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State-of-the-art of kinematic modeling the solar cycle

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Abstract. The kinematic modeling of the solar convection zone remains the workhorse of the solar dynamo to understand the solar cycle. During the past several years, the major progress in understanding the solar cycle using kinematic models is as follows. (1). The Babcock-Leighton (BL) mechanism was confirmed to be at the essence of the solar cycle. (2). The scatter of sunspot tilt angles is identified as a major cause of solar cycle irregularities. (3). The important roles of the magnetic pumping in the dynamo process are recognized. (4). Some 3D kinematic BL type dynamo models have been developed. As a key part of the solar dynamo loop, the surface observable part of the BL mechanism makes the physics-based solar cycle prediction feasible. Including the effects of the tilt scatter on the polar field generation, the possible strength of the subsequent cycle can be predicted when a cycle starts for a few years.

Keywords. Sun: activity, Sun: evolution, Sun: magnetic fields, (Sun:) sunspots

1. Introduction

It is widely accepted that the solar cycle is produced by a dynamo process, which is based on the nonlinear interaction between the velocity field and the magnetic field of the solar plasma. This nonlinear interaction is mathematically described by the well-known magnetohydrodynamical (MHD) equations. Global MHD simulation of the solar convection zone is the most direct way to deal with the solar dynamo problem. Simulations of convection-driven dynamos have recently reached a level of sophistication, which can be demonstrated by Hotta *et al.* (2016), Strugarek *et al.* (2017), Kapyla *et al.* (2017), Brun *et al.* (2017) etc. The simulations reproduce some of the observed features in the Sun, such as equatorward migration of activity belts and irregular cycle variations. Solar-like differential rotation was also presented within a narrow parameter regime (Usually simulations, e.g. Karak *et al.* (2015), tend to produce anti-solar differential rotation. Karak *et al.* (2018) also show that global convection simulations produce much larger convective power at large scales in comparison to observations.). In practice, due to wide separation of spatial and temporal scale characterizing solar convection, the variability seen in the simulations is not directly relatable to that of the Sun. On the other hand, helioseismology gives relatively reliable measurements of the large-scale field. The cycle-related changes in the differential rotation, i.e., the torsional oscillation, is quiet weak (in few m/s, Zhao *et al.* 2016). This validates the kinematic modeling of the solar cycle, in which the velocity field is given and the effects of the magnetic field on flow fields are ignored.

This kinematic regime remained the workhorse of solar dynamo modelling during the past decade. Babcock-Leighton (BL) type dynamos have emerged as a most promising one among the kinematic models. The review will concentrate on the recent progress in modeling the solar cycle and some open questions under the framework of BL-type dynamos.

2. Recent progress in kinematic modeling the solar cycle

Evidences for the BL-type dynamo: Solar dynamo models are the BL types if the poloidal field generation is caused by the BL mechanism, which includes two processes. One is the emergence of the toroidal field through the convection zone to form the sunspot groups with certain tilt angles. The other is the evolution of the tilted sunspot groups over the solar surface. The meridional circulation does not have to play the dominated roles in generating the solar cycle properties, like the equatorward propagation of the toroidal field, cycle period and so on. This property distinguishes BL type dynamos from the typical flux transport dynamos initiated by Wang *et al.* (1991), Choudhuri *et al.* (1995) and the further developed models by several groups. In the typical flux transport dynamos, the meridional flow is responsible for the above features of the solar cycle.

There are two assumptions about the BL type of dynamos based on Babcock (1961) and Leighton (1969). One is that the polar field is THE relevant poloidal field, which means that no more poloidal flux buried below the surface to be responsible for the observed toroidal flux emergence. The other is that the magnetic flux connected to the poles is stretched by the differential rotation for the toroidal field. Based on these two assumptions, we expect to find evidences for BL type dynamos if (1) there is a correlation between the polar field at cycle minimum and the subsequent cycle strength, and (2) Surface poloidal field provides enough flux for the net toroidal field. The good correlation between the polar field at cycle minimum and the subsequent cycle strength is now generally accepted by the community based on the direct observations and the proxy of the geomagnetic index. The deep cycle 23 minimum followed by the weakest cycle 24 during the past one century adds a strong evidence of it. Cameron & Schüssler (2015) determined the toroidal flux in a hemisphere by integrating over a meridional surface and applying Stokes' theorem. They found the net toroidal flux in a hemisphere produced by differential rotation is determined by the emerged magnetic flux at the surface. All of these indicate that the BL mechanism is at the essence of the solar cycle, which can significantly simplify our understanding of the solar cycle. The observed surface poloidal field determines the net torodial flux of the subsequent cycle.

Flux emergence as one end of the BL mechanism: In BL type dynamos, the flux emergence is a key ingredient of the dynamo loop. In contrast, the toroidal flux emergence to form sunspot groups is a byproduct of the dynamo in the traditional mean-field dynamos, in which the poloidal field is generated due to the kinetic helicity of the turbulence in the convection zone (Parker 1955). As traditional mean-field dynamos, the turbulence plays important roles in the emergence of the toroidal flux to get observed features of sunspot groups in BL type dynamo. Recent MHD simulations of the convection zone by Nelson *et al.* (2013) and Weber *et al.* (2011) indicate that the turbulent convection plays an intimate role in both the formation and the rise of the magnetic loops, which are generated through the coupled action of the rotational shear and the turbulent intermittency and rises through the coordinated action of magnetic buoyancy and convective transport. Rotating convection promotes the mean latitudes and tilts consistent with the observed one and helps to produce observed scatter both in the emerging latitudes and in the tilts.

One end of the BL mechanism, the toroidal flux emergence through the convection zone is a complex process. We have only limited knowledge about the details. The other end of the BL mechanism, i.e., the poloidal flux evolution over the surface, however, is observable. It can be simulated using Surface Flux Transport (SFT) models, the details of which can be found in a recent review by Jiang *et al.* (2014b), with well constrained parameters. The linear relation between the polar field at cycle minimum and the subsequent cycle strength can help us to circumvent the complex process of the flux emergence. Hence to understand the cycle variability, we may just understand the polar field variability using SFT models.

Surface Flux Transport as the other end of the BL mechanism: The latitudinal separations of the two polarities of BMRs, i.e., the tilt angles of BMR, play fundamental roles in the polar field generation. Since there is a strong random component of sunspot tilts as shown in Figure 1 of Jiang *et al.* (2014a), we used SFT simulations with a number of different realizations of the scatter to study the effect of the tilt angle scatter on the polar field based on observations. Figure 1 shows that the average axial dipole moment at the end of cycle 17 (a medium-amplitude cycle) from our simulations was 2.73 G. The tilt angle scatter, which was achieved by 50 random realizations obeying the Gaussian distribution with the standard deviation based on the observation, leads to an uncertainty of 0.78 G (standard deviation). In the framework of BL dynamo models, this study provided a measurement of the fluctuating source term of a BL type dynamo due to the scatter of the tilt angles of sunspot groups. The tilt angle scatter therefore constitutes a significant random factor in the cycle-to-cycle amplitude variability. The tilt scatter is also responsible for the weak polar fields during the cycle 23 minimum and thus the weakness of the present cycle 24 (Jiang *et al.* 2015). A number of bigger bipolar regions emerging at low latitudes with a wrong (i.e., opposite to the majority for this cycle) orientation of their magnetic polarities in the north-south direction, which impaired the growth of the polar field. The results based on SFT simulations are shown in right panel of Figure 1. Figure 2 shows a typical example of the special active region, i.e., AR10696. The emergence of such AR is random. Hence they provide constraints on the scope of the solar cycle prediction.

SFTM constraints on BL dynamo modeling: In SFT models there are two assumptions, which are the vertical field over the solar surface and no flux transported across the solar surface. The success of SFT models and the observations validate the assumptions, which provide the constraints on the BL dynamo near surface. The outer boundary condition of the dynamo equation should be vertical, rather than the potential field used by some models. The downward pumping in the near surface layer is required to inhibit the upward diffusion. Within these two constraints, Cameron *et al.* (2012) show that the BL type dynamo can generate the same poloidal field evolution as the one from SFT models. With these constraints, Jiang *et al.* (2013) assimilated the historical record (cycles 15-21) of sunspot groups into the BL dynamo model to derive the poloidal field source. The model reproduced the observed polar field and cycle amplitude variations. This also supports that the BL mechanism is at the essence of the solar cycle.

Cycle fluctuation modeling from SFT modeling to 3D BL type dynamos: The dominated roles of the stochastic effect due to the random features of the sunspot emergence lead to a revival of self-excited BL dynamo recently. Several groups developed BL dynamo models including the intrinsic randomness to understand the variability of the cycle. The representative studies are the 1D model developed by Cameron & Schüssler (2017a) and Cameron & Schüssler (2017b), 2D model by Olemskoy & Kitchatinov (2013a) and Olemskoy *et al.* (2013b), 2D BL dynamo with poloidal source term from 2D SFT model developed by Lemerle & Charbonneau (2017) and Nagy *et al.* (2017), and 3D model by Miesch & Dikpati (2014), Hazra *et al.* (2017) and Karak & Miesch (2017). In all cases, there is no other α-effect for the poloidal field source, except the BL mechanism. The randomness is due to the scatter of tilts about the mean. The models reproduce the characteristics of the variable solar activity on different timescales, including the occurrence and statistics of extended periods of grand minima and grand maxima.

Physics-based cycle prediction: For the dynamo chain, it is a linear predictable process from the poloidal to the toroidal field. From the toroidal field to the poloidal field, random properties of sunspot emergence, especially the tilt angle scatter, constrain the scope the cycle prediction. SFT simulations of the descending phase of Cycle 24 using random sources (emerging bipolar magnetic regions) with empirically determined scatter of their properties provide a prediction of the axial dipole moment during the upcoming activity minimum together with a realistic uncertainty range. Both Cameron *et al.* (2016) and Hathaway & Upton (2016) who did the predictions in this strategy show that Cycle 25 will be of moderate amplitude, not much higher than that of the current cycle. Jiang & Cao (2017) also investigate the possible evolution of the polar fields in two hemispheres during the decay phase of cycle 24 in detail using a similar method to Cameron *et al.* (2016).

3. Open questions and preliminary attempts

Is the tachocline essential for dynamos? Long-held paradigms of the buoyant toroidal magnetic flux tubes are that such tubes form in the tachocline where the strong rotational shear and subadiabatic stratification promote the generation and storage of strong toroidal flux systems. Recent study by Wright & Drake (2016) show that fully convective stars whose X-ray emission correlates with their rotation periods in the same way as in solar-type stars. The MHD simulations of flux emergence by Nelson *et al.* (2013) do not possess a tachocline as well. BL solar dynamo models developed by Kitchatinov *et al.* like Kitchatinov & Nepomnyashchikh (2017), always do not include the effects of the tacholine. The properties of solar cycle still can be well reproduced. All of these pose a possibility that the tachocline might not be an essential ingredient for the solar and stellar dynamo action.

Is the meridional flow essential for dynamos? In the BL dynamo, the spatially separated poloidal and toroidal field require flux transport mechanisms to connect them. It is why that it is sometime called as Flux Transport (FT) dynamos. More details about FT dynamos can be found in a recent review by Karak *et al.* (2014). In long-held paradigms of FT dynamos, the meridional flow plays essential roles. The equatorward return flow is responsible for the equatorward migration in the toroidal flux. The poleward meridional flow near the solar surface causes the poleward migration in the poloidal field. Furthermore, the meridional flow provides a link between the two spatially separated source regions, and hence it dominates the cycle period. Including the radial pumping into BL dynamos, the effect of the meridional flow on the cycle period is weaken significantly (Karak *et al.* 2016). Our preliminary attempt shows that a latitudinal dependent radial pumping can also generate the equatorward migration of the torodial field even the meridional flow has double-cell, with the poleward flow at the bottom (Jiang *et al.* in preparation). But the meridional flow is still a necessary ingredient of the BL dynamo, especially for the surface poloidal field evolution.

How to connect the magnetic flux emerging with BL dynamos? The rise of the toroidal magnetic field through the convection zone due to the magnetic buoyancy to produce bipolar sunspots is one part of the BL mechanism. This inherently complex 3D process usually is included in a 2D dynamo model only through rather crude approximation procedures. Choudhuri & Hazra (2016) gave a very nice review in current procedures of treating the magnetic buoyancy. Three dimensional kinematic models, in which the mean velocity fields are supposed to be axisymmetric and are specified, but the magnetic field is treated in a full 3D fashion were developed by Miesch & Dikpati (2014). Such kind of 3D models will be helpful in understanding the formation of tilted

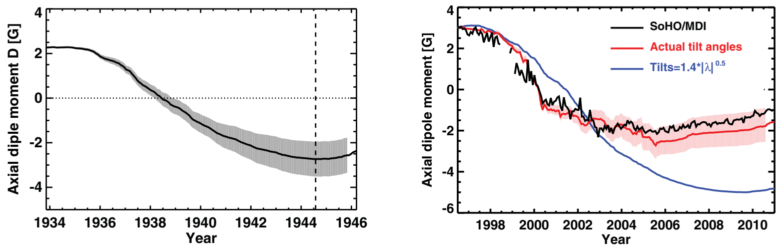

Figure 1. Left panel: Evolution of total axial dipole moment for simulations including random scatter of the tilt angles (obeying the Gaussian distribution with the standard deviation based on the observation, extracted from Jiang *et al.* 2014a). Solid curves show averages of 50 simulations with different sets of random numbers while gray shades indicate the corresponding standard deviations. Right panel: Time evolution of the solar axial dipole moment during cycle 23 (extracted from Jiang *et al.* 2015). The curves correspond, respectively, to observed SOHO/MDI magnetic maps (black), a simulation using the actual tilt angles of bipolar magnetic regions (red), and a simulation using tilt angles according to a fitted latitude dependence (blue).

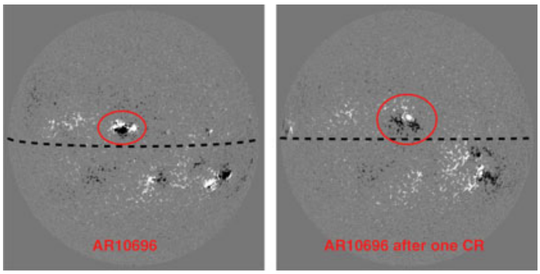

Figure 2. Example of a bipolar magnetic region that significantly weakened the axial dipole moment in the declining phase of cycle 23 (extracted from Jiang *et al.* 2015).

bipolar sunspots and the BL process more realistically. Yeates & Muñoz-Jaramillo (2013) suggest the first method of treating the buoyant rise of a flux tube in 3D BL-dynamo model by including perturbation velocity in 3 components. The next important step in BL dynamos is expected to include the magnetic flux emerging into BL dynamos in 3D realistically.

4. Conclusions

The solar cycle 24 is coming to the end. During the past decade people made good progress in understanding of the solar cycle using the kinematic models, especially in understanding of the variabilities of the solar cycle. Two major points can be concluded as follows. One is that BL mechanisms received a number of evidences, which indicate that it is at the essence of the solar cycle. The other is that the random features of sunspot emergence is an intrinsic stochastic mechanism of the BL dynamo. The solar cycle variability is well simulated by including scatter in the properties of the sunspot emergence into SFT models or 1D-3D BL dynamo models. But there are still some open questions on the interior dynamics, like the roles of the tachocline, the profile of meridional flow, the flux emergence, the nonlinearities and so on. The progress in helioseismogy, stellar magnetic field observations, and MHD simulations will promote the understanding of these open questions.

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References

Babcock, H. W. 1969, *ApJ*, 133, 572
Brun, A. S., Strugarek, A., Varela, J, *et al.* 2017, *ApJ*, 836, 192
Cameron, R. H., Schmitt, D., Jiang, J., & Işik, E. 2012, *A&A*, 542, 127
Cameron, R. H. & Schüssler, M. 2015, *Science*, 347, 1333
Cameron, R. H., Jiang, J., & Schüssler, M. 2016, *ApJL*, 823, L22
Cameron, R. H. & Schüssler, M. 2017a, *A&A*, 599, 52
Cameron, R. H. & Schüssler, M. 2017b, *ApJ*, 843, 111
Choudhuri, A. R., Schussler, M., & Dikpati, M. 1995, *A&A*, 303, L29
Choudhuri, A. R. & Hazra, G. 2016, *Advances in Space Research*, 58, 1560
Hathaway, D. H. & Upton, L. A. 2016, *Journal of Geophysical Research: Space Physics*, 121, 11
Hazra, G., Choudhuri, A. R., & Miesch, M. S. 2017, *ApJ*, 835, 1
Hotta, H., Rempel, M., & Yokoyama, T. 2016, *Science*, 351, 1427
Jiang, J., Cameron, R. H., Schmitt, D., & Işik, E. 2013, *A&A*, 553, 128
Jiang, J., Cameron, R. H., & Schüssler, M. 2014a, *ApJ*, 791, 5
Jiang, J., Hathaway, D. H., Cameron, R. H., Solanki, S. K., Gizon, L., & Upton, L. 2014b, *Space Science Reviews*, 186, 1
Jiang, J., Cameron, R. H., & Schüssler, M. 2015, *ApJL*, 808, L28
Jiang, J. & Cao, J. 2017, *Journal of Atmospheric and Solar-Terrestrial Physics*, doi:10.1016/j.jastp.2017.06.019
Karak, B. B., Jiang, J., Miesch, M. S., Charbonneau, P., & Choudhuri, A. R. 2014, *Space Science Reviews*, 186, 1
Karak, B. B.,Käpylä, P. J., Käpylä, M. J., Brandenburg, A., Olspert, N., & Pelt, J. 2015, *A&A*, 576, A26
Karak, Bidya Binay, Cameron, R. 2016, *ApJ*, 832, 1
Karak, B. B. & Miesch, M. 2017, *ApJ*, 847, 1
Karak, B. B., Miesch, M., & Bekki, Y. 2018, *Physics of Fluids*, 30, 046602
Käpylä, P. J., Käpylä, M. J., Olspert, N., Warnecke, J., & Brandenburg, A. 2017, *A&A*, 30, 490
Kitchatinov, L. L. & Nepomnyashchikh, A. A. 2017, *Astronomy Letters*, 43, 5
Leighton, R. B. 1969, *ApJ*, 156, 1L
Lemerle, Alexandre, Charbonneau, P. 2017, *ApJ*, 834, 2
Miesch, Mark S. & Dikpati, M. 2014, *ApJL*, 785, 1
Nagy, M., Lemerle, A., Labonville, F., Petrovay, K., & Charbonneau, P. 2017, *Solar Physics*, 292, 11
Nelson, N. J., Brown, B. P., Brun, A. S., Miesch, M. S., & Toomre, J. 2013, *ApJ*, 762, 2
Olemskoy, S. V. & Kitchatinov, L. L. 2013a, *ApJ*, 777, 71
Olemskoy, S. V., Choudhuri, A. R., & Kitchatinov, L. L. 2013b, *Astronomy Reports*, 57, 458
Parker, E. N. 1955, *ApJ*, 122, 293
Strugarek, A., Beaudoin, P., Charbonneau, P., Brun, A. S., & do Nascimento, J.-D. 2017, *Science*, 357, 185
Wang, Y.-M., Sheeley, N. R., Jr., & Nash, A. G. 1991, *ApJ*, 383, 431
Weber, M. A., Fan, Y., & Miesch, M. S. 2011, *ApJ*, 741, 11
Wright, N. J. & Drake, J. J. 2016, *Nature*, 535, 7613
Yeates, A. R. & Muñoz-Jaramillo, A. 2013, *Monthly Notices of the Royal Astronomical Society*, 436, 4
Zhao, J. 2016, *Advances in Space Research*, 58, 8

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