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A phenomenological study of the timing of solar activity minima of the last millennium through a physical modeling of the Sun–Planets Interaction

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HIGHLIGHTS

- A physical model of Sun–Planets Interaction is described.
- Solar activity Grand Minima (GM) are related to the Sun's closest approaches to barycenter.
- There are several candidate GM events in the next 1000 yr.

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ABSTRACT

We numerically integrate the Sun's orbital movement around the barycenter of the solar system under the persistent perturbation of the planets from the epoch J2000.0, backward for about one millennium, and forward for another millennium to 3000 AD. Under the Sun–Planets Interaction (SPI) framework and interpretation of Wolff and Patrone (2010), we calculated the corresponding variations of the most important storage of the specific potential energy (PE) within the Sun that could be released by the exchanges between two rotating, fluid-mass elements that conserve its angular momentum. This energy comes about as a result of the roto-translational dynamics of the cell around the solar system barycenter. We find that the maximum variations of this PE storage correspond remarkably well with the occurrences of well-documented Grand Minima (GM) solar events throughout the available proxy solar magnetic activity records for the past 1000 yr. It is also clear that the maximum changes in PE precede the GM events in that we can identify precursor warnings to the imminent weakening of solar activity for an extended period. The dynamical explanation of these PE minima is connected to the minima of the Sun's position relative to the barycenter as well as the significant amount of time the Sun's inertial motion revolving near and close to the barycenter. We presented our calculation of PE forward by another 1000 yr until 3000 AD. If the assumption of the solar activity minima corresponding to PE minima is correct, then we can identify quite a few significant future solar activity GM events with a clustering of PE minima pulses starting at around 2150 AD, 2310 AD, 2500 AD, 2700 AD and 2850 AD.

1. Introduction

The study of solar magnetic variability through the magnetohydrodynamic dynamo mechanisms of α–Ω or the helicity-differential rotation effects on the rotating and convecting fluid motions within the Sun has been a fruitful direction in pointing out the various non-linear aspects of the solar activity behavior, including extended time intervals of activity minima (see Gough, 1990; Tobias et al., 1995; Gough, 2002; Usoskin et al., 2007; Spiegel, 2009; Jouve et al., 2010; Weiss, 2011; Choudhuri and Karak, 2012; Pipin et al., 2012; Brandenburg, 2013;Olemskoy and Kichatinov, 2013; Usoskin, 2013;Augustson et al., 2014; Passos et al., 2014). Pipin et al. (2012) found recently that a combination of the random fluctuations of the dynamo governing parameters and the nonlinear relaxation of the principal dynamo mechanisms can produce quasi-periodic variations on multidecadal to millennial timescales. In general, the solar dynamo theory supports the idea that long-term quasi-periodic variations of solar magnetic activity can result

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from the nonlinear interplay between the magnetic field, differential rotation and helical convective motions. The most important timescales are related to the time taken to re-establish the angular momentum balance (differential rotation) and the hydrodynamic and magnetic helicity balance (associated with the α-effect) in the convection zone caused by perturbations in the large-scale magnetic field. Both processes, i.e. relaxation of the angular momentum transport and the magnetic helicity balance, operate on timescale roughly of about 10 sunspot cycles (see, Pipin, 1999; Pipin et al., 2012). However, the stability of the revealed periods can be questioned, because the dynamo may become non-stationary under the random fluctuations. Moreover, it happens that the dynamical properties of the solar dynamo on the millennial timescale look very similar to the properties of the Brownian motions (Pipin et al., 2013). In the words of Stenflo (2013): "This shows that the simplistic phenomenological model of coherence flux ropes needs to be replaced by a dynamo scenario in which fluctuations on all scales play a major role". This is why the current explanations for the solar activity variations are far from adequate especially considering the fact that most of the parametric dynamo modeling efforts lack the exact specificity in the actual time domain and time arrow for the occurrences of various solar activity minima or Grand Minima, GM, that included the so-called Oort, Wolf, Spörer, Maunder and Dalton minima (hereafter abbreviated as OM, WM, SM, MM and DM) covering known records for the past 1000 yr or so.

In this paper, we propose to study and explore solar activity's "prolonged" minima (in the sense described rather well by E. W. Maunder as early as 1894 (Maunder, 1894); see further discussion in Soon and Yaskell, 2004) occurred during the past ~1000 yr and Sun–Planets Interaction, SPI. To be sure, several past works (see Jose, 1965; Fairbridge and Shirley, 1987; Gokhale, 1998; Landscheidt, 1999; Charvátová, 2000; Juckett, 2000; Javaraiah, 2005; Paluš et al., 2007; Charvátová, 2009; Wolff and Patrone, 2010; Perryman and Schulze-Hartung, 2011; Scafetta, 2012; Tan and Cheng, 2013) have made some important attempts and progress although some of these works focused on different issues and questions than our current work. We based our theoretical study focusing on the well known GM events of the last millennium by adopting the most recently available reconstruction of the proxy sunspot number, by Usoskin et al. (2014). These authors emphasized that a better knowledge and quantitative information on the past geomagnetic activity (Licht et al., 2013) are necessary if we are to extend the secure knowledge of past solar activity variation back 10,000 yr in the past.

We begin our study by performing accurate numerical integration of the Sun's motion around the barycenter of the solar system under the perturbations of the orbiting planets for 1000 yr, into the past. Next, we assume a physical connection between the Sun and planets by adopting the new framework outlined by Wolff and Patrone (2010, WP10). Although the WP10 mechanism involves specific assumptions, we speculate that the most complete SPI mechanisms that modulate the internal properties and limits the operation of the solar dynamo may arise through the modulation of the hydrodynamic helicity parameter. We postulate that the persistent pulses of the storage PE variations may lead to a significant perturbation of the turbulent helicity, i.e., significant quenching of the α-effect that is the standard ingredient for solar dynamo in explaining nonlinear modulation of the solar magnetic variability. Interestingly, Hazra et al. (2014) and Passos et al. (2014) recently commented that both the surface- and deeper solar interior-based sources of α-effect are important and necessary for their models of solar dynamo activity to enter and exit a Maunder-like GM event. In this sense, our proposed mechanism is not to replace the well-founded physical processes of the solar dynamo but instead our new interpretation is that the adopted SPI mechanism may be phenomenologically useful in explaining the well-observed occurrences of these well-documented, past solar activity GM events. What the SPI assumption offers is that the host of quasi-regular oscillations of the observed solar activity variations of the last millennium can be naturally explained given the realistic and persistent nature of the external perturbations imposed on the Sun's internal dynamics by the orbiting planets.

The WP10 theory relies on interchange arguments; i.e., a fluid element (a "cell") is composed of two sub-masses (separated by a radius of gyration R_g) which by interchanging their positions, can store and release PE but conserving angular momentum. This PE storage mechanism is created owing to the rotating star, even if it is solidly rotating, combined with its barycentric motion. The possibility of release this energy is related to pre-existing internal flows of fluid motions. Although the applicability of WP10 mechanism in a real star clearly need specific requirements to be met (e.g., Cionco, 2012), this is the first mechanism devoted to explain modifications of stellar interiors by planetary gravitational perturbations (i.e., taking only into account inertial movements). In this context, WP10 have shown that, of all the possibilities, the large storage of PE (and with the yet-to-be fully specified mechanisms for the release of this PE), can occur when the cell is favorably positioned in alignment to the Sun's center and solar system barycenter direction, and more specifically for the mass elements to be located: (1) in the radiative mixed-shell zone ($0.16R_s$), (2) in the convective envelope ($\sim 0.8R_s$), and (3) in the tachocline ($0.68R_s$), with R_s being the Sun's radius.

In a previous study, Cionco and Compagnucci (2012), focused on the effects within the mixed shell of the Sun's radiative zone, and analyzed PE variations as a function of time but only from ~1600 AD to present. They do not take into account the full roto-translational dynamical evolution of a cell in this zone; they only considered the maximal variation of the PE stored in this fixed zone, while optimally directed toward the barycenter, as a function of the barycentric distance. This earlier work found important PE variations that just preceded the GM (i.e., Maunder and Dalton minima as determined by the inferred number of sunspots) of the 17th and 19th century, and also the current period of significantly weakened solar activity that centered at around Solar Cycle 24 (see e.g., Tan, 2011). These significant drops in sunspot activity were related with apparent solar system dynamical particularities (i.e., giant planets' alignments) which produce a strong radial acceleration and prevented the Sun to properly loop around the barycenter in its normal prograde motion (i.e., when the solar motion is retrograde around the barycenter, see Charvátová, 2000, 2009).

However, as noted above, the available records of solar activity can be extended further back in time using the available Earth-based solar activity proxies like the measurements of cosmogenic isotopes ^{14}C in tree rings, ^{10}Be in ice cores, and even nitrate concentration in ice cores (see Soon et al., 2014). Furthermore, a full dynamical description of the solar system motions (i.e., translation around the barycenter and intrinsic rotation within the Sun) that takes into account of all three critical center of actions within the Sun where PE could be stored and released (i.e., PE > 0) has not yet been done. In this study, we added these two new crucial components for a more comprehensive examination of the relationships between PE variations and the timing of solar activity minima. We wish to explain that we only extend the available proxy solar activity record back to about 1000 yr (i.e., to about 900 AD) in the past because as highlighted above that more accurate information from past geomagnetic variations are necessary. Usoskin et al. (2014) suggested that for the proxy solar activity reconstructed from the ^{14}C record to agree with the independent reconstruction based on ^{10}Be record, one must not extend back to about 2000–3000 yr in the past. This is why we focus narrowly and conservatively on solar activity variations for the past millennium or so.