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Flux transport dynamo: From modelling irregularities to making predictions

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ABSTRACT

The flux transport dynamo, in which the poloidal magnetic field is generated by the Babcock–Leighton mechanism and the meridional circulation plays a crucial role, has emerged as an attractive model for the solar cycle. Based on theoretical calculations done with this model, we argue that the fluctuations in the Babcock–Leighton mechanism and the fluctuations in the meridional circulation are the most likely causes of the irregularities of the solar cycle. With our increased theoretical understanding of how these irregularities arise, it can be possible to predict a future solar cycle by feeding the appropriate observational data in a theoretical dynamo model.

1. Introduction

The flux transport dynamo model, which started being developed about a quarter century ago (Wang et al., 1991; Choudhuri et al., 1995; Durney, 1995), has emerged as an attractive theoretical model for the solar cycle. There are several modern reviews (Choudhuri, 2011, 2014; Charbonneau, 2014; Karak et al., 2014a) surveying the current status of the field. The present paper is not a comprehensive review, but is based on a talk in a Workshop at the International Space Science Institute (ISSI) highlighting the works done by the author and his coworkers. Readers are assumed to be familiar with the phenomenology of the solar cycle and the basic concepts of MHD (such as flux freezing and magnetic buoyancy). Readers not having this background are advised to look at the earlier reviews by the author (Choudhuri, 2011, 2014), which were written for wider readership.

The initial effort in this field of flux transport dynamo was directed towards developing periodic models to explain the various periodic aspects of the solar cycle. Once sufficiently sophisticated periodic models were available, the next question was whether these theoretical models can be used to understand how the irregularities of the solar cycle arise. There is also a related question: if we understand what causes the irregularities of the cycle, then will that enable us to predict future cycles?

We discuss the basic periodic model of the flux transport dynamo in the next Section. Then § 3 discusses the possible causes of the irregularities of the solar cycle. Afterwards in § 4 we address the question whether we are now in a position to predict future cycles. Finally, in § 5 we summarize the limitations of the 2D kinematic dynamo models and the recent efforts of going beyond such simple models.

2. The basic periodic model

One completely non-controversial aspect of solar dynamo models is the generation of the toroidal field from the poloidal field by differential rotation. Since differential rotation has now been mapped by helioseismology, this process can now be included in theoretical dynamo models quite realistically. The toroidal field is primarily produced in the tachocline at the bottom of the convection zone and rises from there due to magnetic buoyancy to create the sunspots. Although some authors have argued that the near-surface shear layer discovered by helioseismology can also be important for the generation of the toroidal field (Brandenburg, 2005), the general view is that magnetic buoyancy would limit the growth of magnetic field in this region of strong super-adiabatic gradient. To this generally accepted view that the toroidal field is primarily produced in the tachocline, the flux transport dynamo model adds the following assumptions.

- The generation of the poloidal field from the toroidal field takes place due to the Babcock–Leighton mechanism.
- The meridional circulation of the Sun plays a crucial role in the dynamo process.

We now comment on these two assumptions.

Bipolar sunspots on the solar surface appear with a tilt statistically increasing with latitude, in accordance with the so-called Joy's law. This tilt is produced by the Coriolis force acting on the rising flux tubes (D'Silva and Choudhuri, 1993). Babcock (1961) and Leighton (1964) suggested that the poloidal field of the Sun is produced from the decay of such tilted bipolar sunspot pairs. There is now enough evidence from observations of the solar surface that the poloidal field does get built up

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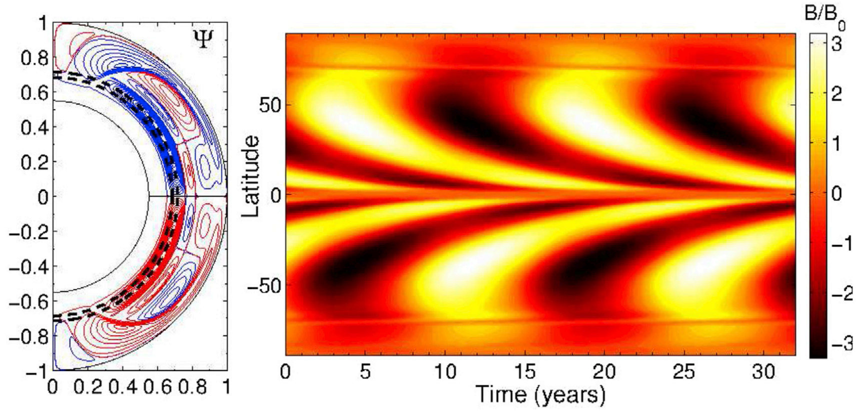

Fig. 1. A complicated meridional circulation used by Hazra et al. (2014a) in a dynamo calculation—red corresponding to streamlines of clockwise circulation and blue to anti-clockwise circulation. Note that the flow near the bottom at low latitudes is equatorward. The butterfly diagram obtained with this circulation is solar-like (sunspot activity drifting to lower latitudes with time). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in this way.

The meridional circulation is observed to be poleward at the solar surface and advects the poloidal field generated there, in conformity with observational data of surface magnetic fields. The material which is advected to the poles has to flow back equatorward through deeper layers within the solar convection zone. Since this circulation is driven by the turbulent stresses in the convection zone, we expect the meridional circulation not to penetrate much below the bottom of the convection zone, although a slight penetration helps in explaining several aspects of observational data (Nandy and Choudhuri, 2002; Chakraborty et al., 2009). The early models of the flux transport dynamo assumed the return flow of the meridional circulation to take place at the bottom of the convection zone, where the toroidal field generated by the differential rotation is advected equatorward with this flow, giving a natural explanation of the butterfly diagram representing the equatorward shift of the sunspot belt (Choudhuri et al., 1995). Such dynamo models have been remarkably successful in explaining many aspects of the observational data (Chatterjee et al., 2004).

While we still do not have unambiguous measurements of the return flow of the meridional circulation, some groups claim to have found evidence for the return flow well above the bottom of the convection zone (Hathaway, 2012; Zhao et al., 2013; Schad et al., 2013). However, Rajaguru and Antia (2015) argue that the available helioseismology data still cannot rule out a one-cell meridional circulation spanning the whole of the convection zone in each hemisphere. Hazra et al. (2014a) showed that, even with a meridional circulation much more complicated than the one-cell pattern assumed in the earlier flux transport dynamo papers, it is still possible to match the relevant observational data as long as there is an equatorward flow at the bottom of the convection zone (see Fig. 1).

3. The origin of the irregularities of the solar cycle

The earliest attempts of explaining irregularities of the solar cycle were by regarding them as nonlinear chaos arising out of the nonlinearities of the dynamo equations (Weiss et al., 1984). Charbonneau et al. (2007) argued that the Gnevyshev-Ohl rule in solar cycles (i.e. the tendency of alternate cycles to lie above and below the running mean of cycle amplitudes) arises out of period doubling due to nonlinearities. However, the simplest kinds of nonlinearities expected in dynamo equations tend to make the cycles more stable rather than producing irregularities and it has been suggested that stochastic fluctuations are more likely to be the primary reason behind producing irregularities (Choudhuri, 1992).

The Babcock–Leighton mechanism for the generation of the poloidal field depends on the tilts of bipolar sunspots. While the average tilt is given by Joy's law, we see considerable scatter around this average tilt, presumably caused by the action of turbulence in the convection zone on the rising flux tubes (Longcope and Choudhuri, 2002). This scatter in the tilt angles is expected to introduce fluctuations in the Babcock–Leighton mechanism (Choudhuri et al., 2007). By including this fluctuation in the dynamo models, it is possible to explain many aspects of the irregularities of the cycles including the grand minima (Choudhuri and Karak, 2009).

One other source of irregularities is the fluctuations in the meridional circulation. A faster meridional circulation will make the solar cycles shorter and vice versa. While we have actual data of meridional circulation variations for not more than a couple of decades, we have data for durations of solar cycles for more than a century, providing indications that the meridional circulation had fluctuations in the past with correlation times of the order of 30–40 years (Karak and Choudhuri, 2011). When the meridional circulation is slow and the cycles longer, diffusion has more time to act on the magnetic fields, making the cycles weaker. On such ground, we expect longer cycles to be weaker and shorter cycles to be stronger, leading to what is called the Waldmeier effect (Karak and Choudhuri, 2011). Also, when the meridional circulation is sufficiently weak, theoretical dynamo models show that even grand minima can be induced (Karak, 2010). To get these results, the correlation time of the meridional circulation fluctuations was taken to be considerably longer than the cycle period. If the correlation time is taken too short, then one may not get these results (Muñoz-Jaramillo et al., 2010). We also emphasize that the effect of diffusion in making longer cycles weaker is vital for getting these results. We need to take the value of diffusivity sufficiently high such that the diffusion time scale is shorter than or of the order of the cycle period. This is not the case in the model of Dikpati and Gilman (2006) in which diffusivity is very low. A longer cycle in such a low-diffusivity model tends to be stronger because differential rotation has time to generate more toroidal field during a cycle, giving the opposite of the Waldmeier effect. Differences between high- and low-diffusivity dynamos were studied by Yeates et al. (2008). Clearly the high-diffusivity model yields results more in conformity with observational data.

By analyzing the contents of C-14 in old tree trunks and Be-10 in polar ice cores, it has now been possible to reconstruct the history of solar activity over a few millenia (Usoskin, 2013). It has been estimated that there have been about 27 grand minima in the last 11,000 years (Usoskin et al., 2007). Since grand minima can be caused both by fluctuations in the Babcock-Leighton mechanism and fluctuations in the meridional circulation, a full theoretical model of grand minima should combine both types of fluctuations. If, at the beginning of a cycle, the poloidal field is too weak due to the fluctuations in the Babcock–Leighton mechanism or the meridional circulation is too weak, then the Sun may be forced into a grand minimum. Assuming a Gaussian distribution for fluctuations in both the Babcock–Leighton mechanism and the meridional circulation,