First Asia-Pacific Solar Physics Meeting
ASI Conference Series, 2011, Vol. 2, pp 131–136
Edited by Arnab Rai Choudhuri & Dipankar Banerjee

Back-reactions of dynamo-generated magnetic fields: torsional oscillations and variations in meridional circulation

Arnab Rai Choudhuri*
Department of Physics, Indian Institute of Science, Bangalore 560012, India

Abstract. The periodically varying Lorentz force of the periodic solar magnetic field generated by the solar dynamo can induce two kinds of motions: torsional oscillations and periodic variations in the meridional circulation. Observational evidence now exists for both these kinds of motions. We discuss our ongoing effort in theoretically studying the variations of the meridional circulation. Then we present our theoretical model of torsional oscillations, which addresses the question why these oscillations start before sunspot cycles at latitudes higher than where sunspots are seen.

Keywords : Sun: magnetic topology – Sun: dynamo – Sun: activity

1. Introduction

The solar cycle is associated with a periodically varying magnetic field produced by the solar dynamo. This periodically varying magnetic field must give rise to a periodically varying Lorentz force. We consider the possible kinds of motions induced by this periodically varying Lorentz force.

To figure out the kinds of motions induced, we need to look at the Navier–Stokes equation with the periodically varying Lorentz force inserted in it. We can consider two kinds of motions separately: (i) the motions in the ϕ direction, and (ii) the motions in (r, θ) plane. It may be mentioned that the equation of continuity has to be satisfied along with the Navier–Stokes equation. The equation of continuity ensures that motions in r and θ directions are coupled together. So we cannot treat those two directions separately. However, motions in the ϕ direction can be treated separately.

*email: arnab@physics.iisc.ernet.in

The basic motion in the ϕ direction is the differential rotation, which can be modified by the periodically varying Lorentz force. Such a periodic variation of the differential rotation—known as *torsional oscillations*—has been known for about three decades since its discovery at the surface by Howard & LaBonte (1980). On the other hand, the basic motion in the (r, θ) plane is the meridional circulation and only recently evidence has started coming that there is a periodic variation of the meridional circulation with the solar cycle (Hathaway & Rightmire 2010). Soon after the discovery of torsional oscillations, some authors started exploring their theoretical implications (Yoshimura 1981; Schüssler 1981; Tuominen & Virtanen 1984). Due to the rapid developments in dynamo theory in the last few years, this subject needs revisiting.

We (Karak & Choudhuri) are working on a theoretical model of the variation of meridional circulation due to the Lorentz force. Some of the basic concerns are discussed in §2. Then in §3 we summarize our recent work on torsional oscillations (Chakraborty, Choudhuri & Chatterjee 2009a).

2. Variations of meridional circulation

The meridional circulation of the Sun plays a crucial role in the flux transport dynamo. However, its theory is still rather poorly understood. Helioseismology provides some information about the meridional circulation in the upper layers of the convection zone (Giles et al. 1997; Braun & Fan 1998; Gonzalez Hermandez et al. 2006; Svanda, Kosovichev & Zhao 2007). But there is no reliable observational data available yet on the nature of the meridional circulation at the bottom of the convection zone, which is crucial for the dynamo (Nandy & Choudhuri 2002).

The classic investigation by Kitchatinov & Rüdiger (1995) showed that the meridional circulation arises out of a slight imbalance between two large terms, requiring a pole-equator temperature difference of about 5°. A consequence of this is that even small fluctuations in any of these large terms may cause significant variations in meridional circulation. On the basis of indirect evidence, Karak (2010) concluded that there have been large variations in meridional circulation in the last few centuries. The variations in meridional circulation also seem to be the main reason behind the well-known Waldmeier effect of solar cycles (Karak & Choudhuri 2011a).

Apart from these random variations of meridional circulation, we expect some systematic periodic variations with the solar cycle. Only recently Hathaway & Rightmire (2010) and Basu & Antia (2010) have presented evidence for this. It appears that the meridional circulation near the surface becomes somewhat weaker at the time of the sunspot maximum. We expect a strong toroidal field at the bottom of the convection zone at the time of the sunspot maximum. Such a toroidal field has a Lorentz force directed towards the rotation axis and has a tendency of slipping poleward (van Ballegooijen & Choudhuri 1988). This poleward slipping tendency will oppose the equatorward meridional circulation at the bottom of the convection zone. We (Karak

& Choudhuri) are now carrying out a detailed calculation to investigate whether the surface observations of the reduction of meridional circulation at the time of sunspot maximum can be explained as arising out of this opposition to meridional circulation due to the poleward slip tendency of the strong toroidal field at the bottom of the convection zone.

It may be mentioned that Nandy, Muñoz-Jaramillo & Martens (2011) have assumed in a recent work that the meridional circulation changes randomly at every solar maximum. We disagree with this assumption and believe that the meridional circulation decreases at the solar maximum due to the Lorentz force of the magnetic fields in a systematic deterministic way. If the Lorentz force quenches the meridional circulation at the time of the solar maximum, one important question is whether this will have any effect on the dynamo. Recently Karak & Choudhuri (2011b) performed a dynamo simulation by assuming that the amplitude of the meridional circulation is quenched according to the equation

$$v_0 = v_0'/[1 + (\overline{B}/B_0)^2], \tag{1}$$

where $\overline{B}$ is the average value of the toroidal field at the bottom of the convection zone. If the value of the turbulent diffusivity is assumed to be sufficiently small ($\eta \sim 10^{10}$–10^{11} cm^2 s^{-1}), then the dynamo becomes unstable on including such a quenching of the meridional circulation. The dynamo remains stable only if the turbulent diffusivity is in the range $\eta \sim 10^{12}$–10^{13} cm^2 s^{-1}. This provides another argument in favour of a high-diffusivity dynamo, strengthening a case already made by several authors (Jiang, Chatterjee & Choudhuri 2007; Goel & Choudhuri 2009; Hotta & Yokoyama 2010; Karak 2010).

3. Torsional oscillations

The small periodic variation in the Sun's rotation with the sunspot cycle, first discovered on the solar surface by Howard & LaBonte (1980), is called torsional oscillations. Helioseismology has now established its existence throughout the convection zone (see Howe et al. 2005 and references therein). Its amplitude near the surface is of order 5 m s^{-1} or about 1% of the angular velocity. Apart from the equatorward-propagating branch which moves with the sunspot belt, there is also a poleward-propagating branch at high latitudes. One intriguing aspect of the equatorward-propagating branch is that it begins a couple of years before the sunspots of a particular cycle appear and at a latitude higher than where the first sunspots are seen. The top panel of Fig. 1 shows the torsional oscillations at the solar surface with the butterfly diagram of sunspots. If the torsional oscillation is caused by the Lorentz force of the dynamo-generated magnetic field as generally believed, then the early initiation of this oscillation at a higher latitude does look like a violation of causality! The main aim of our recent work (Chakraborty, Choudhuri & Chatterjee 2009a, 2009b) has been to explain this which could not be explained by the earlier theoretical models (Durney 2000; Covas et al. 2000; Bushby 2006; Rempel 2006).

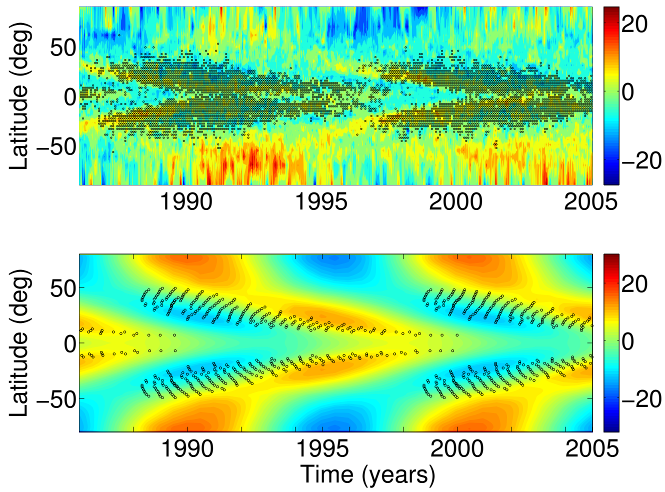

Figure 1. The time-latitude plot of torsional oscillations on the solar surface with the butterfly diagram of sunspots superposed on it. The upper panel is based on observational data of surface velocity v_ϕ measured at Mount Wilson Observatory (courtesy: Roger Ulrich). The bottom panel is from our theoretical simulation.

Our calculations are based on the dynamo model presented by Chatterjee, Nandy & Choudhuri (2004). In order to model torsional oscillations, in addition to the basic equations of the dynamo, we simultaneously have to solve the ϕ component of the Navier–Stokes equation in the form

$$\rho \left\{ \frac{\partial v_\phi}{\partial t} + D_v[v_\phi] \right\} = D_\nu[v_\phi] + (\mathbf{F}_L)_\phi, \tag{2}$$

where $D_v[v_\phi]$ is the term corresponding to advection by the meridional circulation, $D_\nu[v_\phi]$ is the diffusion term, and $(\mathbf{F}_L)_\phi$ is the ϕ component of the Lorentz force. If the magnetic field is assumed to have the standard form

$$\mathbf{B} = B(r, \theta, t)\mathbf{e}_\phi + \nabla \times [A(r, \theta, t)\mathbf{e}_\phi], \tag{3}$$

then the Lorentz force is given by the Jacobian

$$4\pi(\mathbf{F}_L)_\phi = \frac{1}{s^3} J \left(\frac{sB_\phi, sA}{r, \theta} \right), \tag{4}$$

where $s = r \sin\theta$. On the basis of flux tube simulations suggesting that the magnetic field in the tachocline should be of order 10^5 G (Choudhuri & Gilman 1987; Choudhuri 1989; D'Silva & Choudhuri 1993), it is argued by Choudhuri (2003) that the magnetic field has to be intermittent in the tachocline. Hence the full expression of the Lorentz force involves a filling factor as explained by Chakraborty, Choudhuri & Chatterjee (2009a).

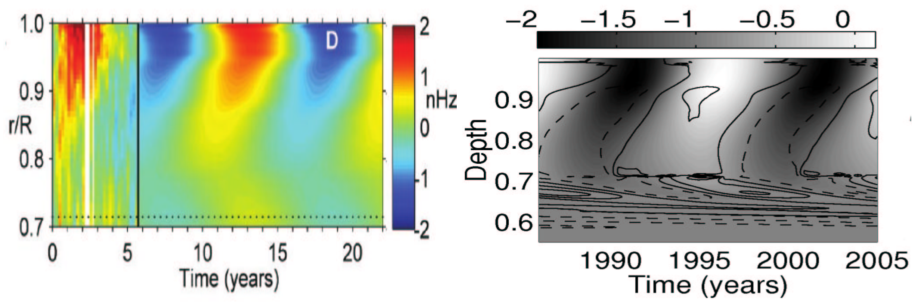

Figure 2. The depth-time plot of torsional oscillations at latitude 20°. The left panel from Vorontsov et al. (2002) is based on SOHO observations, whereas the right panel from Chakraborty, Choudhuri & Chatterjee (2009b) is based on our theoretical simulation. The solid and dashed lines in the right panel indicate the Lorentz force (positive and negative values respectively).

Our theoretical model incorporates a hypothesis proposed by Nandy & Choudhuri (2002), which is essential for explaining the early initiation of the torsional oscillation at high latitudes. According to this Nandy–Choudhuri (NC) hypothesis, the meridional flow penetrates into the stable layers below the convection zone at high latitudes. This causes the formation of toroidal field in the high-latitude tachocline. Sunspots form a few years later when this field is advected to lower latitudes and brought inside the convection zone. We also assume that the stress of the magnetic field formed in the tachocline is carried upward by Alfvén waves propagating along vertical flux concentrations conjectured by Choudhuri (2003).

The incorporation of the NC hypothesis in our theoretical model causes magnetic stresses to build up at higher latitudes before sunspots of the cycle appear, leading to the early initiation of torsional oscillations. The bottom panel of Fig. 1 shows theoretical results of torsional oscillations at the surface with the theoretical butterfly diagram. This bottom panel can be compared with the observational upper panel in Fig. 1. Our theoretical model also gives a satisfactory account of the evolution of torsional oscillations within the convection zone. The depth-time plot of torsional oscillations at a certain latitude given in Fig. 3 of Chakraborty, Choudhuri & Chatterjee (2009b) compares favourably with the observational plot given in Fig. 3(D) of Vorontsov et al. (2002). This is reproduced here in Fig. 2 for completeness. We end by pointing out that our theoretical model of torsional oscillations attempts to explain various aspects of observational data in much greater detail than what had been attempted in previous theoretical models.

References

Basu S., Antia H. M., 2010, ApJ, 717, 488
Braun D. C., Fan Y., 1998, ApJ, 508, L105

Bushby P. J., 2006, MNRAS, 371, 772
Chakraborty S., Choudhuri A. R., Chatterjee P., 2009a, PRL, 102, 041102
Chakraborty S., Choudhuri A. R., Chatterjee P., 2009b, PRL, 103, 099902
Chatterjee P., Nandy D., Choudhuri A. R., 2004, A&A, 427, 1019
Choudhuri A. R., 1989, Solar Phys., 123, 217
Choudhuri A. R., 2003, Solar Phys., 215, 31
Choudhuri A. R., Gilman, P. A., 1987, ApJ, 316, 788
Covas E., Tavakol R., Moss D., Tworkowski, A., 2000, A&A, 360, L21
D'Silva S., Choudhuri A. R., 1993, A&A, 272, 621
Durney B. R., 2000, Solar Phys., 196, 1
Giles P. M., Duvall T. L., Scherrer P. H., Bogart R. S., 1997, Nature, 390, 52
Goel A., Choudhuri A. R., 2009, RAA, 9, 115
Gonzalez Hernandez I., et al., 2006, ApJ, 638, 576
Hathaway D. H., Rightmire L., 2010, Science, 327, 1350
Hotta H., Yokoyama T., 2010, ApJ, 709, 1009
Howard R., LaBonte B. J., 1980, ApJ, 239, L33
Howe R., et al., 2005, ApJ, 634, 1405
Jiang J., Chatterjee P., Choudhuri A. R., 2007, MNRAS, 381, 1527
Karak B. B., 2010, ApJ, 724, 1021
Karak B. B., Choudhuri A. R., 2011a, MNRAS, 410, 1503
Karak B. B., Choudhuri A. R., 2011b, Solar Phys., submitted
Kitchatinov L. L., Rüdiger, G., 1995, A&A, 299, 446
Nandy D., Choudhuri A. R., 2002, Science, 296, 1671
Nandy D., Muñoz-Jaramillo A., Martens, P. C. H., 2011, Nature, 471, 80
Rempel M., 2006, ApJ, 647, 662
Schüssler M., 1981, A&A, 94, L17
Svanda M., Kosovichev A. G., Zhao J., 2007, ApJ, 680, L161
Tuominen I., Virtanen H., 1984, AN, 305, 225
van Ballegooijen A. A., Choudhuri A. R., 1988, ApJ, 333, 965
Vorontsov S. V., et al., 2002, Science, 296, 101
Yoshimura H., 1981, ApJ 247, 1102