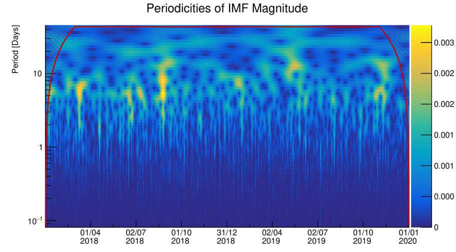
→ Since the SSN and IMF magnitude both follow the 11 years activity cycle, the SSN is a good indicator of solar activity

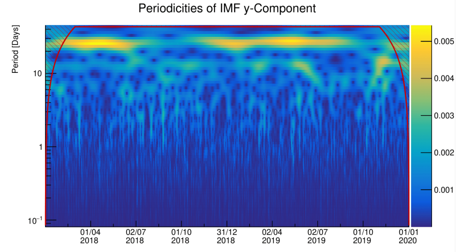




IMF Magnitude vs. IMF y-Component

- The IMF y-component is more dependent on the 27 days cycle than the IMF magnitude





Conclusions

- ➔ It was possible to create visual representations of the Parker spiral magnetic field model
- ➔ We developed tools to analyse the different periodicites of the solar observables
- ➔ We observed that the IMF y-component follows the 27 days cycle
- ➔ We observed that solar activity follows the 11 years activity cycle (as expected)