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Grand minima under the light of a low order dynamo model

Dário Passos[a,*], Ilídio Lopes[a,b]

[a] CENTRA, Departmento de Física, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] Departamento de Física, Universidade de Évora, Colégio António Luis Verney, 7002-554 Évora, Portugal

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ABSTRACT

In this work we use a low order dynamo model and study under which conditions can it reproduce solar grand minima. We begin by building the phase space of a proxy for the toroidal component of the solar magnetic field and we develop a model, derived from mean field dynamo theory, that gives the time evolution of the toroidal field. This model is characterized by a non-linear oscillator whose coefficients retain most of the physics behind dynamo theory. In the derivation of the model we also include stochastic oscillations in the α effect. We found evidences that stochastic fluctuations in α effect can trigger grand minima episodes in this model under some considerations. We also explore other ways of creating grand minima by looking into the physical mechanisms that compose the coefficients of the oscillator. The balance between meridional circulation and magnetic diffusivity as well as the field intensification by buoyancy driven instabilities, might have a crucial role in inducing grand minima.

1. Introduction

The Sun presents variability in several time scales, ranging from days to decades. The mechanisms behind this variability are still poorly understood although the common ground for most of them involve magnetic fields and turbulence. One of the main signatures of the solar magnetic activity is the cyclic formation of spots in the solar photosphere, usually known as sunspots. This sunspot cycle is also accompanied by changes in the solar spectrum. However, this cyclic activity is not regular since the peak amplitude and duration of the cycles changes with time. Sometimes these cycles even appear to be completely suppressed during long periods of time, giving rise to a specific kind of solar phenomena, the so called grand minima. In these periods the Sun appears to be in a very calm state, almost not exhibiting any sign of magnetic activity (spots, flares, etc…). The origin of these long periods of "solar inactivity" is still unknown and pose interesting scientific challenges.

It is believed that the solar magnetic cycle has its origin in a dynamo process that operates in the convection zone and converts kinetic energy from the solar plasma flows into magnetic energy. When we have a grand minimum, the dynamo changes its operation regime and apparently shuts off for some time. The most famous grand minima that is registered is the Maunder Minima which occurred between the years of 1645 and 1715 (Eddy, 1976). During this period, although there were no apparent signs of activity, several studies indicate that the dynamo was still operating (e.g. Beer et al., 1998; Miyahara et al., 2004).

To fully understand the intrinsic physics behind the dynamo one needs to resort to the magneto-hydrodynamic theory (MHD) which can be a very complex and difficult subject to fully grasp (Charbonneau, 2005). Thankfully nowadays the fast development of computer science allows us to study these complex equations through the implementation of numerical dynamos. These "tools", presently represent the best way of studying the processes involved in the dynamo operation. Some encouraging results on possible mechanisms behind grand minima have been presented in the last years (Charbonneau and Dikpati, 2000; Charbonneau et al., 2004; Moss et al., 2008; Brandenburg and Spiegel, 2008; Choudhuri and Karak, 2009).

As an alternative to MHD some authors, mainly in the 1990's, used low-dimensional chaotic systems to describe the behavior of the solar magnetic cycle (e.g. Ruzmaikin, 1981; Ostriakov and Usoskin, 1990; Serre and Nesme-Ribes, 2000). Low order models are simpler to compute but their interpretation can sometimes be tricky. Since they involve the collapse of the number of variables into a space with lower variables number, some information might be lost during the transformation. A low-order systems can be seen as a "projection" of a higher order system where the final result depends on the initial system and the "projection method" used. Due to this, it should be noted that reduced-order systems are often abstract representations which can loose physical meaning (Aantoulas and Sorensen, 2001). By paying attention to these sensible points, dynamical system analysis involving low order models has proved to be a great tool in science. In more recent years, work developed by, e.g. Mininni et al. (2001),

* Corresponding author. Tel.: +351 218417938.
E-mail addresses: dariopassos@ist.utl.pt (D. Passos), ilidio.lopes@ist.utl.pt (I. Lopes).

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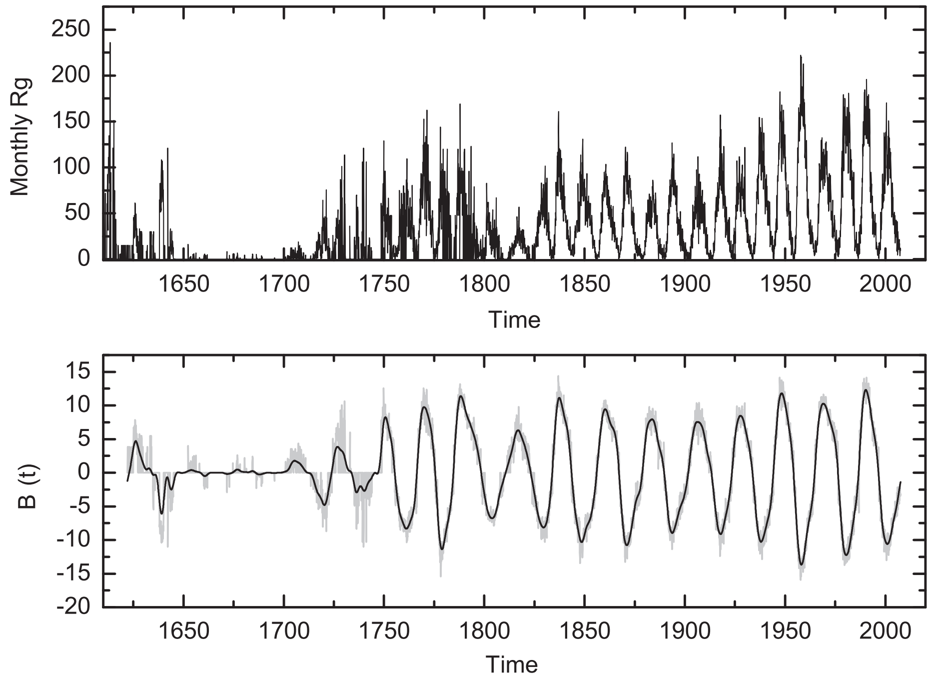

Fig. 1. Top: Group Sunspot Number. Bottom: In black we have the built proxy for the toroidal field, $B(t)$, superimposed to $\pm\sqrt{Rg}$ in gray.

Pontieri et al. (2003), Wilmot-Smith et al. (2005), Passos and Lopes (2008), Lopes and Passos (2009) suggests that within certain conditions, some of the observed properties of the solar magnetic field can be explained by low order dynamical models.

In this work we intend to give a side perspective to the possible grand minima origins using a low-order dynamical system derived from dynamo theory. Although more limited than computational models this approach might be useful to build up intuition on physical processes.

The model we use here is analogous to the one presented in Passos and Lopes (2008) and describes the evolution of the toroidal component of the solar magnetic field. Looking to the model's parameters we intend to study under which conditions can it reproduce grand minima. In order to compare this model with observational results, we use the sunspot number to build a proxy for the toroidal component and we look for the effects of grand minima in the phase space of this proxy. This gives us an experimental signature for grand minima that we should be able to reproduce with our model. We finish this present work with a discussion about the results obtained.

2. Data and grand minima

In order to study grand minima, we need to use solar activity records that go back in time to at least 1610, in order to include one of the most relevant grand minimum, the Maunder Minimum. For that purpose, we use the revised Sunspot Group Numbers (monthly averages), Rg, from Hoyt and Schatten (1997) and available at NOAA database.[1] After 1995 the time series is completed with the International Sunspot Number.

As it is generally accepted, sunspots are a consequence of the toroidal magnetic field inside the convection zone, more specifically we can say that the sunspot number is proportional to the magnetic energy ($\propto B^2$) beneath the photosphere. Thus, we use Rg to build a proxy for this component of the field simply by assuming that $B(t) \propto \pm\sqrt{Rg}$. To account for field reversals we change the sign of $B(t)$ by hand for every sunspot cycle. To identify solar minima we used a low pass filter and selected the lowest values of the data series. Since identifying individual cycles in the period of the Maunder Minimum is very difficult, we decided to divide it into four separate "suppressed" cycles. At this point we would like to note that since the amplitude of Rg during this period is very small, for the purpose of this work, a different choice would not have made an impact. In order to get the average behavior of the time series and eliminate "fast" transients (lower than 2.6 years), the proxy data is smoothed using a FFT filter (see Fig. 1). At this point we would like to note that the use of sunspots to build the $B(t)$ proxy and the methodology applied, is going bind us to a characteristic dynamo scale whose behavior can, in principle, be reproduced by a low order model.

As observed by Polygiannakis et al. (1996) a phase space reconstruction of the sunspot number hints that its behavior might be described by a non-linear oscillator. We pursue this idea but instead we use the proxy that we built. In order to construct our phase space, the numerical derivative, $\mathrm{d}B/\mathrm{d}t$, is computed using a time step of twelve months.

Despite a small randomness, the trajectories of $B(t)$ in the phase space appear to be stable, and seem to indicate that the solution for this oscillator is some kind of attractor. The only moment that the oscillator seems to seriously deviate from its "natural" action area (it collapses) is during the Maunder Minimum period (from approx. 1650 to 1720), depicted in gray in Fig. 2. This is the experimental signature of grand minima that we will try to reproduce with the low-order model.

3. Low order dynamo model with a stochastic α effect

In order to find an expression for a possible non-linear oscillator that might explain the behavior presented in the phase space of the toroidal field depicted in Fig. 2, we follow the ideas of Mininni et al. (2001) and Pontieri et al. (2003). The model presented here is also discussed in Passos and Lopes (2008) although with a different objective and derivation. Instead of

[1] http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html