

The unusual minimum of sunspot cycle 23 caused by meridional plasma flow variations

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Direct observations over the past four centuries¹ show that the number of sunspots observed on the Sun's surface varies periodically, going through successive maxima and minima. Following sunspot cycle 23, the Sun went into a prolonged minimum characterized by a very weak polar magnetic field^{2,3} and an unusually large number of days without sunspots⁴. Sunspots are strongly magnetized regions⁵ generated by a dynamo mechanism⁶ that recreates the solar polar field mediated through plasma flows⁷. Here we report results from kinematic dynamo simulations which demonstrate that a fast meridional flow in the first half of a cycle, followed by a slower flow in the second half, reproduces both characteristics of the minimum of sunspot cycle 23. Our model predicts that, in general, very deep minima are associated with weak polar fields. Sunspots govern the solar radiative energy^{8,9} and radio flux, and, in conjunction with the polar field, modulate the solar wind, the heliospheric open flux and, consequently, the cosmic ray flux at Earth^{3,10,11}.

The creation and emergence of tilted, bipolar sunspot pairs and their subsequent decay and dispersal through flux transport processes determine the properties of the solar magnetic cycle^{6,12–17}. The average tilt angle of the sunspots of cycle 23 did not differ significantly from earlier cycles². However, the axisymmetric meridional circulation of plasma¹⁸—which is observationally constrained only in the upper 10% of the Sun, where it has an average poleward speed of 20 m s^{-1} —is known to have significant intra- and intercycle variation^{19–22}. The equatorward counterflow of this circulation in the solar interior is believed to have a crucial role; it governs the equatorward migration and spatiotemporal distribution of sunspots and determines the solar cycle period^{6,22,23}. We perform kinematic solar dynamo simulations to investigate whether internal meridional flow variations can produce deep minima between cycles in general, and, in particular, explain the observed characteristics of the minimum of cycle 23 (Supplementary Information)—a comparatively weak dipolar field strength and an unusually long period without sunspots.

We use a recently developed axisymmetric, kinematic solar dynamo model²⁴ to solve the evolution equations for the toroidal and poloidal components of the magnetic field. This model has been further refined using a buoyancy algorithm that incorporates a realistic representation of bipolar sunspot eruptions following the double-ring formalism^{25,26} and qualitatively captures the surface flux transport dynamics leading to solar polar field reversal⁷ (including the observed evolution of the radial component of the Sun's dipolar field). To explore the effect of changing meridional flows on the nature of solar minima, it is necessary to introduce fluctuations in the meridional flow. The large-scale meridional circulation in the solar interior is believed to be driven by Reynolds stresses and small temperature differences between the solar equator and poles; variations in the flows may be induced by changes in the driving forces or through the feedback of magnetic fields²⁷. The feedback is expected to be highest at the solar maximum (polar field minimum), when the toroidal magnetic field in the solar interior is the strongest. We therefore perform dynamo simulations by randomly varying the

meridional flow speed between 15 and 30 m s^{-1} (with the same amplitude in both the hemispheres) at the solar cycle maximum, and study its effect on the nature of solar cycle minima. Details of the dynamo model are described in Supplementary Information.

Our simulations extend over 210 sunspot cycles corresponding to 1,860 solar years; for each of these simulated cycles, we record the meridional circulation speed, the cycle overlap (which includes the information on the number of days with no sunspots) and the strength of the polar radial field at cycle minimum. Figure 1 shows the sunspot butterfly diagram and surface radial field evolution over a selected 40-yr slice of the simulation. Here cycle to cycle variations (mediated by varying meridional flows) in the strength of the polar field at minimum and the structure of the sunspot butterfly diagram are apparent, hinting that the number of spotless days during a minimum is governed by the overlap (or lack thereof) of successive cycles.

We designate the minimum in activity following a given sunspot cycle, say n , as the minimum of n (because the sunspot eruptions from cycle n contribute to the nature of this minimum). We denote the amplitude of the meridional flow speed after the random change at

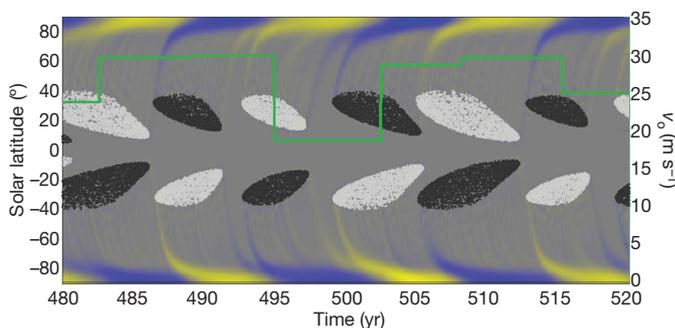


Figure 1 | Simulated sunspot butterfly diagram with a variable meridional flow. Starting with the pioneering telescopic observations of Galileo Galilei and Christopher Scheiner in the early seventeenth century, sunspots have been observed more or less continuously up to the present. Except for the period AD 1645–1715, known as the Maunder minimum, when hardly any sunspots were observed, the sunspot time series shows a cyclic variation going through successive epochs of maximum and minimum activity. This cyclic temporal variation in the latitude of sunspot emergence gives rise to the ‘butterfly’ diagram. In this simulated butterfly diagram, the green line shows the meridional flow speed, v_0 , which is made to vary randomly between 15 and 30 m s^{-1} at sunspot maxima and to remain constant between maxima. The varying meridional flow induces cycle-to-cycle variations in both the amplitude as well as the distribution of the toroidal field in the solar interior from which bipolar sunspot pairs buoyantly erupt. This variation is reflected in the spatiotemporal distribution of sunspots, shown here as shaded regions (the lighter shade represents sunspots that have erupted from positive toroidal field and the darker shade represents those that have erupted from negative toroidal field). The sunspot butterfly diagram shows a varying degree of cycle overlap (of the ‘wings’ of successive cycles) at cycle minimum. The polar radial field strength (yellow, positive; blue, negative) is strongest at sunspot cycle minimum and varies significantly from one cycle minimum to another.

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the maximum of cycle n by v_n , which remains constant through the minimum of cycle n and changes again at the maximum of cycle $n + 1$. According to this convention, the speed during the first (rising) half of cycle n would be v_{n-1} . To explore the relationship between the varying meridional flow, the polar field strength and cycle overlap, we generate statistical correlations between these quantities separately for the northern and southern solar hemispheres from our simulations over 210 sunspot cycles. We note that slight hemispheric asymmetries arise in the simulations owing to the stochastic nature of the active-region emergence process.

Unexpectedly, we find that there is no correlation between the flow speed at a given minimum (say v_n) and cycle overlap (or the number of spotless days) during that minimum, and the polar field strength at that minimum, B_n , is only moderately correlated with v_n (Fig. 2a, b). Because transport of magnetic flux by the meridional flow involves a finite time, it is likely that the characteristics of a given minimum could depend on the flow speed at an earlier time. We find that this is indeed the case (Fig. 2c, d), with cycle overlap (or the number of spotless days) and the

polar field strength at a given minimum, n , being strongly correlated with the flow speed v_{n-1} (that is, meridional flow during the early, rising, part of cycle n). We also find that the cycle overlap is moderately correlated and that the polar field strength is strongly correlated with the change in flow speed between the first and second halves of the cycle (Fig. 2e, f). Taken together, these results show that a fast flow during the early part of the cycle, followed by a relatively slower flow during the later, declining, part of the cycle, results in a deep solar minimum.

The main characteristics of the minimum of solar cycle 23 are a large number of spotless days and a relatively weak polar field strength. In Fig. 3, we plot the polar field versus cycle overlap and find that very deep minima are in fact associated with relatively weak polar field strengths. Thus, the qualitative characteristics of the unusual minimum of sunspot cycle 23 are self-consistently explained in our simulations driven by changes in the Sun's meridional plasma flow. Our model predicts that, in general, extremely deep solar minima—with a large number of spotless days—would also be characterized by relatively weak solar polar field strengths.

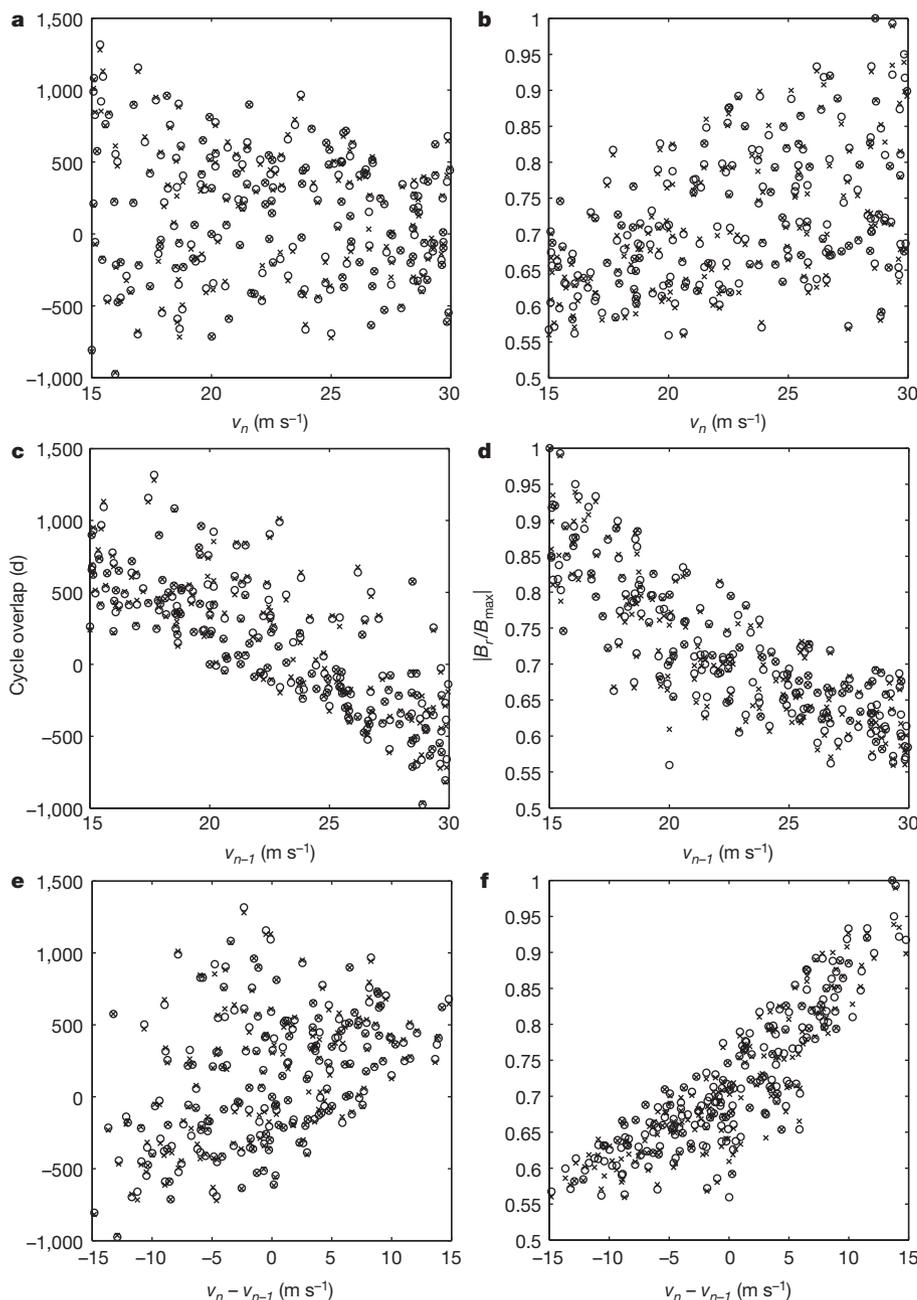


Figure 2 | Cycle overlap and polar field strength at solar minimum in response to variable meridional flows. Here v_n denotes flow speed during the minimum of sunspot cycle n , v_{n-1} denotes the speed during the early, rising, part of cycle n and $v_n - v_{n-1}$ denotes the change in flow speed between the declining and rising parts of the cycle. Cycle overlap is measured in days. Positive overlap denotes the number of days on which simulated sunspots from successive cycles erupted together, whereas negative overlap denotes the number of spotless days during a solar minimum; large negative overlap implies a deep (that is, long) minimum. The polar field ($|B_p/B_{\max}|$) is represented by the peak radial field attained during a solar minimum normalized with respect to the maximum radial field attained during the complete model run (here $B_{\max} = 16.66 \times 10^3$ G; see Supplementary Information for a discussion of polar field amplitudes). The relationship between the above parameters is determined by the Spearman's rank correlation coefficient (210 data points for each solar hemisphere, with northern- and southern-hemisphere data depicted as crosses and circles, respectively). **a**, Cycle overlap versus v_n ; correlation coefficient: $r = -0.13$ (northern hemisphere), -0.13 (southern hemisphere); confidence level: $P = 93.42\%$ (northern hemisphere), 94.53% (southern hemisphere). **b**, Polar field strength versus v_n ; $r = 0.45, 0.45$; $P = 99.99\%, 99.99\%$. **c**, Cycle overlap versus v_{n-1} ; $r = -0.81, -0.80$; $P = 99.99\%, 99.99\%$. **d**, Polar field strength versus v_{n-1} ; $r = -0.83, -0.83$; $P = 99.99\%, 99.99\%$. **e**, Cycle overlap versus $v_n - v_{n-1}$; $r = 0.45, 0.45$; $P = 99.99\%, 99.99\%$. **f**, Polar field strength versus $v_n - v_{n-1}$; $r = 0.87, 0.87$; $P = 99.99\%, 99.99\%$. Evidently, a change from fast to slow internal meridional flow results in deep solar minima.

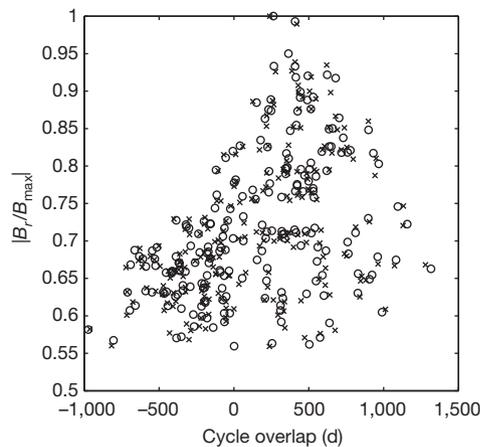


Figure 3 | Polar field strength versus cycle overlap at solar minimum.

Simulated normalized polar field strength is plotted versus cycle overlap at sunspot cycle minimum. Spearman's rank correlation estimate: $r = 0.46$, 0.47 and $P = 99.99\%$, 99.99% for data from the northern (crosses) and southern (circles) hemispheres, respectively. The results show that a deep solar minimum with a large number of spotless days is typically associated with a relatively weak polar field—as observed during the minimum of sunspot cycle 23.

We find that our model results are robust with respect to reasonable changes in the driving parameters. Simulations with continuous flow variations (as opposed to discrete changes), relatively higher magnetic diffusivity and a different threshold for buoyant active-region eruption all yield qualitatively similar relationships between the nature of solar minima and flow speed variations (Supplementary Information).

Valuable insights into our simulation results may be gained by invoking the physics of meridional-flow-mediated magnetic flux transport. A faster flow (v_{n-1}) before and during the first half of cycle n would sweep the poloidal field of the previous cycle quickly through the region of differential rotation responsible for toroidal field induction; this would allow less time for toroidal field amplification and would hence result in a sunspot cycle (n) which is not too strong. The fast flow, followed by a slower flow during the second half of cycle n and persisting to the early part of the next cycle, would also distance the two successive cycles (that is, successive wings in the sunspot butterfly diagram), contributing to a higher number of spotless days during the intervening minimum. Moreover, a strong flow during the early half of cycle n would sweep both the positive and the negative polarity sunspots of cycle n (erupting at mid to high latitudes) to the polar regions; therefore, lower net flux would be available for cancelling the polar field of the old cycle and building the field of the new cycle—resulting in a relatively weak polar field strength at the minimum of cycle n . We believe that a combination of these effects contributes to the occurrence of deep minima such as that of solar cycle 23.

Independent efforts using surface flux transport simulations show that surface meridional flow variations alone (observed during solar cycle 23; see also Supplementary Information) are inadequate for reproducing the weak polar field of cycle 23 (ref. 28). Dynamo simulations—which encompass the entire solar convection zone—are therefore invaluable for probing the internal processes that govern the dynamics of the solar magnetic cycle, including the origin of deep minima such as that of cycle 23. We anticipate that NASA's recently launched Solar Dynamics Observatory will provide more precise constraints on the structure of the plasma flows deep in the solar interior, which could be useful for complementing these simulations.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions D.N. conceived the principal idea and, in conjunction with P.C.H.M. and A.M.-J., planned the simulations, which were performed by A.M.-J. under the guidance of D.N. and P.C.H.M. D.N. led the interpretation of the results and all authors contributed to writing the paper.

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