SOLAR CYCLE VARIATIONS ON THE MILLENNIAL TIME SCALE: A CHALLENGE FOR SOLAR DYNAMO THEORY

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The Sun is a variable star. Although the amount of total solar irradiance is fairly constant (within 0.1%) in time, leading to the somewhat confusing term "solar constant", solar magnetic activity does change greatly, as can be readily traced by the sunspots. The number of visible spots on the Sun grows for several years and then gradually decreases, repeating this pattern in a cyclic manner with a period of about 11 years. This is well-known as the 11 year solar cycle, which modulates space weather and affects in various ways the life of human beings, especially now when our civilization is so dependent on the satellite technology.

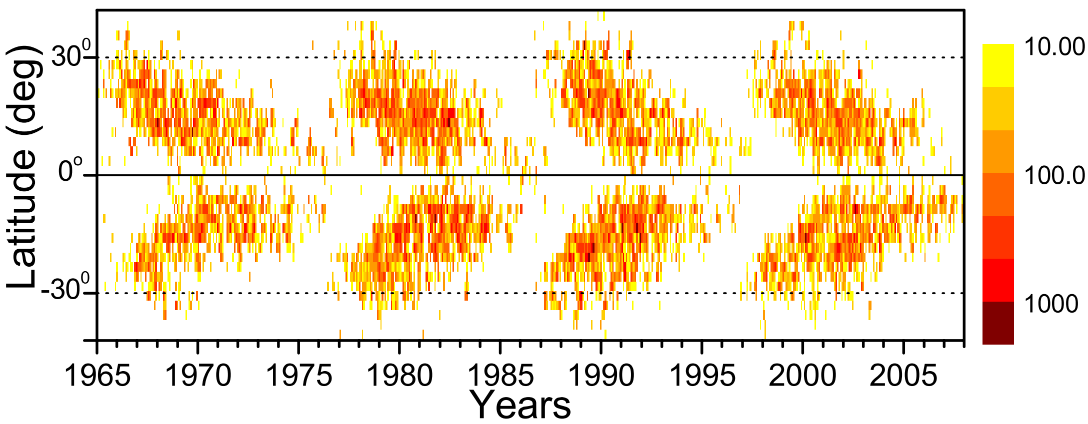

Figure 1. Latitudinal distribution of sunspots (the butterfly diagram) for the last four solar cycles. Color represents the sunspot area in millionths of the solar disc (color scale on the right). Data are from the Greenwich Observatory.

A conventional index of solar activity is related to sunspot formation and quantified by the relative sunspot number, which is defined as the tenfold number of distinct sunspot groups plus the number of individual spots observed at a given moment (usually at 12:00 UT every day) on the solar disc. Note that this relative sunspot number is always larger than the number of observed spots, e.g., the minimum possible non-zero sunspot number is 11 (one sunspot forms also one group, which scores 10, giving 10×1+1=11). Sunspots have been scientifically observed, by recording the results and often drawing the solar disc, since 1610, i.e. soon after the invention of the telescope. Thus we currently possess a 400-year long series of sunspot data, which is one of the longest direct instrumental datasets in existence.

The underlying physical mechanism of the 11 year cycle is the equatorward propagation of a belt of

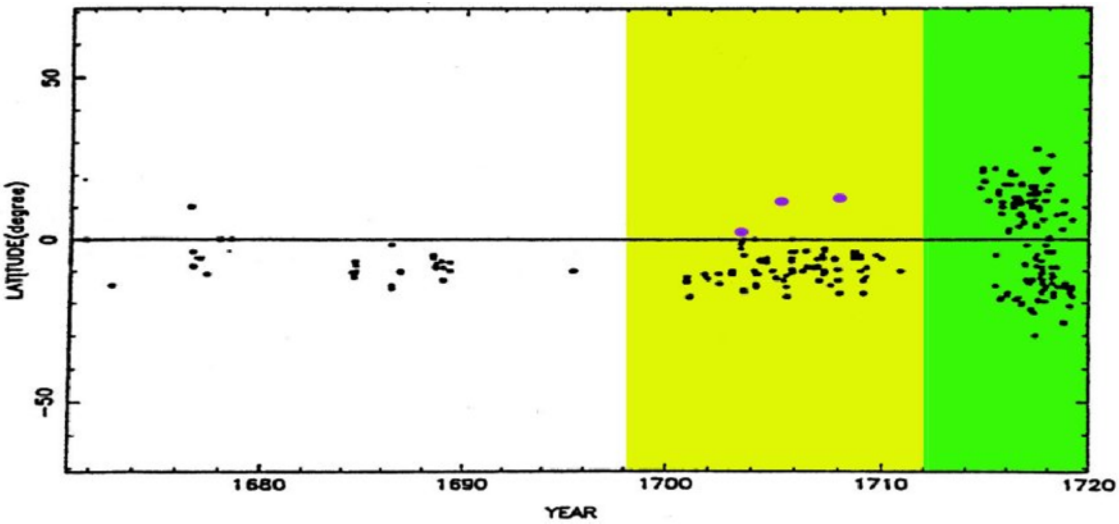

Figure 2. Sunspot butterfly diagram for the end of the Maunder minimum, according to the data from ref. [6]. One can see irregular asymmetric cycles before 1696, a fairly regular but asymmetric cycle in 1696-1712 (yellow background) and a normal symmetric cycle after 1712 (green background).

enhanced magnetic field somewhere inside the Sun. This periodic migration of magnetic field is believed to be driven by the solar dynamo, which is a result of the joint action of the solar rotation and the convective flows. The dynamo operates in the outer layer (about 30% of the radius) of the Sun in which turbulent convection occurs - the convective zone. The propagation of this activity wave at the solar surface during the 11-year cycle can be illustrated by what is known as the "butterfly diagram" (Fig. 1), in which the latitude of observed sunspots is plotted against the time of their appearance. The diagram resembles a sequence of butterflies. This kind of diagram to visualize the spatial-temporal patterns of the solar cycle was first used by the British astronomer Walter Maunder and the German astronomer Gustav Spörer in the late 19th Century. The butterfly diagram demonstrates the simultaneous propagation of two activity waves, one in each solar hemisphere, from middle latitudes towards the solar equator. We note that there is another wave of coronal bright features that propagates poleward from the mid-latitudes.

Generally the 11-year cycle of solar magnetic activity is a relatively well-understood phenomenon which has been discussed in many scientific papers and books. The details are, however, still not fully resolved. Cycles are not perfectly regular, as, e.g., the wings of individual butterflies have different span, tilt and amplitude, and also the total durations of the cycles vary. Even more dramatically, from time to time the driving engine of the cycle becomes idle leading to a peculiar state of solar activity with few or no visual spots on the Sun for several decades. Such a period of suppressed solar surface activity is usually called a Grand Minimum.

The most recent Grand Minimum occurred in the late 17th century, early in the era of telescopic observations. It was Walter Maunder again who recognized from archival data that the solar activity from the middle of 17th until the beginning of the 18th centuries was very unusual, in that sunspot records from this period were very rare. However, the absence of records does not inevitably mean the absence of sunspots, and Maunder's contemporaries were quite sceptical about his finding. It really is hard to believe that 17th century solar astronomers did observe sunspots accurately and consistently. However, as time passed, the evidence supporting Maunder's idea grew. The late American astronomer John ("Jack") Eddy demonstrated in 1976 [1] that the concentration of the radiocarbon cosmogenic isotope measured in tree rings growing at the time of the Maunder Minimum was unexpectedly high, implying low solar activity, but this evidence was still indirect. The ultimate piece of evidence, completing the puzzle, came from the archives of the Observatoire de Paris. This institution was founded by Louis XIV, the King of France, just at the beginning of the Minimum, with the primary goal of regular sunspot monitoring. A brilliant sequence of French observers performed a very long and careful monitoring of the Sun. In particular, Jean Picard routinely and carefully observed the Sun over a decade, thoroughly recording the results in a notebook, and saw only one sunspot during that period. It is an example of

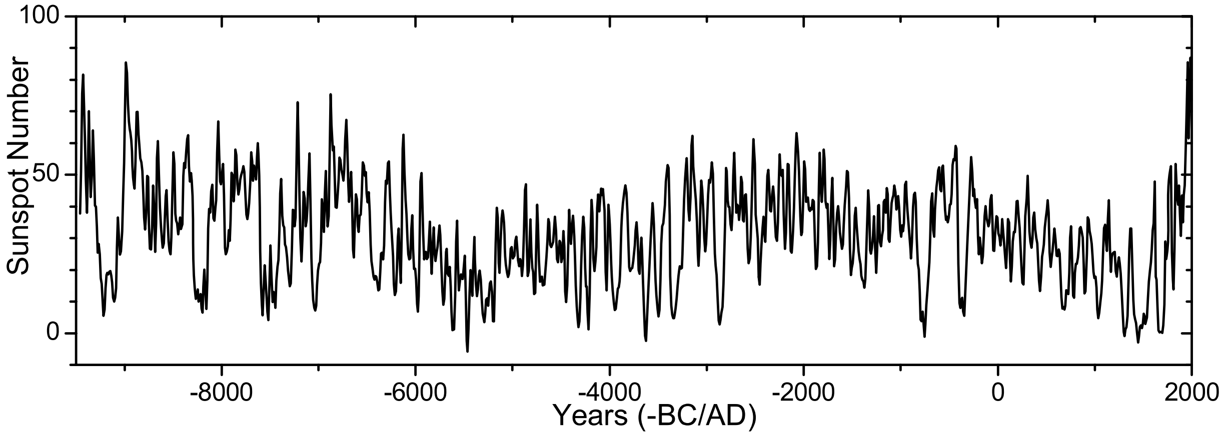

Figure 3. Long-term reconstruction [7] of solar activity from radiocarbon ^{14}C records.

outstanding scientific persistence, which would hardly have been possible without direct Royal patronage of the project. There were other astronomers in Italy and Germany who also observed the Sun during that time. Unfortunately, some records have been lost in course of time, and presently we know only their summaries as cited in later reports. However, many records did survive until the present day.

Careful work by contemporary astronomers has yielded a robust reconstruction of solar activity variations during the time of the Maunder Minimum, which shows a strong suppression of sunspot appearance. These results supported Maunder's interpretation and the Grand Minimum of 1645-1715 was given his name. Other indirect data, such as archival records of the aurora borealis or cosmogenic isotope concentrations, suggest that the solar dynamo was not completely "off" during this time, but kept operating at a reduced level that was barely sufficient to produce a few spots. Further detailed analysis has demonstrated that sunspots were not completely absent during the Maunder minimum. Some sunspots were observed even during the so-called "deep" phase of the Minimum. Thanks to the careful drawings of the solar disc kept in archives, it is possible to construct an informative butterfly diagram, at least for some parts of the Minimum. This diagram looks remarkably different from that of more normal times (Fig. 2). In particular, the (vestigial) wings of the "butterflies" are sometimes visible in one hemisphere only.

The list of peculiarities of the solar cycle variability is not limited to the Maunder Minimum with its suppressed and asymmetric sunspot occurrence. An analysis of the long term sunspot data reveals some other peculiarities such as various deviations from both the North-South and axial symmetries, large variations of the cycle amplitude and duration, short excursions in solar activity such as the Dalton minimum near 1805, etc.

During the 20th Century, substantial progress was made in methods of physical and chemical analysis, in particular acceleration mass spectrometry (AMS), which made it possible to use proxy data such as the cosmogenic isotope record to study solar activity further into the past. Isotopes such as ^{14}C or ^{10}Be are produced in the Earth's atmosphere solely by energetic cosmic rays, whose flux is modulated by the solar magnetic activity. Thus, measurements of the isotope concentration in independently dated natural archives such as tree rings or polar ice cores provide a quantitative estimate of solar variability in the past, with a more-or-less reliable reconstruction reaching to as far as 11,400 years ago (Fig. 3). These proxy data have undoubtedly confirmed the existence of the Maunder Minimum in the 17th Century, but they also showed that it is not an extraordinary phenomenon. A few dozens of similar Grand

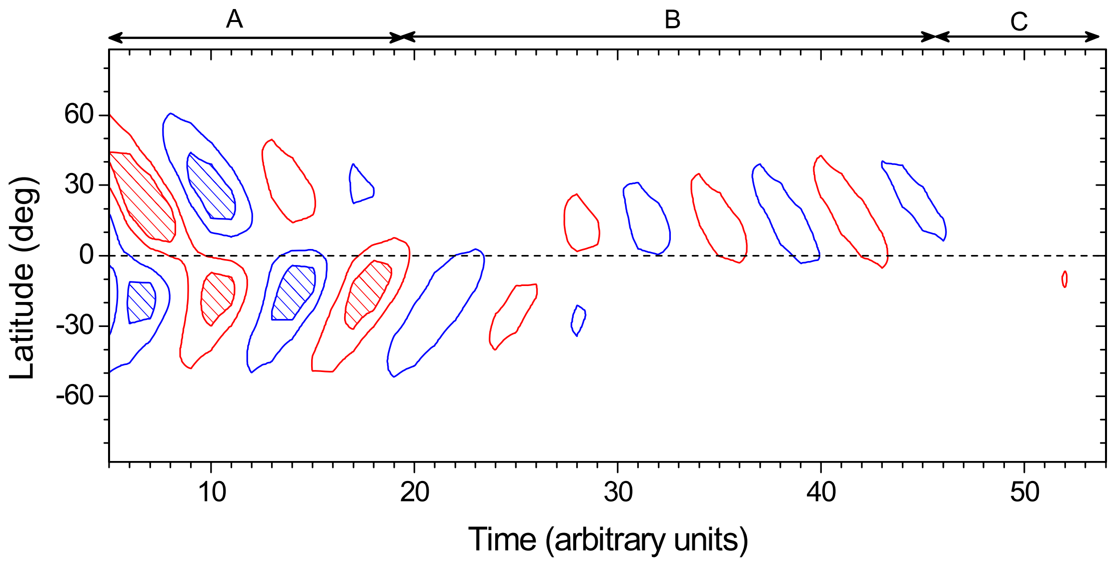

Figure 4. Latitude-time distribution of the toroidal magnetic field (an analogue of the sunspot butterfly diagram) from one of the simulation runs. The equi-spaced contours represent the strength of the field, with red/blue indicating positive/negative values. Labels A, B, and C denote regular cycles, asymmetric cycles, and a Grand Minimum, respectively.

Minima have been identified as occurring during the last 10,000 years.

These findings present an obvious challenge for solar dynamo theory. It is not enough to find a mechanism driving a regular cycle, it is important to find why and how its effect becomes imperfect. This goes beyond a purely academic interest. It appears that such distortions in the activity mechanism can affect the solar irradiance (the amount of solar radiation that strikes the Earth) and also the flux of cosmic rays**,** and thus the Earth's climate. Moreover, recent observations suggest that the coming solar cycle may be also quite peculiar. In other words the problem is relevant not only to the times of Louis XIV, but also to us now.

A general expectation is the peculiarities discussed above seem likely to require a different physical mechanism from that responsible for the dynamo-driven normal cycles, although other possibilities have been also discussed. This is because these phenomena have timescales quite different from the cycle length, and their manifestations are rather different one from the other. We have attempted to elucidate the problem [2,3], trying first a simple way to perturb the stable cycle. The starting point is that the solar dynamo engine is driven mainly by two components that act as generators - the solar differential rotation and the mirror asymmetry of the solar magnetohydrodynamic (MHD) convection. The latter arises because the action of the Coriolis force in a rotating stratified fluid of the solar convection zone makes the convection statistically mirror-antisymmetric with respect to the solar equator. It is basically the same mechanism which makes the river beds on the Earth asymmetric (the right-hand bank is usually higher and more eroded than to the lower left-hand bank in the northern hemisphere), and also causes winds to blow anticlockwise around low pressure regions in the northern hemisphere, and vice versa in the southern. The effect of the mirror asymmetry effect on the dynamo action is parameterized by a quantity commonly known as α.

Common sense and stellar physics tell us that solar rotation is something much more substantial than mirror asymmetry, and its timescale of variation is expected to be billions of years rather than decades. On the other hand, experience from direct numerical simulations of MHD turbulence shows that the quantity α can be quite noisy, with large variations about its mean value, and these may occur on relatively short timescales. We attempted [2] to determine how important random fluctuations in α can be for the solar cycle. This idea is not very new, e.g. the Dutch astronomer Peter Hoyng [4] discussed this possibility a decade ago, but it was not then explored in full detail.

We performed a long-term simulation of a simple model of the solar dynamo, known as the Parker migratory dynamo as proposed by the American astrophysicist Eugene Parker in 1955 [5]. We ran this model with a noisy α-term to simulate solar activity on a time scale of 10,000 years - the range of solar activity reconstruction from cosmogenic isotope data. Of course, such simulations do not aim to reproduce the solar activity evolution in full detail. This is impossible because the fluctuations in the α-term of the dynamo are random, and so, we can only study similarities in a statistical sense by adopting plausible statistical properties for the relevant quantities. Keeping this in mind, our results look promising. In some simulation runs we obtained simulated butterfly diagrams (an example extracted from such a run is shown in Fig. 4) which contain some known types of distortion of the regular cycles (labelled as A), such as asymmetries with respect to the solar equator (B), a Grand Minimum (C), etc. A long-term series of the simulated solar activity in terms of the averaged magnetic energy depicts quasi-random occurrences of Grand Minima and Grand Maxima that are generally similar to those deduced from the long-term record of cosmogenic isotopes (Fig. 3).

We feel that the success of a simple approach connecting the various distortions of the ideally regular sunspot cycle to only one physical mechanism is plausible and instructive, and satisfies the principle of "Occam's razor". We appreciate, however, that this is not the end but rather a promising beginning to the story. However, it certainly remains possible that the observed distortions of the sunspot cycle discussed above can originate from a more complicated physical mechanism than the one we have considered. Further more detailed research is certainly required to elucidate these and other issues.

References

[1] Eddy, J.A., The Maunder Minimum, *Science*, 192, 1189–1202, 1976.

[2] Usoskin, I.G., D. Sokoloff and D. Moss, Grand Minima of solar activity and the mean-field dynamo, *Solar Phys*, 254, 345-355, 2009.

[3] Moss, D., D. Sokoloff, I. Usoskin, V. Tutubalin, Solar Grand Minima and Random Fluctuations in Dynamo Parameters, Solar Phys., 250, 221-234, 2008.

[4] Hoyng, P.: 1993, Helicity fluctuations in mean field theory: an explanation for the variability of the solar cycle?, *Astron. Astrophys.* 272, 321-339.

[5] Parker, E.: 1955, Hydrodynamic dynamo models, *Astrophys. J.,* 122, 293-314.

[6] Ribes, J.C., and E. Nesme-Ribes, The solar sunspot cycle in the Maunder minimum AD1645 to AD1715, *Astron. Astrophys.*, 276, 549, 2003.

[7] Usoskin, I.G., S.K. Solanki, G.A. Kovaltsov, Grand minima and maxima of solar activity: new observational constraints, *Astron. Astrophys*., 471, 301–309, 2007.