Synchronization in the solar system

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Abstract— The solar activity over the last 10'000 years, as reconstructed from cosmogenic radionuclides stored in terrestrial archives, shows a couple of very stable albeit intermittent periodicities. Recently, the same periodicities have been discovered in the torque exerted by the planets on the sun's tachocline. While the mechanism through which the planets couple to the sun's magnetic field is still unknown, this synchronization phenomenon deserves renewed attention from the nonlinear dynamics community.

1. Introduction

Recently, evidence from data for a synchronization of the motion of the planets and the (magnetic) solar activity has been reported [Abreu et al., 2012]. This has led to a debate about the significance of these findings within the solar physics community [Cameron and Schüssler, 2013, Charbonneau, 2013], where the dogma prevails that the sun can be considered as an isolated system because of the weakness of the planetary forcing.

Within the nonlinear dynamics community, synchronization effects between weakly coupled nonlinear oscillators are well understood. From the perspective of dynamical system's theory it is hardly a surprise to see synchronization in the solar system, bearing in mind that it emerged over the past 4.5 billion years from a rather homogeneous cloud of dust, even if the planets' influence on the sun is very weak.

The sunspot record, covering more than 400 years of direct observations of solar activity, supports the idea that the solar magnetic field can be understood as a nonlinear oscillator that is gravitationally driven by the planets [Paluš et al., 2007, Paluš and Novotna, 1999]. However, by which mechanism weak exterior gravitational fields couple to the sun's magnetic field is unclear.

While sunspot records are available for only a couple of centuries, the data analysis in [Abreu et al., 2012] is based on 10'000 yr long records of radionuclides, which are a proxy for solar activity. An analysis of these records has revealed that the solar activity cycle is modulated by several quasi-periodic cycles showing period-doubling characteristics and aperiodic grand minima with a characteristic time scale exceeding several tens of cycle periods [Hanslmeier, A. et al., 2013]. Thus, solar activity seems to be "on the edge of chaotic behaviour". It is the purpose of this conference contribution to draw renewed attention of the nonlinear dynamics community to these records, in order to achieve a better understanding of the observed synchronization of solar activity with planetary forcing.

The establishment of a robust synchronization of the solar activity with the planetary orbits would have important implications for the predictability of solar activity and its influence on the climate of space and Earth.

2. Stable cycles in solar activity

Unfortunately the direct observations of solar activity based on sunspots are limited to the period since the invention of the telescope in 1609. However, indirect observations based on the cosmogenic radionuclides ^{10}Be and ^{14}C provide information of solar activity for about 10'000 years. The solar wind streaming away from the sun and forming the heliosphere is carrying frozen-in solar magnetic fields, which prevent galactic cosmic rays from reaching the earths atmosphere where they produce ^{10}Be and ^{14}C by interacting with nitrogen and oxygen. As a consequence, measuring these radionuclides in natural archives provides a measure of how strongly the solar magnetic field has modulated the galactic cosmic ray intensity in the past. This measure can be expressed by the so-called solar modulation potential Φ [Beer et al., 2012].

The power spectrum of the solar modulation potential shows a couple of sharp lines within a noise spectrum that resembles red noise. These lines have been detected in many different data sets (such as ^{14}C measurements in tree rings, ^{10}Be measurements in ice sheets, etc.) and are commonly accepted to reflect cycles of solar activity [Stuiver and Braziunas, 1993, McCracken et al., 2013]. Some of them, like the ≈87 yr Gleissberg cycle or the ≈208 yr deVries cycle, are even named after their discoverers. Furthermore, wavelet analysis shows that while the periods are extremely stable over time, their amplitudes are strongly modulated (see Fig. 1).

3. Evidence for planetary coupling

In order to test the hypothesis of a planetary influence on solar activity, Abreu et al derived, from NASA

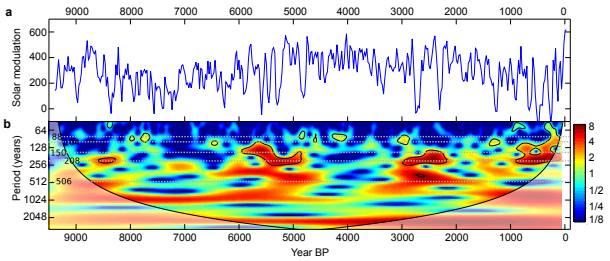

Figure 1: Properties of solar activity reconstructed from cosmogenic radionuclides. a) Solar activity for the past 9400 years, as specified by the solar modulation potential Φ determined using the cosmogenic radionuclides ^{10}Be and ^{14}C [Steinhilber et al., 2012]. b) Corresponding wavelet analysis of solar activity Φ showing the temporal evolution of the amplitudes of the various periodicities. The dashed horizontal lines illustrate the distinct periodicities at 88 yr, 104 yr, 150 yr, 208 yr, and 506 yr. The red areas indicate high power and blue areas low power. The black contours show the 5% significance regions (i.e., 95% confidence level). *Reproduced with permission from Astronomy and Astrophysics, © ESO.*

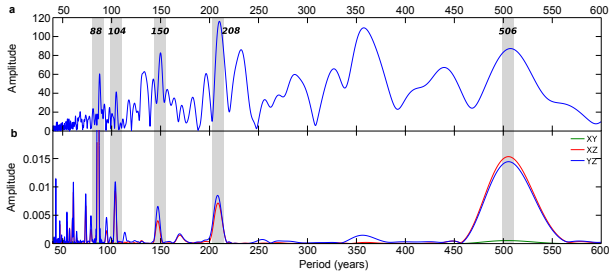

Figure 2: Comparison between solar activity and planetary torque in the frequency domain. a) Fourier spectrum of the solar activity quantified by the solar modulation potential Φ. b) Fourier spectrum of the annually averaged torque modulus $|\mathbf{N}(t)|$ (different colors correspond to different torque components). The spectra display significant peaks with very similar periodicities: the 88 yr Gleissberg and the 208 yr de Vries cycles are the most prominent, but periodicities around 104 yr, 150 yr, and 506 yr are also seen. *Reproduced with permission from Astronomy and Astrophysics, © ESO.*

records of ephemerides, the torque exerted by the planets on the sun's tachocline, a thin layer between the radiative and the convective zone of the sun. Many solar physicists believe that it is in the tachocline where the dynamo generates and stores the toroidal magnetic flux that eventually gives rise to solar active regions.

Comparing the power spectra of the planetary torque and the solar modulation potential shows that they share many of their strongest lines, with remarkable accuracy (see Fig. 2). Furthermore, a wavelet analysis shows that torque and solar modulation modes tend to be in phase when the latter has a large amplitude (see Fig. 3).

The mechanism through which the weak gravitational field of the planets couples to the magnetic field of the sun is still unclear. A possible explanation has been suggested in [Abreu et al., 2012]. The crucial point is that the tachocline plays a key role in the dynamo process [Galloway and Weiss, 1981, van Ballegooijen, 1982, Charbonneau, 2010]. The tachocline is on the one hand a layer of strong shear, which is a basic ingredient of the dynamo process. On the other hand, it more or less coincides spatially with the layer of overshooting convection at the bottom of the convection zone. The overshoot layer is thought to be crucial for the storage and the amplification of the magnetic flux tubes that eventually erupt at the solar photosphere to form active regions. One of the key factors determining the storage capacity of the overshoot layer is the superadiabaticity δ, which is a dimensionless measure of the stratification of the specific entropy in a medium. The maximum field strength of a flux tube that can be stored at a given latitude in the overshoot layer depends very sensitively on the value of δ, which is about -10^{-4} to -10^{-5}. Small variations in δ of about -10^{-4} may decide whether a flux tube becomes unstable at $2 \cdot 10^4$ G or at 10^5 G. Flux tubes that do not reach a strength close to 10^5 G before entering the convection zone cannot reach the solar surface as a coherent structure and therefore cannot form sunspots [Moreno-Insertis et al., 1995]. Thus the tiny tidal effect could influence the magnetic storage capacity of the tachocline by modifying the stratification of entropy (δ), and thereby altering the maximum field strength of the flux tubes that can be stored there. The exact way in which this tiny modification (1 part in 10^4 or 10^5) of the entropy stratification is produced by the tidal forces is the missing link in the theory. We suggested that a resonance effect mediated by gravity waves may provide that link. Since the coupling takes place –by assumption– in the tachocline, the tidally excited gravity waves [Goldreich and Nicholson, 1989a, Goldreich and Nicholson, 1989b, Goodman and Dickson, 1998, Barker and Ogilvie, 2010] may be modified by the shear of the environment. Shear may be an important ingredient because, under appropriate conditions, it allows a disturbance to grow by systematic extraction of energy from the flow [Craik, 1968].

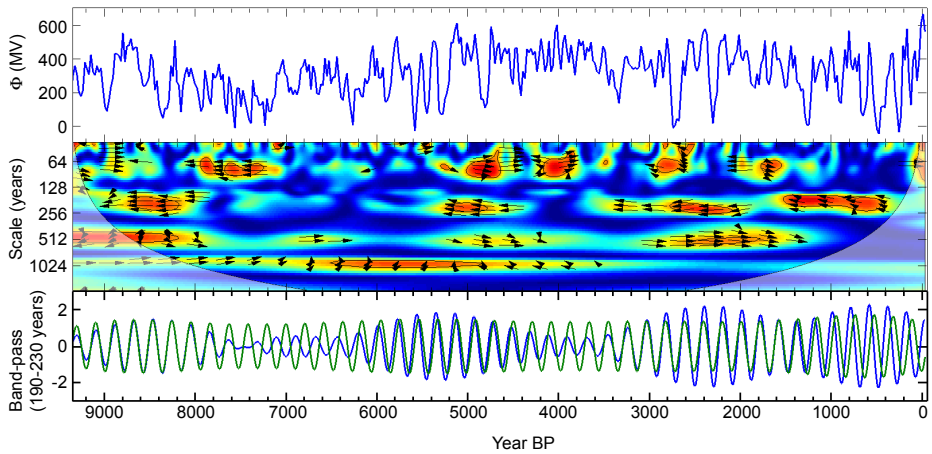

Figure 3: Comparison between solar activity and the YZ component of planetary torque in both frequency and time domain. a) Solar activity Φ reconstructed from cosmogenic radionuclides [Steinhilber et al., 2012]. b) Wavelet coherence between observation (Φ) and torque ($|\mathbf{N}(t)|$). Arrows indicate the relative phase between both series (pointing to left, anti-phase; to right in phase). The constant phase between Φ and the torque for the bands centred at 208 yr and 506 yr are an indication of phase locking. The black contours show the 5% significance regions (95% confidence level). c) Band-pass-filtered annually averaged torque (green curve) along with Φ (blue curve inverted scale) around the 208 yr periodicity (de Vries). Note that the intervals where forcing (torque) and the response (Φ) are in anti-phase correspond to time periods when Grand Minima are more frequent, which is also evident in the wavelet analysis, supporting the assumption of a physical coupling between the planets and the sun. *Reproduced with permission from Astronomy and Astrophysics, © ESO.*

4. Conclusions

The similarity of the spectra of the solar activity and the planetary torque, over the last 10'000 years, is compelling (see Fig. 2). It might also be surprising, as the planetary forcing on the sun is extremely weak. To understand this apparent synchronization phenomenon, we need to identify the mechanism through which the planets couple to the complex processes that give rise to the observed solar activity. On the other hand, a more data-driven analysis, inspired by the theory of weakly coupled non-linear oscillators, might shed further light on this phenomenon.

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