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Double Peaks of the Solar Cycle: An Explanation from a Dynamo Model

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Abstract

One peculiar feature of the solar cycle that is yet to be understood properly is the frequent occurrence of double peaks (also known as the Gnevyshev peaks). The double peaks, and also multiple peaks and spikes, are often observed in any phase of the cycle. We propose that these peaks and spikes are generated due to fluctuations in the Babcock–Leighton process (the poloidal field generation from tilted bipolar magnetic regions). When the polar field develops, large negative fluctuations in the Babcock–Leighton process can reduce the net polar field abruptly. As these fluctuations in the polar field are propagated to the new toroidal field, these can promote double peaks in the next solar cycle. When fluctuations in the polar field occur outside the solar maximum, we observe their effects as spikes or dips in the following sunspot cycle. Using an axisymmetric Babcock–Leighton dynamo model, we first demonstrate this idea. Later, we perform a long simulation by including random scatter in the poloidal field generation process and successfully reproduce the double-peaked solar cycles. These results are robust under reasonable changes in the model parameters, as long as the diffusivity is not too much larger than 10^{12} cm^2 s^{-1}. Finally, we analyze the observed polar field data to show a close connection between the short-term fluctuations in the polar field and the double peaks/spikes in the next cycle. Thereby, this supports our theoretical idea that the fluctuations in the Babcock–Leighton process can be responsible for the double peaks/spikes in the observed solar cycle.

Key words: dynamo – magnetohydrodynamics (MHD) – Sun: activity – Sun: interior – Sun: magnetic fields – sunspots

1. Introduction

The sun's magnetic activity, commonly measured using the sunspot number or sunspot area, oscillates with a period of about 11 years. This is popularly known as the solar cycle or sunspot cycle. Interestingly, every solar cycle is different from the previous ones in terms of the cycle duration and amplitude. Apart from this variation, several short-term variations exist in the observed solar data (Lean & Brueckner 1989; Bazilevskaya et al. 2014; McIntosh et al. 2015; Mandal et al. 2017).

One distinct and puzzling observable among these short-term variations is the occurrences of double peaks. It has been observed that during the solar maximum, when sunspot number reaches its maximum value, solar cycle occasionally shows two peaks (Feminella & Storini 1997; Norton & Gallagher 2010; Georgieva 2011; Bazilevskaya et al. 2014). These are also known as Gnevyshev peaks, and the gap between these two peaks at the solar maximum is known as the Gnevyshev gap (Gnevyshev 1967, 1977). Although observed in many earlier cycles, this double-peak feature has received special attention in recent years mainly because the last three solar cycles were double-peaked; see (Phillips 2013). We note that these double peaks are not the artifacts of insufficient observations but are real features (Norton & Gallagher 2010). We also note that this feature is not only limited to the sunspot number or area data, but is also observed in other proxies of the solar activity, e.g., coronal activity (Gnevyshev 1963; Kane 2009, 2010).

One could argue that the double peak is a result of the fact that when two hemispheres reach their maxima at two different times, the combined solar activity can have two peaks. By making a careful analysis of the solar data, we show that a time difference between the maxima of two hemispheric solar activity may lead to a double peak; however, this happens rarely. In fact, most of the time, the double peak occurs only in one hemisphere (Norton & Gallagher 2010). Importantly, the double-peak type spikes are not only observed during solar maximum, but they are also seen at any phase of the solar cycle. When the spike appears near a solar maximum, we see it as a double peak.

The double peaks and spikes are possibly the manifestations of the recently discovered quasiperiodic "burst" or oscillations with periods of 6–18 months in the solar activity (McIntosh et al. 2015). Using magnetohydrodynamics shallow-water model, Dikpati et al. (2017, 2018) have shown that the energy exchange among magnetic fields, Rossby waves, and differential rotation in the solar tachocline can lead to quasiperiodic nonlinear oscillations, which possibly correspond to the observed burst of solar activity. Also see Zaqarashvili et al. (2010) and Zaqarashvili (2018) for studies connecting the Rossby waves in the tachocline with the short-term oscillations.

However, there could be a different mechanism of producing double peaks and spikes in the solar cycle. Irregular fluctuations are inherent in the solar dynamo and can appear in any phases of the solar cycle. When strong fluctuations appear near the solar maximum, we may see them as double peaks. In this study, using a dynamo theory, we identify the source of these fluctuations and explore how these fluctuations could promote double peaks in the solar cycle.

Over last two decades, the solar magnetic cycle has been modeled with great details using the Babcock–Leighton dynamo models, also named as the flux transport dynamo models (Choudhuri et al. 1995; Durney 1995; Dikpati & Gilman 2009; Charbonneau 2010; Karak et al. 2014). In this model, the poloidal field is generated from the decay and dispersal of tilted bipolar magnetic regions (BMRs) near the solar surface. This field is largely transported to the poles through meridional flow. From the surface, the poloidal field is then transported down to the deep convection zone (CZ) through meridional circulation, turbulent diffusion, and pumping, where differential rotation stretches this field to produce a toroidal field. The toroidal field then rises up the surface due to magnetic buoyancy and gives tilted BMRs. It is believed that the tilt is introduced due to the Coriolis force during the rise of the toroidal flux in the CZ (D'Silva & Choudhuri 1993). The observed correlation between the surface polar flux and the next cycle strength supports this part of the dynamo model (Dasi-Espuig et al. 2010; Kitchatinov & Olemskoy 2011; Muñoz-Jaramillo et al. 2013; Priyal et al. 2014). The new BMRs again decay and produce a poloidal flux, which forms the seed for the next cycle.

The tilt angle of a BMR is crucial in generating a net poloidal flux as has been realized in the surface observations (Dasi-Espuig et al. 2010), as well as surface flux transport models (Jiang et al. 2014) and a 3D (or 2 × 2D coupled) dynamo model with explicit BMR depositions (Hazra et al. 2017; Karak & Miesch 2017; Lemerle & Charbonneau 2017). In observations, we find a considerable scatter of the mean BMR tilt around its systematic variation with the latitude—Joy's law (Howard 1991; Stenflo & Kosovichev 2012; McClintock et al. 2014; Senthamizh Pavai et al. 2015; McClintock & Norton 2016). This scatter is the primary cause of the variation in the polar field (e.g., Jiang et al. 2014; Hazra et al. 2017; Karak & Miesch 2017; Nagy et al. 2017). The effect of the scatter is very profound when BMRs appear near the equator (Cameron et al. 2013; Karak & Miesch 2018). Other effects, such as the fluctuations in the net BMR flux, BMR emergence rates, time delay of BMR emergence, meridional circulation speed, etc., can also introduce additional variation in the polar flux (Karak & Miesch 2017; Lemerle & Charbonneau 2017; Nagy et al. 2017). Ultimately, it is the fluctuations in the Babcock–Leighton process that are the primary cause of the variation in the polar field and consequently in the sunspot cycle, as has been pointed out earlier by Charbonneau & Dikpati (2000), Choudhuri et al. (2007), and Choudhuri & Karak (2009).

In this study, we show that the fluctuations in the Babcock–Leighton process can also occasionally produce short-term fluctuations in the polar field. These fluctuations can be propagated to the toroidal field and, therefore, can cause double peaks in the next solar cycle. As these fluctuations can occur at any phase of the polar field buildup, the fluctuations can appear at any phase of the solar cycle. When they occur outside the solar maxima, we observe them as spikes and dips. We explicitly identify the fluctuations in the polar field from the observed data and show that this can be responsible for the double peaks in the solar cycle.

2. Confirmation of Double Peaks in the Solar Data

Before we discuss the physical source of the double peak, let us first reestablish its existence in the observed solar data. For this purpose, we utilize the Greenwich/National Oceanic and Atmospheric Administration (NOAA) sunspot area data,[4] which covers a period of ∼140 years. We use sunspot area data instead of a sunspot number because a longer hemispheric sunspot number is not available. In order to bring out the prominent spikes in the solar cycle, we smooth the monthly averaged sunspot area data with a Gaussian smoothing filter of FWHM = 1 year. Figure 1 shows these smoothed data for the northern (red curve), southern (blue), and combined (dotted) hemispheres. When we look at the combined data, we observe that cycles 14, 16, 20, 21, 22, and 23 have definite double peaks. However, upon examining the individual hemispheric data, we find that many cycles have double peaks and spikes only in one hemisphere. In fact, almost all cycles, except cycles 17 and 19, have double peaks or even multiple peaks. For only a few cycles (16, 20, 21, and 22), double peaks occurred in both hemispheres. We also note that the peaks are not limited to the solar maxima, and they are seen in the rising or declining phase of the cycle as well; see the northern hemisphere of cycles 17 and 21; and both hemispheres of cycles 15, 18, and 20.

As discussed in Section 1, the double peak might appear when the peaks of two hemispheric activities do not synchronize. This has happened for cycles 22 and 24 in which the north and south hemispheres do not peak at the same time, and the net sunspot area becomes double-peaked. However, this cannot happen always. For example, cycles 12, 14, 17, 18, and 19 have little time lags between two hemispheric maxima but do not show clear double peaks. Therefore, we believe that the double peak is real. This is also in agreement with the analysis of Norton & Gallagher (2010). Moreover, occasionally we observe multiple peaks (cycles 16 and 20). Therefore, this supports our initial guess about the fluctuations in the solar dynamo process that are responsible for producing these spikes and double peaks.

3. Theoretical Model

In this study, we use a kinematic axisymmetric Babcock–Leighton dynamo model in which we solve following equations in the solar convection zone (Chatterjee et al. 2004):

$$\frac{\partial A}{\partial t} + \frac{1}{s}(\boldsymbol{v} \cdot \boldsymbol{\nabla})(sA) = \eta_p\left(\nabla^2 - \frac{1}{s^2}\right)A + \alpha B, \tag{1}$$

$$\frac{\partial B}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial \theta}(v_\theta B)\right] = \eta_t\left(\nabla^2 - \frac{1}{s^2}\right)B + s(\boldsymbol{B}_p.\nabla)\Omega + \frac{1}{r}\frac{d\eta_t}{dr}\frac{\partial B}{\partial r}, \tag{2}$$

where A and B are the potential of the poloidal magnetic field ($\boldsymbol{B}_p$) and the toroidal magnetic field, respectively, such that $\boldsymbol{B} = \boldsymbol{B}_p + B\hat{\boldsymbol{e}}_\phi$, with $\boldsymbol{B}_p = \boldsymbol{\nabla} \times A\hat{\boldsymbol{e}}_\phi$, $s = r\sin\theta$ with θ being the colatitude, $\boldsymbol{v} = v_r\hat{\boldsymbol{e}}_r + v_\theta\hat{\boldsymbol{e}}_\theta$ is the meridional flow, Ω is the angular velocity, η_p and η_t are the diffusivities of the poloidal and toroidal fields, respectively, and α is the coefficient describing the generation of the poloidal field from the toroidal

[4] https://solarscience.msfc.nasa.gov/greenwch.shtml

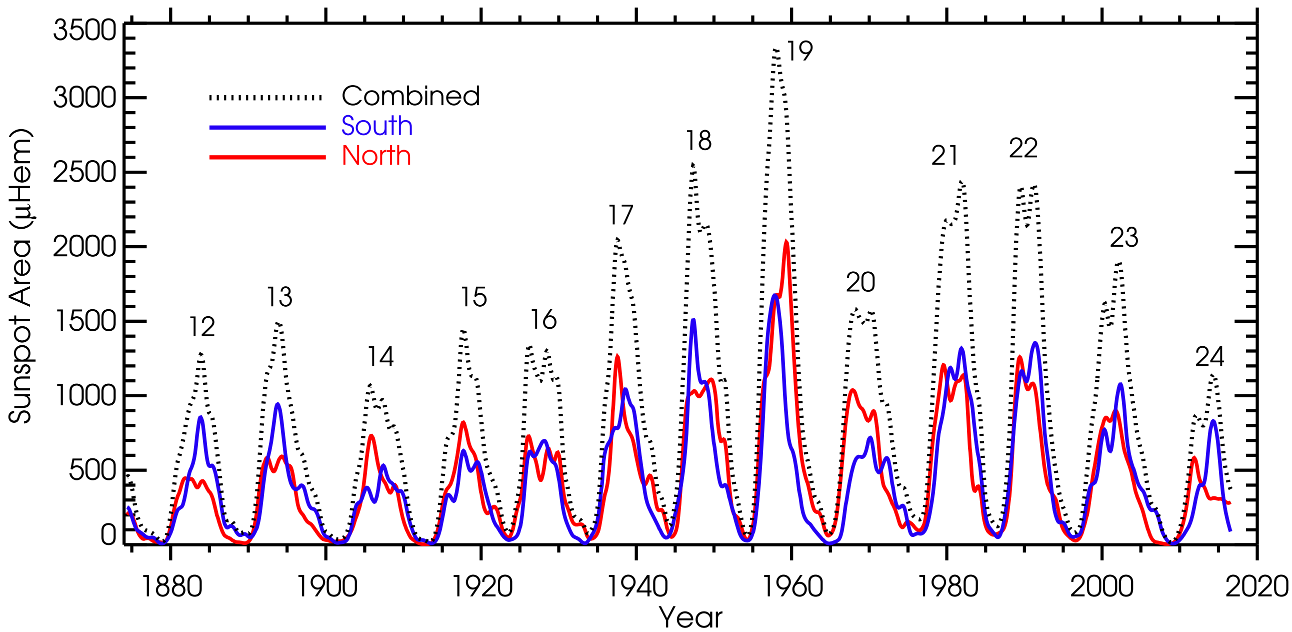

Figure 1. Temporal variation of the monthly sunspot area (in millionths of a solar hemisphere) for individual hemispheres, as well as the combined data. Cycle numbers are also labeled on the figure.

field and mimics the Babcock–Leighton process. Thus

$$\alpha = \frac{\alpha_0}{4}\cos\theta\left[1 + \mathrm{erf}\left(\frac{r - 0.95R}{0.025R}\right)\right] \times \left[1 - \mathrm{erf}\left(\frac{r - R}{0.025R}\right)\right], \quad (3)$$

where $\alpha_0 = 50$ m s^{-1}, and R is the solar radius.

We do not describe details of other ingredients of the model here, but refer the readers to the key publication by Chatterjee et al. (2004). The exact parameters used in this publication are the same as given in Yeates et al. (2008) and Karak & Nandy (2012) with the key parameters of $v_0 = 26$ m s^{-1}, $\eta_2 = 1 \times 10^{12}$ cm^2 s^{-1}, and $\eta_0 = 2 \times 10^{12}$ cm^2 s^{-1}.

Although our Babcock–Leighton type dynamo model (including many recent models, e.g., Miesch & Dikpati 2014; Lemerle & Charbonneau 2017) produces many basic features of the solar cycle reasonably well, it produces much stronger polar field at the surface than the present observational reported values. Dikpati & Gilman (2001) and Dikpati et al. (2002) have shown that this problem can be elevated (at least partially) by increasing the surface diffusivity of the magnetic field and adding an additional source for the poloidal field in the tachocline. On the other hand, Kitchatinov & Nepomnyashchikh (2016) have shown that a diamagnetic pumping near the base of the convection zone can help. However, as many of the parameters in this model are not constrained by observations, and no high-resolution magnetograms of the polar magnetic field are available at present, we ignore the discrepancy between the theory and observations in this work; also see the discussion in Choudhuri (2003).

4. Theoretical Results

4.1. Demonstrating the Idea

Before we present our theoretical results of the double-peaked solar cycle, let us first describe our idea. We propose that the double peaks (including multiple peaks and spikes) in the solar cycle are caused by the fluctuations in the Babcock–Leighton process of generating the poloidal field. To demonstrate that this idea is working in our model in the first place, we do the following experiment. We take our dynamo model, as described above, and when it is producing a stable/relaxed solution, we stop the model at a solar maximum when the polar field has started developing ($t = 6.85$ year in Figure 2). Then we reverse the α, i.e., we make $\alpha_0 = -50$ m s^{-1} in Equation (3) in both hemispheres and continue the run for six months. After that, we change α_0 back to 50 m s^{-1} and extend the run for some years.

As soon as α_0 gets flipped, the model generates an opposite-polarity poloidal field in low latitudes, as seen in the surface radial field of Figure 2(a). This oppositely generated polar field reduces the original polar field considerably and causes fluctuations in the mean polar field; see Figure 2(b). We note that the polar field shows two spikes after the sudden reduction. This is due to the fact that the opposite polar field that is produced at low latitudes (due to the reversed α) took some time to be transported to the high latitudes, and by that time, the polar field was still trying to grow rapidly. Anyhow, the abrupt fluctuations in the polar field cause a reduction in the resulting toroidal field of the next cycle (as the poloidal field is the ultimate source of the toroidal field). A time delay of about seven years between the polar field and the toroidal field is reflected (Figure 2) due to the time taken by the meridional flow and the diffusion in transporting the field from the surface to the base of the CZ. As expected, if the α_0 is reversed for a longer time, then the double peak becomes more extended; see the dotted lines in Figures 2(a) and (b), for which the α was reversed for eight months instead of six months. Interestingly, this simulation spent only two extra months with a reversed α but produced much deeper double peaks than the other one. The reason is that model spent extra two months near the heightened level of polar field. In summary, when the polar field is growing, a large reduction in the α causes a double peak in the next solar cycle.

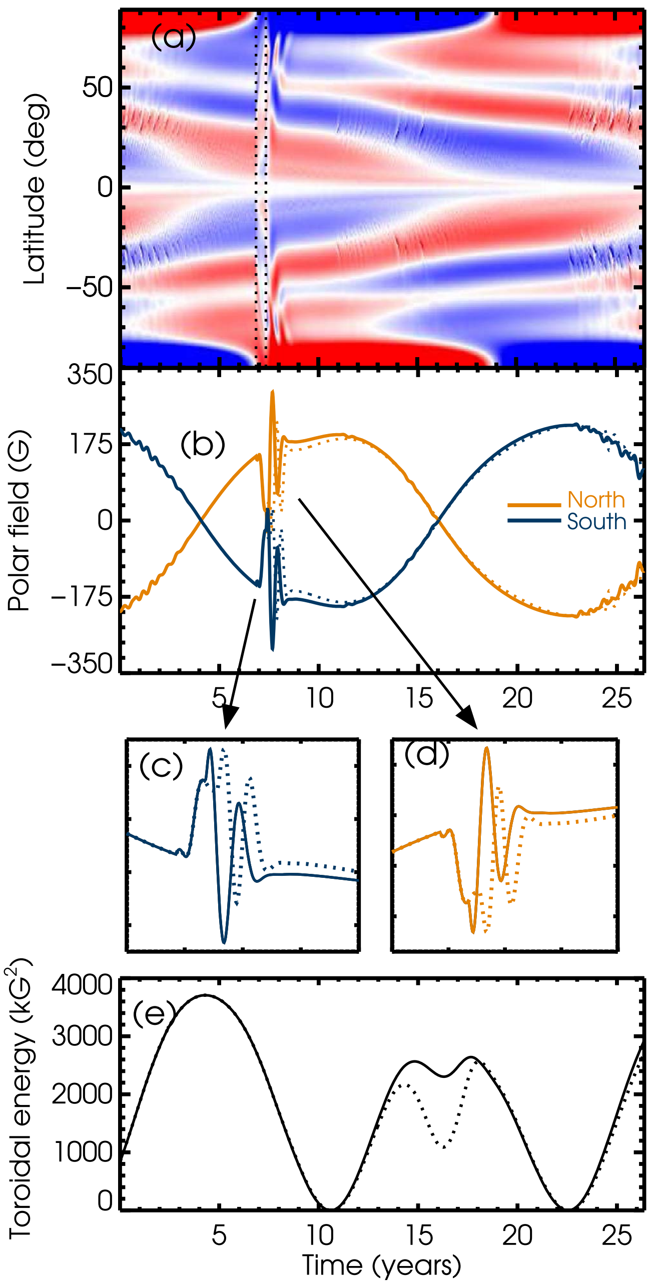

Figure 2. Panel (a): butterfly diagram of the surface radial field. Two dotted vertical lines show the six month window during which the α_0 was reversed. Panel (b): the mean surface polar field (in G) computed within latitudes of $\pm 55°$ to $\pm 89°$. Panels (c) and (d): same as in panel (a), but an enlarged view of the polar fields shown for 5–10 years. Panel (e): toroidal magnetic energy in kG^2 obtained at $r = 0.7R$ and 15° latitude. Dotted lines in panels (b)–(e) are obtained from a different simulation in which the α_0 was reversed for eight months instead of six months.

4.2. Results of Stochastically Forced Dynamo Simulations

We now model the solar cycle by varying α stochastically in Equation (1). We replace α_0 in Equation (3) with $\alpha_0 + \alpha_{\rm fluc}\,\sigma(t,\ \tau_{\rm corr})$, where $\alpha_{\rm fluc} = 100$ m s^{-1}, i.e., a 200% level of fluctuations, σ is a uniform random deviate whose value lies between −1 and 1, and $\tau_{\rm corr}$ is the correlation time after which the fluctuation is updated to a new value. As the mean lifetime of the BMRs is about a month, we take $\tau_{\rm corr} = 1$ month. We note that recently Kitchatinov et al. (2018) also suggest that in order to match the distribution of the observed cycle period, the coherence time of the α fluctuations has to be around one solar rotation (25.4 days). We further note that in this case, the fluctuations are introduced independently in two hemispheres, as the fluctuations in Babcock–Leighton process is expected to be uncorrelated in hemispheres. With this level of fluctuations in α, our model produces a variation (about 46%) in the peak polar field that is comparable to the variation (52%) computed from the proxy of the polar field presented in Muñoz-Jaramillo et al. (2012).

A result of the 500 years simulation of our stochastically forced dynamo model is shown in Figure 3. We do not understand how to translate the toroidal field in the deep interior to the observed sunspot number. We use the prescription followed by Charbonneau & Dikpati (2000) and build a proxy of the sunspot number in the northern (southern) hemisphere from the magnetic energy density at 15° (−15°) latitude at the base of the convection zone ($r = 0.7R$).

At a first glance, we find that the model beautifully reproduces the observed solar cycle with double peaks in many solar cycles. In additional to double peaks, some cycles, in fact, show multiple peaks around the solar maxima and spikes in the rising and declining phase of the solar cycle. As seen in the observed solar cycle data, the double peak may not necessarily occur in two hemispheres simultaneously. Only for four cycles in this figure do the double peak appeared in both hemispheres (cycles M1, M11, M26, M33, and M37). For other cycles, the double/multiple peaks appear only in one hemisphere. As discussed in the Section 1 and as seen in the observed data, when two hemispheres are not synchronized and when two hemispheric maxima have a time difference, we may see a double peak. We observe that the maxima of cycles M3, M4, M8, M10, M11, M13, M18, M19, M22, M30, M32, M35, M39, and M40 have significant time lags, but only cycles M10, M18, M32, M35, and M39 are clearly double-peaked, while the rest are not. Thus, merely a phase lag of two hemispheric activities may not necessarily lead to a double-peaked solar cycle.

4.3. Are the Results Sensitive to the Details of the Model?

One may wonder whether our modeled double-peaked solar cycles presented in Section 4 are sensitive to the details of the parameters. To check this, we perform several simulations at different values of parameters. First, we do two simulations: in one, we reduce the diffusivity of the poloidal field to its half i.e., $\eta_0 = 1 \times 10^{12}$ cm^2 s^{-1}, and in another, we double the value. As the dynamo growth rate is largely dependent on the value of diffusivity, we also need to change the value of α_0 in these simulations to 10 m s^{-1} and 80 m s^{-1}, respectively. We find that the higher-diffusivity simulation produces less prominent and infrequent double peaks, while the lower-diffusivity simulation produces very frequent and pronounced double peaks. This is expected because the diffusion tries to smooth out the fluctuations acquired in the poloidal field (also see Karak & Choudhuri 2011). However, when the level of fluctuations is increased, frequent double peaks again appear even in the higher-diffusivity simulation. Next, we execute the following three simulations: (i) at two different values of the speed of meridional flow, namely $v_0 = 20$ m s^{-1} and $v_0 = 32$ m s^{-1} (instead of 26 m s^{-1}, as used in the main simulation), and (ii) one at $\alpha_0 = 30$ m s^{-1} (instead of 50 m s^{-1}). No other parameters are changed in these runs. All three simulations produced qualitatively similar double peaks and spikes, as shown in Figure 3. Then we perform four

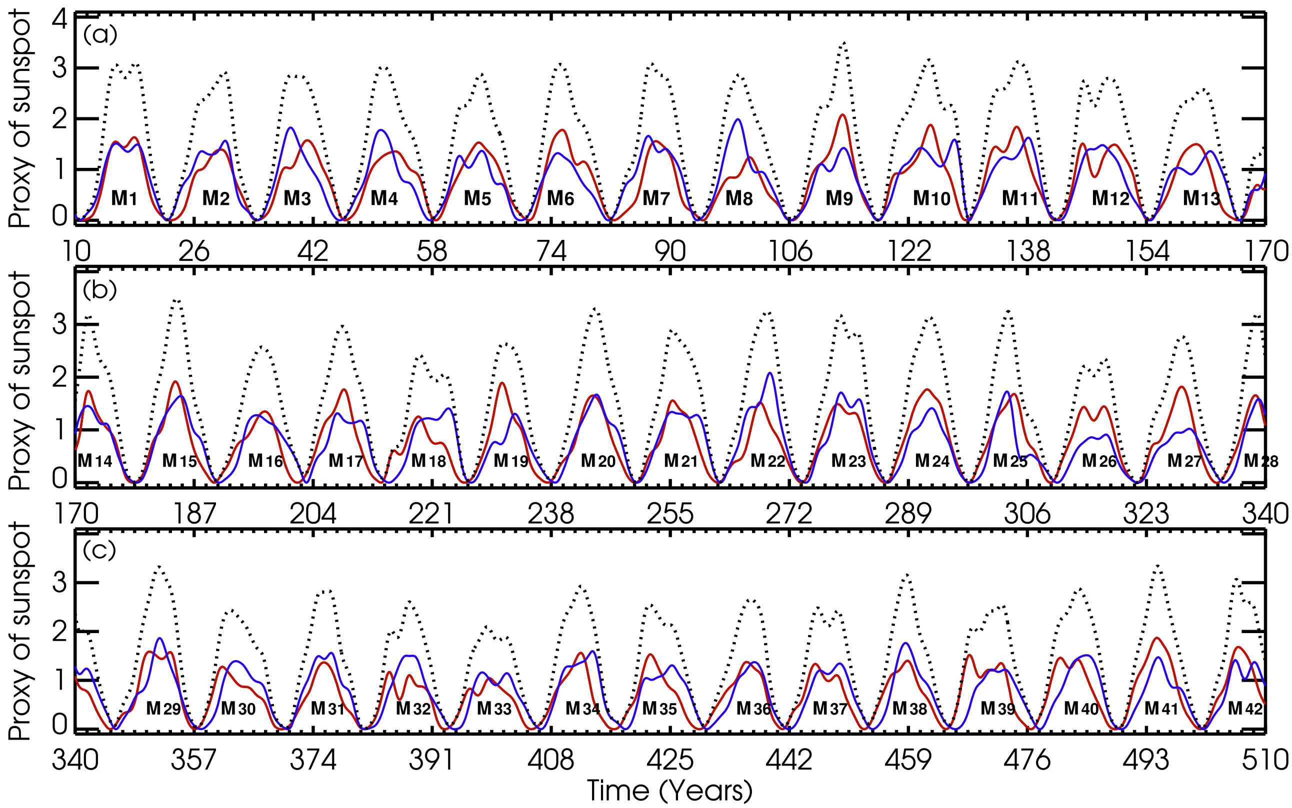

Figure 3. Proxy of the sunspot number obtained from our stochastically forced dynamo model. Black, red, and blue dotted lines correspond to the total, northern, and southern hemispheric sunspot numbers, respectively. Cycles are numbered with labels M# to facilitate the discussion.

simulations at 50%, 100%, 150%, and 250% levels of fluctuations in α. Obviously, when the level of fluctuations is increased, we get more frequent and more prominent double peaks and vice versa. We find that when the fluctuation level is reduced below 100%, the double peaks and spikes disappear; see Figure 4 for the results of simulations with 100% and 250% levels of fluctuations in α. Finally, we change the coherence time, $\tau_{\rm corr}$, and perform two simulations at $\tau_{\rm corr} = 15$ days and two months. We find that a larger $\tau_{\rm corr}$ produces more prominent and frequent double peaks (and vice versa). We also perform a simulation by including 4 m s^{-1} downward magnetic pumping in our model in the same way as was done in Karak & Cameron (2016) and find that our final conclusion remains unchanged. In fact, we find that the downward magnetic pumping helped to transport the polar flux efficiently to the base of the CZ and thus helped to produce more prominent double peaks.

5. Observational Support of the Idea

In previous sections, we have shown that large negative fluctuations in the α effect can introduce a large reduction in the poloidal field, which ultimately causes double peaks (including multiple peaks and spikes) in the solar cycle. Is this really happening in the Sun and is there any observational evidence for that? These questions are exactly what we explore here. In the Babcock–Leighton process, the poloidal field is generated from the decay and dispersal of the tilted BMRs on the solar surface, which is seen in the solar observations (Dasi-Espuig et al. 2010; Kitchatinov & Olemskoy 2011; Cameron & Schüssler 2015). The BMR tilt, however, has a large scatter around Joy's law (Howard 1991; Stenflo & Kosovichev 2012; McClintock et al. 2014; Senthamizh Pavai et al. 2015; McClintock & Norton 2016). Due to this scatter, BMRs can occasionally get wrong tilts and can produce an opposite-polarity polar field. This is actually seen in the observed magnetic field data. In Figure 5, circles mark the opposite-polarity surges possibly caused by the wrongly tilted sunspots. Because of these opposite-polarity surges, we see clear fluctuations in the mean polar field, as shown by the corresponding circles in Figure 5(b). These fluctuations in the polar field are the cause of the observed double peaks in the subsequent sunspot cycle.

For example, fluctuations in the polar field in cycle 21, as marked by c_1 and c_2 in the southern and northern hemispheres (Figure 5), are possibly the cause of the observed double peaks in sunspot cycle 22, as shown in Figure 1. Similarly, the fluctuations marked by c_3 and c_4 in the southern and northern hemispheres are the cause of the double peaks in sunspot cycle 23 in their respective hemispheres, as seen in Figure 1. Base on our theoretical experiment presented in Figure 2, we emphasize that a large fluctuation in the polar field growing phase is crucial. Therefore, the wrong polar surge in the southern hemisphere of cycle 22, as marked by c3 in Figure 5(a), was enough to produce a prominent spike in the subsequent sunspot cycle 23 of the same hemisphere (Figure 1).

In cycle 23's southern hemisphere polar field, two little negative surges marked by C_5 produce a little dip in the polar field, as shown in Figure 5(b), which in turn stalled the rising phase of sunspot cycle 24 of the same hemisphere. In the northern hemisphere polar field, two surges marked by C_6 and C_8, produce two little dips in the mean polar field, as shown in Figure 5(b). However, the level of the fluctuations in these two cases are so weak that no detectable double peak is seen in the

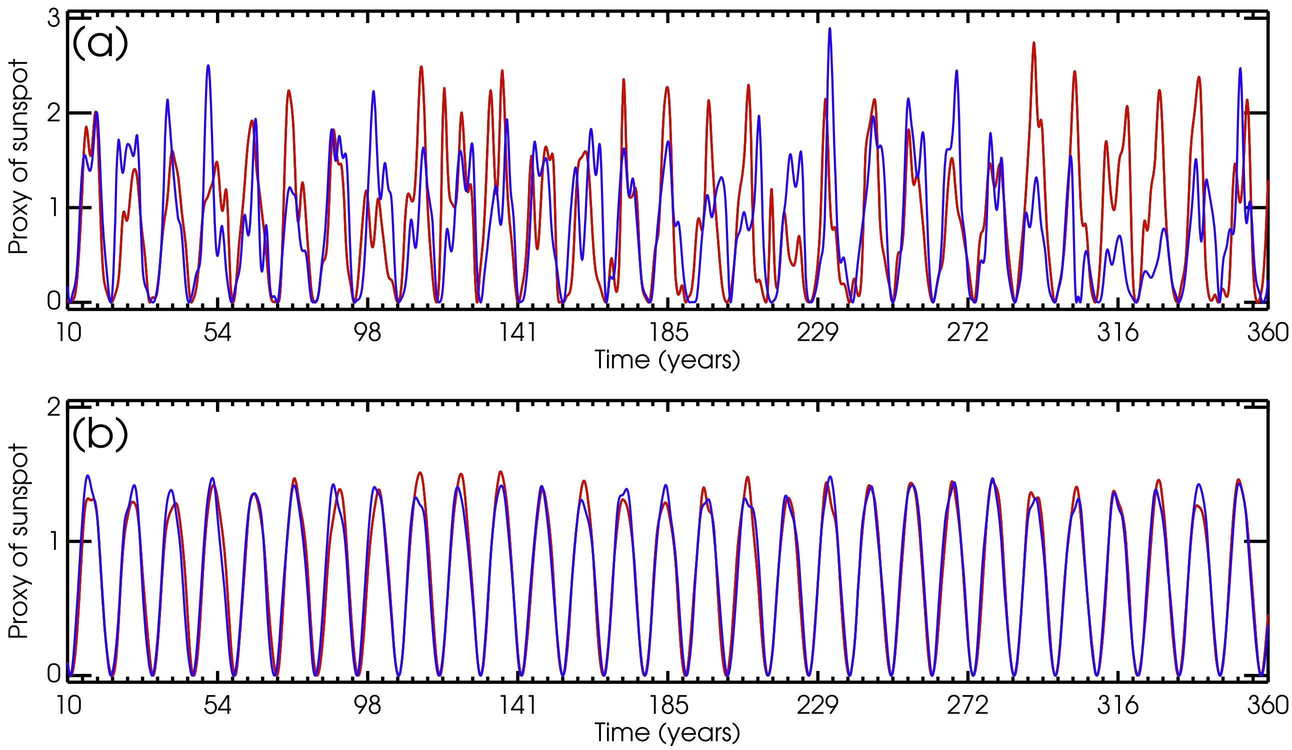

Figure 4. (a) Same as Figure 3, but obtained from simulations with 250% (top) and 100% (bottom) fluctuations in α.

subsequent sunspot cycle 24 (Figure 1, north). In this case, the overall polar field was not able to grow due to many negative polarity surges and consequently, the solar cycle 24 decreased rapidly in the northern hemisphere. From Figure 5(b), another fact we discover is that the rapid buildup of the polar field of cycles 22 and 23 in the northern hemisphere helped to peak the subsequent sunspot cycles 23 and 24, respectively, in the same hemisphere first.

Finally, we notice that there is a prominent surge in the northern hemisphere of cycle 24's polar field, as marked by C_{10} in Figure 5. Therefore, based on our theoretical model, as well as observations, we predict that in the northern hemisphere of the forthcoming solar cycle 25 will have a dip in the rising phase.

We have seen that our theoretical idea is supported by the available observed data of the last three cycles. Now the question is, does this idea work also in previous cycles when we do not have a direct measurement of the polar field? By making a careful inspection of a proxy of the polar field, as presented in Figure 14 of Muñoz-Jaramillo et al. (2012) and our sunspot cycles shown in Figure 1, we find that our idea holds also for the previous cycles. For example, fluctuations in the proxy of polar field data (Figure 14 of Muñoz-Jaramillo et al. 2012) around 1910 (both hemispheres), 1920 (north), 1930 (both), 1942 (north), 1960 (both), and 1976 (south), respectively, are possibly responsible for the double peak(s)/spike(s) in the corresponding hemisphere of the subsequent sunspot cycles 15, 16, 17, 18, 20, and 21. In Figure 1, we recall that the strongest sunspot cycle, cycle 19, did not show any double peaks or prominent spikes in both the hemispheres. Interestingly, the polar field (around 1955) for the cycle 19 also did not show any significant fluctuations. In fact, a little halt in the northern hemisphere polar field around 1950 probably caused a little spike in the same hemisphere sunspot number around 1958. Although promising, we must remember that a detailed comparison with the polar field and the subsequent solar cycle may be misleading, as this polar field data is not the actual measurement but is a proxy and is also poorly binned.

6. Conclusion and Discussion

In this study, we have theoretically modeled the double peaks and spikes observed in the solar cycle. We have shown that large negative fluctuations in the Babcock–Leighton process can abruptly decrease or even reverse the polar field for a short time. This is observed in the form of frequent polar surges of wrong polarity field in surface polar field data available for last four solar cycles (Section 5). The proxy of polar field data for the previous cycles (for which the polar field measurement is not available; Muñoz-Jaramillo et al. 2012) also shows occasional fluctuations. As the polar field is the seed for the next cycle, the fluctuations in the polar field can be propagated in the subsequent solar cycle, and they can cause short-term fluctuations in the solar cycle. When the abrupt decrease in the polar field happens in the growing phase of the polar field, we observe a clear double peak in the subsequent sunspot cycle.

We have presented this idea by making a clean experiment in which we have artificially flipped the source of the poloidal field (α) for six months, and as a result, a momentary reversed polar field promotes a clear double peak in the next sunspot cycle. Next, we performed a set of long simulations by including random scatter in α and reproduce many double-peaked solar cycles.

To the best of our knowledge, this is the first systematic effort to model the double-peaked solar cycle, although three previous attempts exist. First, Gnevyshev (1967) argued that the double-peaked solar cycle is caused by two different processes occurring at two different latitude bands. When the time interval between maxima of these two processes is large, the double peak is seen in the latitude-averaged solar activity. If

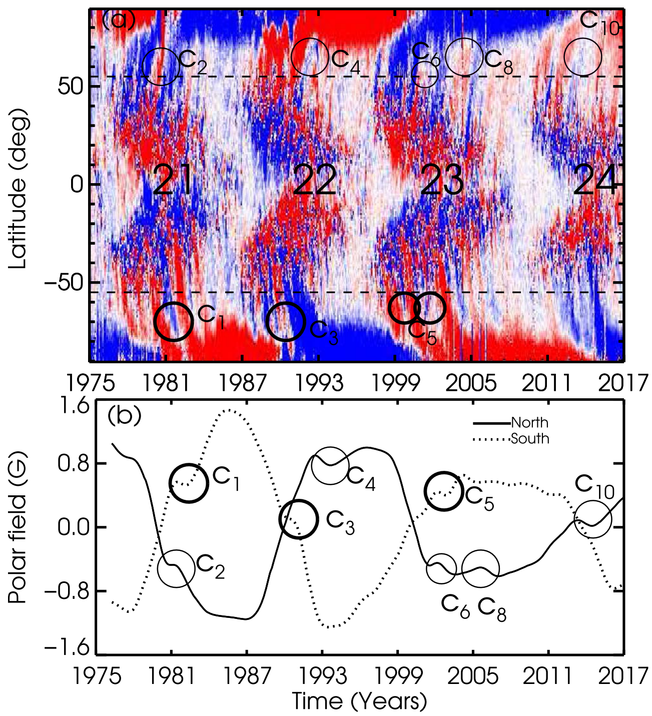

Figure 5. Panel (a): butterfly diagram of the surface radial magnetic field obtained from the National Solar Observatory (NSO/KPVT and SOLIS). The blue and red colors represent the negative and the positive fields. Panel (b): temporal variation of the Wilcox Solar Observatory (WSO) polar field observations for the two hemispheres. These polar measurements are constituted from 55° latitude and above for both hemispheres. Data source: http://wso.stanford.edu/Polar.html.

this is the correct explanation of double peaks, then the question remains: what are these two physical process and what determines the time lag between them? Second, Georgieva (2011), based on the mechanism of flux transport dynamo, showed that the double peaks are the manifestation of two surges of the toroidal field. One surge is generated from the poloidal field that is advected due to meridional circulation all the way on the poles, down to the base of CZ, and finally to low latitudes; and the other surge is generated from the poloidal field that is diffused to the base of the CZ directly from the surface. Georgieva (2011) suggested that when the timescales involved in two surges of toroidal field do not coincide, double peaks in the sunspot cycle are observed. However, no modeled double-peak solar cycle was presented. To our knowledge, if this idea applies to the flux transport dynamo model, then we would have observed a double peak even without including fluctuations in the Babcock–Leighton process. Without introducing fluctuations in α, we have not observed any double peaks in any simulations in the parameter ranges we have explored. Therefore, this idea does not work, at least in our model. Finally, quasiperiodic nonlinear oscillations in the tachocline (Dikpati et al. 2017, 2018), as discussed in Section 1, could be a possible cause of the double-peaked solar cycle, although a detailed model is needed.

One strong supporter of our idea is that the fluctuations in the Babcock–Leighton process are identified in the observed polar field, as well as in the proxy of the polar field data (as discussed in Section 5). Recent independent studies (Cameron et al. 2013; Jiang et al. 2015; Mordvinov et al. 2016; Kitchatinov et al. 2018) also support the polar field fluctuations, and they have proposed that these fluctuations are the cause of the variation in the subsequent solar cycle. Another strong supporter is the fact that the double peaks are observed independently in two hemispheres and in any phase of the solar cycle. If the double peaks are caused by the fluctuations in the dynamo process, then they are expected to appear in any hemisphere, and, in fact, in any phase of the solar cycle. This is exactly observed in the Sun. Occasional spikes or dips observed in the rising or declining phases of the solar cycle are also caused by the same origin.

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