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# All Quiet on the Solar Front: Origin and Heliospheric Consequences of the Unusual Minimum of Solar Cycle 23

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***Abstract***. The magnetic activity of the Sun shapes the heliospheric space environment through modulation of the solar wind, interplanetary magnetic field, cosmic ray flux and solar irradiance. Sunspots – strongly magnetized regions on the solar surface – also spawns solar storms such as flares and coronal mass ejections which generate severe space weather affecting space-based technologies. The Sun's magnetic output varies in a cyclic manner going through phases of maximum and minimum activity. Following solar cycle 23 the Sun entered a prolonged and unusually long minimum with a large number of days without sunspots that was unprecedented in the space age. This long phase of very low solar activity resulted in record high cosmic ray flux at Earth, weak solar wind speeds and low interplanetary magnetic field. We provide an overview of this peculiar solar minimum, critically explore theories for its origin and argue that the unusual conditions in the heliosphere that we experienced during this minimum eventually originated in solar internal dynamics.



**Keywords**: sun, sunspots, solar activity, magnetic fields,

## Introduction: The Heliosphere at the Minimum of Solar Cycle 23

Sunspots have been observed for many centuries now with direct and continuous observations starting in the early 17th Century with the invention of the telescope. The sunspot time series showed that the number of sunspots observed on the surface of the Sun varies in a periodic manner with an average period of about 11 years, while periods of individual cycles range from 9-14 years (see Fig. 1). In early 20th century it was discovered that sunspots are strongly magnetized, with magnetic field strengths on the order of 1000 Gauss (G). This established that the sunspot cycle was in fact a manifestation of an underlying magnetic cycle in the Sun. The peak sunspot number observed during the maximum of the solar cycle – i.e., the amplitude of the sunspot cycle – fluctuates. Although the characteristics of the minimum also vary from one cycle to another, this phase of the cycle was considered uninteresting and did not garner much attention until recently.

Around the year 2006 solar cycle 23 started ending, going towards a minimum in activity that was entirely in keeping with the solar cycle. However, the minimum that ensued was completely unexpected. It stretched on and on, resulting in the blankest Sun in almost a century. The number of spotless days in 2008 was only surpassed by the year 1913 (at the minimum of cycle 14). The cumulative number of spotless days around the minimum of cycle 23 was almost twice that of an average minimum and close to that of cycle 14 (Fig. 2; see also Fig.1 in supplementary online information from Nandy, Muñoz-Jaramillo, and Martens, 2011). This made this recent solar minimum highly unusual and interesting, attracting the attention of the scientific community and resulting in a thorough investigation of its causes and consequences – which are still ongoing. We note in passing that a average or weak amplitude sunspot cycle is not necessarily followed by a very deep minimum. Only solar cycle 14 had more spotless days than the current minimum. Since then there have been three cycles with peak amplitudes lower than that of cycle 23 but they were not followed by minimums as deep as that of cycle 23.

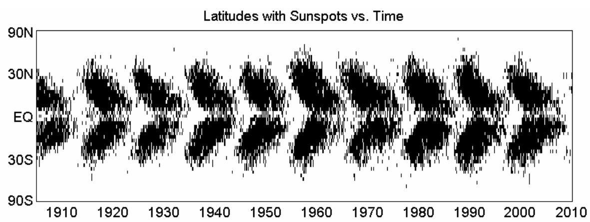


Figure 1: A solar butterfly diagram showing the latitudinal (y-axis) variation of sunspot emergence over the last century (x-axis) covering solar cycles 14-23. The dark regions denote latitudes where sunspots emerge. The periodic cycle in both the Northern and Southern hemisphere is clearly visible. The cycle begins with sunspots emerging at high latitudes and ends at low latitudes. A careful examination of the figure indicates that there is variable overlap between cycles at solar minima. A longer period with no overlap would mean a large number of spotless days and a deeper minimum. This data is courtesy of Greenwich Observatory and David H. Hathaway.

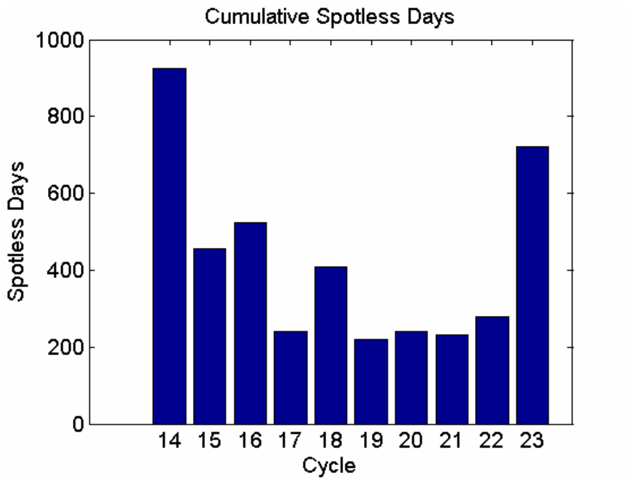


Figure 2: The cumulative number of sunspot-less days around the minimum of different solar cycles observed over the last century. The cycle numbers are indicated on the x-axis while the number of spotless days is depicted by vertical bars whose values are along the y-axis. Clearly, cycle 23 is surpassed in spotless days only by cycle 14, which came almost a century ago.

Of course it was not just the lack of sunspots that was peculiar of this minimum. The polar field of the Sun has been observed directly over the last three cycles. Magnetogram data shows that of these three, the last minimum had the weakest polar field (Fig. 3). The polar fields of the Sun are thought to be an integral part of the solar dynamo mechanism because the polar fields varies and reverse their polarity with a 11 year periodicity (with a 900 phase delay relative to the sunspot cycle) and therefore this observation also sets important constraint on the origin of this peculiar minimum (see also Schrijver and Liu, 2008).

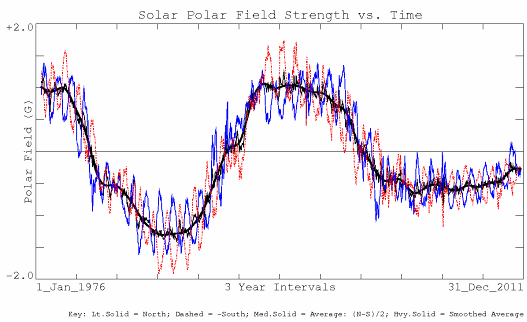


Figure 3: Data from the Wilcox Solar Observatory showing the variation of the solar polar field strength (y-axis) with time (x-axis). The North-South average peak polar field (thick black curve) at the minimum of cycle 23 has been the weakest amongst the last three cycles.

The presence of sunspots modulates the energy output of the Sun (Krivova, Balmaceda, and Solanki, 2007), i.e., its irradiance, which is thought to have implications for the climate (see e.g., the review by Nandy and Martens, 2007). Typically, when averaged over timescales of one solar rotation period or longer sunspots positively correlate with solar irradiance which is thought to be due to the decay and breakup of sunspots into bright plage and facular material over timescales of many weeks (but see Fröhlich, 2011). A long absence of sunspots would therefore imply low solar irradiance. Indeed, during the minimum of sunspot cycle 23, there was a prolonged period of very low solar irradiance (Krivova, Solanki, and Schmutz, 2011). The solar (10.7 cm) radio flux which has been continuously measured since the second world war was also the weakest during this minimum.

The solar polar fields play a role in determining the solar wind conditions during solar minima. The low polar fields of cycle 23 resulted in a weak solar wind. The large-scale global magnetic field of the Sun is carried through the interplanetary space by the solar wind and this becomes the heliospheric open flux – which acts as a shield against cosmic rays. The weak polar fields resulted in a weak open flux in the heliosphere which in turn resulted in record high cosmic ray counts since direct instrumental records have been kept over the last half-a-century (Leske et al., 2011). Together with a lack of solar storms for a prolonged period, low irradiance and radio flux, weak solar wind and high cosmic ray flux – a combination of extreme heliophysical conditions was witnessed during the last minimum.

These atypical conditions have had measurable and often unanticipated effect on the state of the heliosphere (Zhao and Fisk, 2011) in which the solar system is immersed. The turbulence levels dropped to low levels and this began early (Janardhan et al., 2011) – presumably signifying a long-term drop in solar activity that is thought to have begun well before cycle 23. The heliospheric current sheet displayed a high tilt and asymmetry (Mursula and Virtanen, 2011). The energetic and particulate conditions during this minimum has consequences for planetary atmospheres such as that of Venus (Zhang et al., 2007), the Earth's ionosphere (Libo et al., 2011) and indeed climate (Haigh et al., 2010); it is interesting to note here that many of these studies threw up unexpected or new results – plausibly because of the extreme conditions that were never before encountered in the space age.

## The Solar Dynamo Mechanism

What could have resulted in this deep solar minimum? To explore this question, one must first understand the basis of solar magnetism. The interior of the Sun exists in a plasma state because of the high temperature there. This plasma is highly conducting and conducive to the amplification of magnetic fields through the magnetohydrodynamic (MHD) dynamo mechanism (Charbonneau, 2010). Since the magnetic activity of the Sun is produced by the dynamo mechanism, fluctuations such as a strong or weak maximum or a deep or average minimum should have its basis in the dynamo mechanism. While the subject of dynamo theory is technical and involves numerical simulations, here, we will qualitatively describe the main features of this dynamo mechanism such that an appreciation of the underlying physics is possible.

Most stars are born with a weak dipolar field inherited from the molecular cloud from which they are formed. These magnetic fields are frozen in with the plasma in the stellar interior, where the diffusive timescales are much larger than the flow timescales. Thus plasma flows in the stellar interiors can stretch and twist magnetic fields. We know that the Sun rotates differentially, both in latitude as well as radius with a region of strong radial differential rotation concentrated in the tachocline (Charbonneau et al., 1999) at the base of the solar convection zone (SCZ). This differential rotation stretches any initial poloidal (dipolar or r-$\theta$) component to a toroidal component (in the $\phi$-direction). The toroidal field can be stored and amplified in the tachocline region and when they are sufficiently strong, they can rise to the solar surface due to magnetic buoyancy (Parker, 1955a; Nandy, 2002). The action of the Coriolis force on the rising flux tubs generate a tilt relative to the local parallel of latitude (D'Silva and Choudhuri, 1993), which is manifested as the tilt-angle of bipolar sunspot pairs.

During the buoyant rise of these toroidal flux tubes, the magnetic fields can be twisted back into the r-$\theta$ plane to regenerate the poloidal field thus completing the dynamo cycle (Parker 1955b); this is known as the (mean-field) dynamo α-effect. Another mechanism for regenerating the poloidal field is the decay and dispersal of the flux of tilted bipolar sunspot pairs (which have a net dipole moment) due to the action of near-surface flux-transport processes such as turbulent diffusion, meridional circulation and differential rotation (Babcock, 1961, Leighton, 1968). It is believed that the Babcock-Leighton (BL) mechanism is capable of working on stronger fields, while the mean field dynamo α-effect gets quenched (and becomes ineffective) when the field is strong. Dynamo simulations based on the BL idea are capable of reproducing various aspects of solar activity (Nandy and Choudhuri, 2001, 2002; Muñoz-Jaramillo, Nandy, and Martens, 2009, 2011; Muñoz-Jaramillo et al., 2010) and are also used to explore stellar magnetism (Nandy, 2004). Recent observations strongly support the BL mechanism as the main source of poloidal field generation and dynamo action in the Sun (Dasi-Espuig et al., 2010) and it is fair to say that the BL dynamo mechanism is a leading contender towards a successful model of the solar cycle.

We do not delve deeper into dynamo theory here. For a comprehensive review on the subject readers are referred to Charbonneau (2010) and for further discussions on current trends and outstanding issues in understanding the solar cycle readers are referred to Nandy (2010a; 2010b).

## Origin of the Unusual Minimum of Solar Cycle 23

Fluctuations in the solar cycle can arise due to variations in the physical processes that drive the dynamo mechanism. What fluctuations could explain the unusual minimum of solar cycle 23? We know that the mean of the tilt angle distribution of bipolar sunspots pairs for solar cycle 23 (which governs the BL mechanism) was not significantly different from previous cycles (Schrijver and Liu, 2008). The average level of turbulent diffusivity or flux pumping is also not expected to be significantly different from one cycle to another. However, the meridional circulation – which goes deep into the SCZ, varies significantly in between and across solar cycles (González Hernández et al., 2006).

If the main source of poloidal field is located at near-surface layers as envisaged in the BL mechanism then turbulent diffusion, meridional circulation and turbulent flux pumping are expected to play major roles in transporting the poloidal flux back to the solar interior where the toroidal flux is generated, stored and amplified. Observational signatures of these flux transport processes may also be imprinted in the solar cycle and heliospheric processes (Georgieva, 2011; Georgieva and Kirov, 2011). Which flux transport process predominantly communicates between these dynamo source-regions in the SCZ determines some important aspects of the dynamo process, including its memory (Yeates, Nandy, and Mackay, 2008). However, the timing and period of the cycle – even if the dynamo is working in a diffusion dominated regime in the SCZ – is thought to be predominantly modulated by the meridional circulation (Yeates, Nandy, and Mackay, 2008). This consideration, coupled with the fact that the meridional flow exhibits significant variability have motivated us to explore the effects of meridional flow fluctuations in governing the nature of solar minima (Nandy, Muñoz-Jaramillo, and Martens, 2011).

We do not ask the question what causes the meridional flow to change, nor do we try to self-consistently produce these changes. We just assume that changes in the meridional circulation do occur and based on the principle of Occam's razor, we assume that the amount of fluctuation is random. We have performed simulations with these changes in the flow occurring at the maximum of solar cycles – where it is expected that the presence of strong toroidal fields in the solar interior will alter the imbalance of forces that drive the meridional flow (equator-pole temperature difference and Reynolds stresses in the convection zone).

As outlined in Nandy, Muñoz-Jaramillo, and Martens (2011), we find that a faster flow in the early half of a cycle, followed by a slower flow in the latter half – produces a deep solar minimum with the characteristics of the minimum of solar cycle 23. It is important to highlight here that only such variations, self-consistently reproduce both the (main) characteristics of solar cycle 23 minimum – namely a large number of spotless days as well as a relatively weak polar field.

Why are such flow changes successful in producing a deep minimum and a weak polar field? We believe that this is due to the following reasons. During the early half of the cycle highly tilted bipolar sunspot pairs emerge at high latitudes close to the poles – with a high net dipole moment (the Joy's law distribution of tilt angles is such that high latitude sunspot pairs are more tilted). In principle, these high latitude active regions can generate average to strong polar fields for the new ongoing cycle if their leading polarity flux is cancelled or transported preferentially towards the equator, while the following polarity moves to the poles to cancel the older cycle polar flux and build the new cycle flux. However, if the meridional flow is stronger than average, than both the leading and following polarities move together to the poles, imparting less net flux for the new cycle. This results in a slow cancellation of the older cycle polar field and weak build up of the new cycle polar field – a situation that clearly matches the polar field dynamics during solar cycle 23 (Schrijver and Liu, 2008). Moreover, a stronger meridional flow in the early half of the cycle – when the toroidal field is still being built up from the poloidal field of the previous cycle – does not allow enough time for toroidal field induction to take place. Thus the toroidal field itself is not extraordinary strong and the cycle ends earlier at higher latitudes relative to the equator. A subsequent, slower flow, just distances the next cycle toroidal field from the current cycle – thereby preventing too much of an overlap between the cycles – such that sunspots from the two cycles do not emerge together. This prevention of overlap is the key to producing a large number of spotless days. On the other hand, a proper algorithm for the emergence of tilted bipolar sunspot pairs and near-surface flux transport dynamics is the key to accurately capturing polar field dynamics. A combination of all these processes in our simulations, we believe, allowed us to successfully reproduce the characteristics of the minimum of solar cycle 23.

## Discussions

Note that observations of surface meridional flows typically show a solar cycle modulation with flows that increase and decrease sinusoidally in anti-phase with the sunspot cycle; i.e., a slower meridional flow is seen at solar maximum and a faster flow is observed at minimum (Hathaway and Rightmire, 2010). This is presumably due to the feedback of magnetic fields on the flows, or, inflows that are driven by thermodynamic imbalances forced by the effect of magnetic fields on convection at near-surface layers (Cameron and Schüssler, 2011) and are different from the large-scale internal flow variation that is required in our model to reproduce the characteristics of cycle 23 minimum.

Note that in recent postings Choudhuri (2011) and Karak and Choudhuri (2011) – motivated by the solar cycle modulation of surface flows as observed in the near-surface layers – criticize our usage of a random change in the meridional flow. First they assert that the flow changes should be deterministic and then go on to show that the deterministic solar cycle modulation cannot produce a deep minimum. Apparently they were not aware that Jiang et al. (2010) had already pointed out that these deterministic flow changes cannot produce the weak polar fields observed during the minimum of cycle 23 (a work that we were aware of and had already discussed in Nandy, Muñoz-Jaramillo, and Martens, 2011). We reiterate that the flow changes we require in our simulations to reproduce a deep minimum are not the deterministic, sinusoidal flow changes that are observed at the near-surface layers. As already argued in Nandy, Muñoz-Jaramillo, and Martens (2011) and clearly demonstrated in Cameron and Schüssler (2011) – the near-surface flow variations does not necessarily imply similar variations in the deeper flow.

In the Supplementary Information in Nandy, Muñoz-Jaramillo, and Martens (2011), we have shown that our results are robust to reasonable changes in dynamo driving parameters, including the adoption of a much stronger turbulent diffusivity. Moreover, we demonstrate therein that the meridional flow change does not have to be random and instantaneous right at solar cycle maximum; they can vary continuously over a few years around the maximum and still generate qualitatively similar results regarding the nature of solar minima.

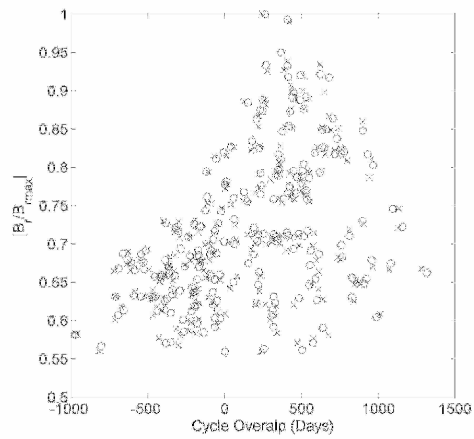


Figure 4: Relative polar field strength during solar minima (y-axis) versus overlap between cycles during the same minima (x-axis) from our dynamo simulations with a variable meridional flow (Nandy, Muñoz-Jaramillo, and Martens, 2011). Negative overlap signifies a deep minimum with a large number of spotless days. Our simulation results show that deep minima are in general associated with weak polar fields (data points near the bottom-left corner), thereby reproducing the main characteristics of the minimum of solar cycle 23

Based on helioseismic observations, Howe et al. (2009) find that the zonal flow band corresponding to solar activity had been moving equatorward faster during the previous minimum relative to the phase around the minimum of cycle 23. Basu and Antia (2010) – also based on helioseismic observations – find that the deterministic surface modulation at near surface layers are not so apparent at deeper layers and that at deeper layers, the meridional flow was likely faster at the previous minimum relative to the minimum of solar cycle 23. In Fig. 4 (top panel) of Basu and Antia (2010) – corresponding to the coefficient that is relevant for single cell per hemisphere flows as used in most dynamo models – it is clear that the deeper component of the meridional flow was in fact faster during the previous minimum and early part of cycle 23 and then slowed down to a lower value. These helioseismic observations from the deeper layers of the SCZ support our simulation results.

In conclusion, our results indicate that plasma flow dynamics in the solar interior were responsible for the unusual nature of the minimum of solar cycle 23. This highlights the interconnectedness of the heliosphere – with plasma processes and subtle variations deep within the Sun modulating solar magnetic activity in a way that profoundly impacts space environmental conditions and planetary atmospheres such as that of the Earth.

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