THE GRAND SOLAR MINIMA AND THE SOLAR DYNAMO

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Both the direct sunspot observations and the indirect solar activity proxies indicate the existences of the solar grand minima during which time the solar activities are greatly reduced. They are usually coincided with periods of lower-than-average global temperatures. The existences of the grand minima pose a challenge for the solar dynamo. The main features of the grand minima and the new dynamo models to explain their existences will be reviewed in the paper.

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1. Introduction

Before the era of Galileo Galilei and Xu Guangqi, people observed the sunspots mainly by the naked eyes. Sunspots were seen and discussed in China since antiquity. A Chinese oracle bone from about 3200 years has already the related records. Telescope were being purchased in Europe and used for astronomical purpose after 1610 and in China by the 1620s.¹ Galileo was the first to use the telescope to study the heavens systematically. During the summer months of 1612, Galileo made a series of sunspot observations. From which he concluded that the spots must be on the surface and are not spherical planets or moons passing before the sun. There also have other pioneers of sunspots observation, for example, Thomas Harriot, Christoph Scheiner, Johannes Fabricius and so on who recorded the sunspots.

In 1848, Rudolf Wolf, director of observatory at Bern and later at Zurich organized a number of European observatories to record spots on a regular basis and by a standard scheme, thus inaugurating an international effort which continues today. He also undertook a historical search and analysis of old data on the sun in the literature and in observatory archives. Thus we have the Wolf sunspot number or Zurich sunspot number today. Due to the low quality of Wolf sunspot number before 1850s, Hoyt and Schatten performed an extensive archive search and nearly doubled the amount of original information compared to the Wolf series. They produced a new series of sunspot called the group sunspot numbers in 1998.² This series include all available observations and cover the period since 1610.

2. Grand Solar Minima

Figure 1 is the time evolution of the monthly group sunspot number (red curve) and the monthly Wolf sunspot number (blue curve). There is a distinct feature that during the middle of 17th century to the beginning of 18th century, sunspots have almost completely vanished. This is famous Maunder minimum.³ During the end of 18th century and the beginning of 19th century, the sunspot numbers are also significantly weak. It is called Dalton minimum.

In addition to direct solar observations, there are also indirect proxies, which are used to study solar activity in the pre-telescopic era. The most common proxy of solar activity is formed by the data on cosmogenic radionuclides. Figure 2 (adopted from Usoskin (2008))⁴ gives the reconstructed sunspot numbers using ^{10}Be and ^{14}C since the year of 800. We may see that the phenomenon that solar activity is greatly reduced also exist in the early era. The one with center in 1470 and duration 160 years is called Spörer minimum. The one with center in 1305 and duration 70 years is called Wolf minimum and the earlier one concentrated in 1040 and persist 60 years is called Oort minimum.

Fig. 1. The time evolution of group sunspot number R_G (red curve) since 1610 and Wolf sunspot number R_Z (blue curve) since 1700.

Fig. 2. Five grand minima since the year of 800. The overlapped 10-year averaged sunspot number are adopted from Usoskin (2008).

The presence of grand minima in solar activity on the long-term scale has been mentioned numerously using the radioisotope ^{14}C data in tree rings. The grand minima identified in the reconstruction of the last 11000 years present the following features. Firstly, there are 27 grand minima in the last 11000 years. The cumulative duration of the grand minima is about 1900 years, indicating that the sun spends about 17% of its time in a quiet state. Secondly, the minima have two distinct types.⁵ One is short minima of duration 50 -80 years which is called Maunder-type. And the other is longer minima which is called Spörer-like minima. The thirdly one is that their occurrence is not a result of long-term cyclic variations, but is defined by stochastic or chaotic processes.

The Maunder minimum is a representative of grand minima in solar activity. There is some uncertainty in the definition of its duration. The formal duration is 1645-1715. It has following features. Firstly, transition from the normal high activity to the deep minimum was sudden without any apparent precursor. Secondly, recovery of sunspot activity from the deep minimum to normal activity was gradual, passing through a period of nearly-linear amplification of the 11-year cycle. A very important feature of sunspot activity during the Maunder minimum was its strong north-south asymmetry, as sunspots were only observed in the southern solar hemisphere during the end of the Maunder minimum.⁶ Moreover, there is a dominant 22-year periodicity in sunspot activity through out the Maunder minimum, with a subdominant 11-year cycle emerging towards the end of the Maunder minimum.⁷

The significance of the solar grand minima study at least has two aspects. Firstly, they are coincided with a period of lower-than-average global temperatures. Paintings can serve as a database for the pursuit of past climatic changes. During 17th century, large amount of painting described the ice-dominated world of that time. The second reason to study the solar grand minima is its importance to solar physics community. Its existence poses a challenge for the solar-dynamo theory. Now let us come to the second part which is about the dynamo.

3. Solar Dynamo

In 1955, Parker proposed that the sunspot cycle is produced by an oscillation between toroidal and poloidal components,⁸ just as we see an oscillation between kinetic and potential energies in a simple harmonic oscillator.⁹ The strong sunspot field presents the toroidal field and the weak and diffuse field outside the sunspots corresponds to the poloidal field. There is a common opinion that the differential rotation in the tachocline stretches the poloidal field to generate the strong toroidal field. Concerning the conversion of toroidal field to the poloidal field, it is far more problematic. There are three popular mechanisms. They are cyclonic turbulence, (M)HD instabilities or Babcock-Leighton mechanism.

All kinematic solar dynamo models have some basic ingredients in common.¹⁰ The first is the solar structural model including the location of the core-envelope interface. The second is the magnetic diffusivity. The third is about the velocity

profiles which include the differential rotation profile and the possible meridional flow.

The existence of quiescent epochs of strongly suppressed activity randomly interspersed within periods of normal cyclic activity is referred to intermittency. Much effort has already been invested in this field which can be classified into two types. The first way to trigger intermittency in a dynamo model is to let nonlinear dynamical effects, for example a reduction of the differential rotation and alpha-quenching. The second way to trigger intermittency is by the introducing of stochastic noise. In the following subsections, I shall give two current attempts to explain the grand minima.

3.1. Grand minima with flux transport dynamo

Choudhuri and Karak (2009)¹¹ and Karak (2010)¹² took the Babcock-Leighton type flux transport dynamo to explain the grand minimum from the dynamo. In the model, the conversion of the toroidal field to the poloidal field is by the decay of tilt active regions. The process of the Babcock-Leighton type flux transport dynamo can be described as following. (i) The strong toroidal field is produced by the stretching of the poloidal field by differential rotation in the tachocline. (ii) The toroidal field generated in the tachocline gives rise to active regions due to magnetic buoyancy and then the decay of tilted bipolar active regions produces the poloidal field by the Babcock-Leighton mechanism. (iii) The meridional circulation advects the poloidal field first to high latitudes and then down to the tachocline.

For axisymmetric magnetic fields, it can be represented as $\mathbf{B}(r, \theta, t) = B(r, \theta, t)\mathbf{e}_\phi + \nabla \times [A(r, \theta, t)\mathbf{e}_\phi]$, where B and A respectively correspond to the toroidal and poloidal components. Axisymmetric velocity includes the meridional flow and the differential rotation. Plugging these into the induction equation, we may obtain the evolution of poloidal and toroidal components of the magnetic field in the flux transport dynamo as

$$\frac{\partial A}{\partial t} + \frac{1}{r \sin \theta} (\mathbf{v} \cdot \nabla) (r \sin \theta A) = \eta_p \left(\nabla^2 - \frac{1}{r^2 \sin^2 \theta} \right) A + \alpha B, \quad (1)$$

$$\begin{aligned} \frac{\partial B}{\partial t} + \frac{1}{r} \left[\frac{\partial}{\partial r} (r v_r B) + \frac{\partial}{\partial \theta} (v_\theta B) \right] &= \eta_t \left(\nabla^2 - \frac{1}{r^2 \sin^2 \theta} \right) B \\ &+ r \sin \theta (\mathbf{B}_p \cdot \nabla) \Omega + \frac{1}{r} \frac{d\eta_t}{dr} \frac{\partial}{\partial r} (r B). \end{aligned} \quad (2)$$

The parameters which need to be specified are as follows. The first is differential rotation which is well provided by the helioseismology. The second one is the turbulent diffusivity. Its surface value may be estimated by the random walk of the super-granulation. It only weakly varies over the solar cycle. The third one is the poloidal field source parameter, i.e. alpha-term. Jiang *et al.* (2007)¹³ pointed

out that the poloidal field builds up during the declining phase of the cycle which introduces randomness in the solar cycle. The forth parameter is the meridional flow. Variability of the meridional flow has been detected during cycle 23. It acts as a clock to regulate the period of the solar cycle. Stronger meridional circulation gives a shorter period and vice versa.

Hence the main sources of irregularities or stochastic fluctuations in the flux transport dynamo are the fluctuations in Babcock-Leighton process of generating of poloidal field or the fluctuations in the meridional circulation.

Let's first see Choudhuri and Karak (2009)¹¹ which included the fluctuations of the poloidal field generation. The cumulative effect of fluctuations in the Babcock-Leighton process during the decaying phase of a cycle can be modeled by stopping the dynamo code at the end of a sunspot cycle and then multiplying the poloidal field function $\mathbf{A}$ by a factor γ . Two values of γ for the two hemispheres are used in order to model the hemispheric asymmetry. After stopping the code at a sunspot minimum and making these changes, they run the code for several cycles without any further interruption. Their results are remarkably similar to the observational butterfly diagram and the observational sunspot number plot mentioned earlier.

Karak (2010)¹² investigated the influence of the meridional flow on both cycle-to-cycle amplitude variation of the solar cycle and producing grand minima. They propose that at the beginning of the Maunder minimum, the amplitude of meridional flow dropped to a low value and then after a few years it increased again to the original value but at different rates in two hemispheres. The flow in northern hemisphere is increased at a slightly lower rate than that in the southern hemisphere. The features of the Maunder minima were remarkably reproduced in the model as well.

It seems that the grand minima have been well explained by the above two models. However, they have some possible problems. Let's first see the fluctuations in Babcock-Leighton process of poloidal field generation. Our recent study indicated that the generation of poloidal field has close relation with the latitudes and tilt angles of the active regions emerged during a cycle.¹⁴ For each active region, its latitude and tilt angle present scattering. But their cycle averaged values are anti-correlated with the cycle strength. Hence the generation of the poloidal field is not completely random.

The second one is the fluctuations in meridional flow. Cameron and Schüssler (2010)¹⁵ explain the cycle-related variations as the observed localized inflows into the active region belts. No variation of the overall meridional flow amplitude is required. Furthermore, we successfully obtain the polar field regular reversals without cycle variation of meridional flow using the surface flux transport model.¹⁶

3.2. Grand minima with surface flux transport model

Except the dynamo model, the surface flux transport model is another effective way to study the solar surface field evolution. The model describes the evolution

of magnetic flux on the solar surface, which emerges in form of bipolar magnetic regions. The radial component of the magnetic field is passively transported on the solar surface under the effect of differential rotation, meridional flow and surface diffusivity.

Wang and Sheeley (2003)¹⁷ and Mackay (2003)¹⁸ applied the surface flux transport model to study the solar surface field evolution in Maunder minimum. The former mentioned features of Maunder minimum are well recovered in Wang and Sheeley (2003). But they still achieved this by adjusting the meridional flow.

Recently, we used semi-synthetic records of emerging sunspot groups based on sunspot number data as input for a surface flux transport model to reconstruct the evolution of the large-scale solar magnetic field and the open heliospheric flux from the year 1700 onward, as shown in Figure 3.¹⁶ The results agree well with the available observational or empirically derived data and reconstructions. They were achieved without variation of meridional flow. This opens the possibility for us to study the magnetic field evolution during Maunder minimum.

Fig. 3. The reconstructed large-scale solar magnetic field (Panel (a): total flux; Panel (b): polar field) and the open heliospheric flux (Panel (c)) from the year 1700 onward.

4. Conclusion

Firstly, grand minima are typical phenomena in solar behavior. Secondly, the intermittency of solar behavior has been studied through the nonlinearities or stochastic fluctuations in the dynamo models. Thirdly, surface flux transport model has been adopted to study the field evolution during the grand minimum. Fourthly, the existence of grand minima still is a challenge for the solar dynamo theory

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