Effects of Double-Cell Meridional Circulation on the Solar Dynamo and Activity Cycles

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Motivation. Multi-cellular MC: relevance for the Sun



Observational proxy	Uni-cellular	Multi-cellular
Mitra-Kraev & Thompson 2007; Hathaway 2012; Zhao 2012	-	+(2)
Komm et al 2005; Schad et a 2012	+	-
Theoretical arguments Mean-field models, Kitchatinov 2012,	+	-
Numerical simulations: Miesch et al 2006, Käpylä et al 2012, Guererro et al 2013	-	+

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 Increasing number of cells in horizontal direction results to decrease the scale of B-field in this direction.

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- Increasing number of cells in horizontal direction results to decrease the scale of B-field in this direction.
- Keeping direction of the flow at the bottom and the top we can imagine that:
 - Odd number of circulation cells in radius is physically equivalent to one-cell pattern+ vertical diffusion
 - Even number of circulation cells in radius is equivalent to double-cell pattern+ vertical diffusion

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Mean field solar dynamo model

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \boldsymbol{\mathcal{E}} \right),$$

Mean flow : differential rotation, \overline{U} , by Howe et al (2008), and meridional circulation (analytic profile) Mean electromotive force $\mathcal{E} = \overline{\mathbf{u} \times \mathbf{b}}$ (Pipin 2008;Pipin&Kosovichev 2013):

$$\begin{aligned} \boldsymbol{\mathcal{E}} &= \hat{\boldsymbol{\alpha}} \circ \overline{\mathbf{B}} + \hat{\boldsymbol{\delta}} \circ \boldsymbol{\Omega} \times \boldsymbol{\nabla} \times \overline{B} + \mathbf{V}^{p} \times \overline{\mathbf{B}} \\ &- \eta_{T} \boldsymbol{\nabla} \times \overline{B} - \eta_{T}^{(\mathcal{A}\Omega)} \frac{\boldsymbol{\Omega}}{\Omega^{2}} \left(\boldsymbol{\Omega} \cdot \nabla \right) \times \overline{\mathbf{B}} - \eta_{T}^{(\mathcal{A})} \left\{ \boldsymbol{\nabla} - \mathbf{g} \left(\mathbf{g} \cdot \nabla \right) \right\} \times \overline{\mathbf{B}} \end{aligned}$$

Non-linear α -effect $\alpha_{ij} = \psi_{\alpha}(B) C_{\alpha} \sin^2 \theta \alpha_{ij}^{(H)}(\Omega) + C_{ij}^{(\chi)}(\Omega) \overline{\chi}$, magnetic helicity conservation, $\overline{\chi} = \overline{\mathbf{a} \cdot \mathbf{b}}$, (Blackman & Field 2001; Hubbard & Brandenburg 2012; Pipin et al 2013):

$$\frac{d}{dt}\int\left\{\overline{\chi}+\overline{\mathbf{A}}\cdot\overline{\mathbf{B}}\right\}dV = -\eta_m\int\left\{\overline{\mathbf{B}}\cdot\overline{\mathbf{J}}+\overline{\mathbf{b}}\cdot\overline{\mathbf{j}}\right\}dV - \int\nabla\cdot\mathcal{F}^{\chi}dV$$

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Internal parameters



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No circulation



Triple- cell MC? Does it work similar to one-cell MC?

Scenario:

- ► The new activity started at the bottom, at $\sim 60^{\circ}$. The poloidal magnetic field (contour lines) is generated by the α and $\Omega \times J$ effects in the whole CZ.
- Most part of toroidal field circulates in following to the bottom cell (cf BL-models!) and the poloidal field follows the top cell where the turbulent generation has maximum.

Latitudinal drift of the maximum of the toroidal magnetic field flux



- Near the surface the activity higher ~ 5° then results from observations and the model without circulation shows the exponential drift.
- ► In the middle of the CZ the model with 12m/s gives the best fit => < => = <>

Amplitude of toroidal field, axial dipole, and period



- Strength of the toroidal field and the cycle period decrease when the circulation speed increases. There is a plateau 7 - 14m/s
- Strength of the axial dipole increase within the plateau
 - May be a resonance between the turbulent generation and the convergent meridional flows in the middle of CZ?

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Synchronization of sunspot and polar activity



- Qualitatively same relations for the model with and without circulation. The maxima of the polar magnetic field and the axial dipole correspond to the minima of the sunspot number and vice-versa.
- In the case of ideal synchronization the two subsequent cycles would produce the parabolic curve in the phase diagrams. It is also found for the Cycles 21 and 22.
- Cycle 23 had a smaller magnitude, and started with the polar magnetic field of about 1 G in the minimum as the previous two cycles. The question is why it did not reach levels of two previous cycles?

The basic dynamo modes:

Krause & Raedler (1980)



Parity braking: Brandenburg et al (1989), Knobloch et al(1998)

In relation to Grand Minima: Sokoloff & Nesme-Ribes (1994), Tobias (1997), Pipin (1999)

Some evidences were presented in poster by Andrés Muños-Jaramillo

Conclusions

- With the subsurface rotational shear layer, the mean-field distributed-dynamo model explains the butterfly diagram as a Parker-Yoshimura dynamo wave.
- The meridional flows do not play a principal role, but still can affect the evolution of magnetic fields. In particular, the double-cell circulation improves the agreement with the observations.
- Double-cell circulation does not change synchronization between the activity of the toroidal field and polar field reversals.
- Remark: Polar field precursor works well in different types of dynamos, it does not matter if it is distributed-dynamo or the flux-transport dynamo (see also Pipin, Sokoloff & Usoskin 2012).