Is a Deep One Cell Meridional Circulation Essential for Flux Transport Solar Dynamo?

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Importance of Meridional circulation

Solar magnetic field generation is a periodic process.

- Considering differential rotation ($\Omega$) of sun and Babcock-Leighton ($\alpha$) mechanism regions are coupled by diffusion.

  In Northern Hemisphere:
  - $\alpha \frac{\partial \Omega}{\partial r} > 0 \Rightarrow$ Poleward Propagation.
  - $\alpha \frac{\partial \Omega}{\partial r} < 0 \Rightarrow$ Equatorward Propagation.

This is well known Parker–Yoshimura Sign rule. (*Parker*1955; *Yoshimura*1975)

For sun, in northern hemisphere $\alpha \frac{\partial \Omega}{\partial r} > 0 \Rightarrow$ Poleward Propagation $\Rightarrow$ Contradict observation $\Rightarrow$ Dynamo theory in difficulty.
Meridional circulation helps dynamo wave to overcome Parker-yoshimura sign rule & to propagate along equatorward direction.

It advects the poloidal field towards the pole.
Meridional circulation: Observation

- Poleward flow near the surface is well established and its speed $\sim 20$ m/s. (Hathaway 1996; Haber et al. 2002; Basu & Antia 2000)

- Use mass conservation principle to construct the full profile of the meridional circulation.

- Though there is no observational evidence supporting the return flow of meridional circulation at the base of the convection zone. 
  $\Rightarrow$ only uncertainty in the model.

Figure: Streamlines for one cell Meridional circulation used in FTDM
Recent Observational evidences

- Recently Hathaway (2012) tracked supergranules to claim an equatorward reverse flow at a depth of only 70 Mm. ⇒ Shallow meridional circulation.

- Zhao et al. (2013) found a double cell structure using helioseismic inversion method.

- Poleward flows from \((R_\odot - 0.91 R_\odot)\) and from \((0.82 R_\odot \text{–at least } 0.75 R_\odot)\). An equatorward return flow about \(0.09R_\odot\) thick in between.

- Schad et al. (2013) found complex spatial structure of multiple flow cells distributed in depth and latitude.

- Also found evidence of meridional flow reaches down to the base of the convection zone.

Figure: Credit-(Zhao et al. 2013)
Results from global simulations

- Global convection simulation also shows complicated multiple circulation, and sometimes time-varying. (Miesch et al. 2010; Käpylä et al. 2012; Featherstone et al. 2013; Warnecke et al. 2013)

- Red anti-clockwise, blue clockwise

- We can assume meridional circulation as a free parameter and choose various forms to study their effects on the dynamo.

From Miesch et al. (2010)

From Featherstone et al. (2013)
Previous Theoretical Works

- Guerrero & de Gouveia dal Pino (2008) used strong equatorward pumping to get solar like behaviour.

- Bonnano et al. (2006) used latitudinal distribution of cells.
- Solar like behaviour reproduced.

- Jouve & Brun (2007) used radially stacked two cells.
- Poleward propagation.
Shallow meridional circulation

We do calculation using shallow meridional circulation.

Poleward propagation found in accordance with Parker-Yoshimura sign rule. Solar like behaviour is not reproduced.
Two-cell circulation with continuity of flow between the cells also gives poleward propagation. Meridional circulation is poleward at the bottom.

Two-cell circulation with equatorward flow at the bottom gives solar-like butterfly diagram.
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Two-cell circulation with equatorward flow at the bottom gives solar-like butterfly diagram

But there is a discontinuity of flow.
Radially stacked three cells

If we want equatorward meridional circulation at the bottom with continuity of flow between cells, we need three cells.

Results:

- Solar like behaviour reproduced.
- Period of dynamo depends on the velocity of the lower cell only. \( T \sim v_l^{-0.72} \)

Complicated cells

We have carried out simulation taking multi-cell meridional circulation also.

Blue–Anticlockwise
Red – clockwise

- Solar like behaviour reproduced as long as there is an equatorward flow at the bottom of the convection zone
Conclusions

- An equatorward meridional flow at the bottom of the convection zone is necessary for dynamo wave to propagate towards equatorward direction.

- If there is a return flow at the shallow depth with no flows underneath and if there is poleward flow at the bottom of the convection zone FTDM will not work.

- As long as the equatorward flow is there FTDM works and we get solar like behaviour.

- Period of dynamo is mostly determined by the velocity of the flow at the lower most cell.
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Thank You