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

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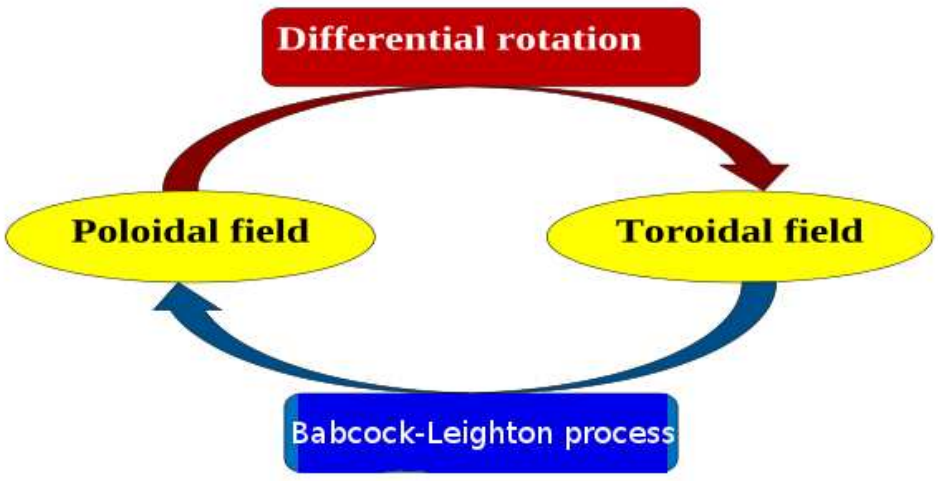
Importance of Meridional circulation

Solar magnetic field generation is a periodic process.



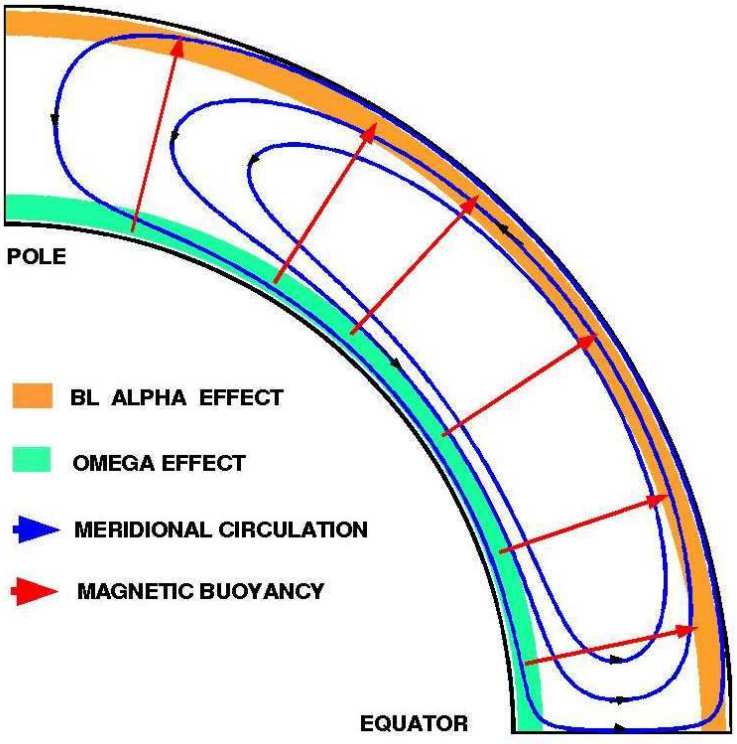
- Considering differential rotation(Ω) of sun and Babcock-Leighton(α) mechanism regions are coupled by diffusion

  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.

(Choudhuri, Schüssler & Dikpati 1995; Durney 1995)



- 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.

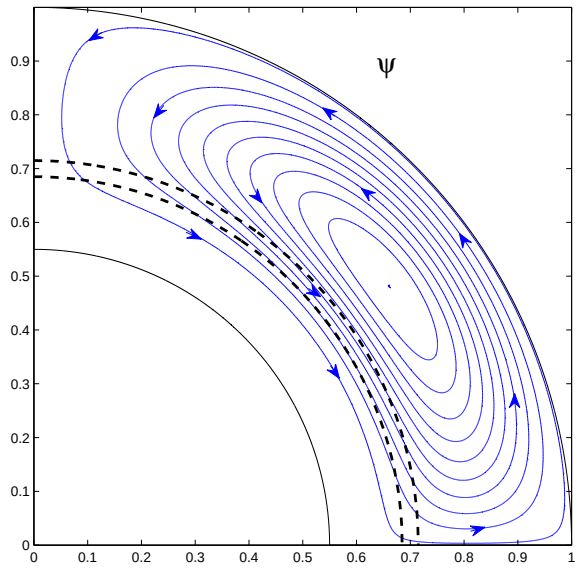


Figure: Streamlines for one cell Meridional circulation used in FTDM

Recent Observational evidences

- Recently *Hathaway*(2012) tracked supergranules to claim an equatorward reverse flow at a depth of only 70 Mm.
  $\Rightarrow$ 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 $R_\odot$ –at least 0.75 $R_\odot$).
  An equatorward return flow about 0.09$R_\odot$ thick in between.

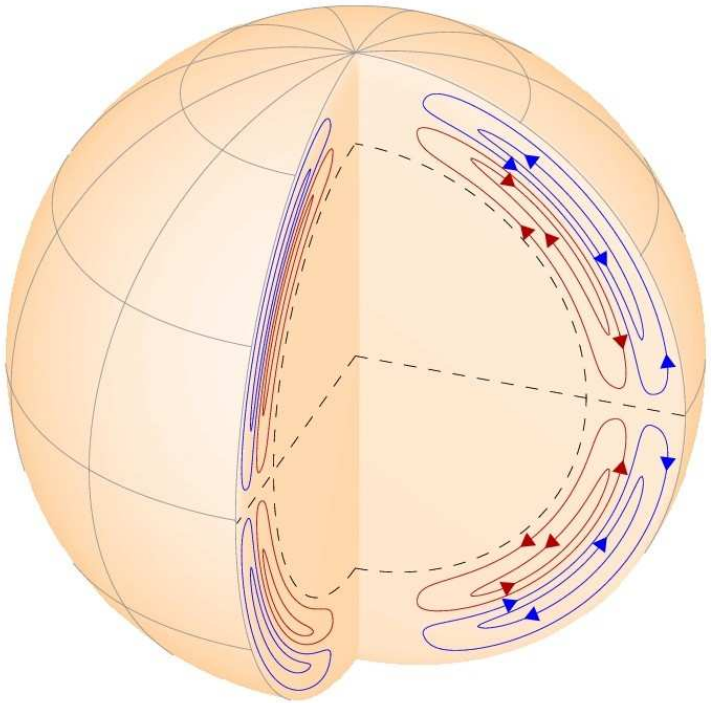


Figure: Credit-(Zhao et al. 2013)

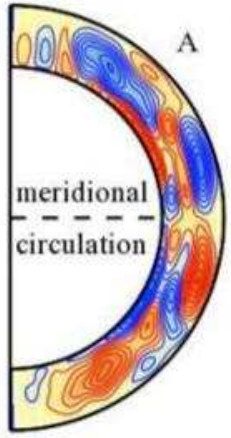
- Schad et al. (2013) found complex spatial structure of multiple flow cells distributed in depth and latitude.

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

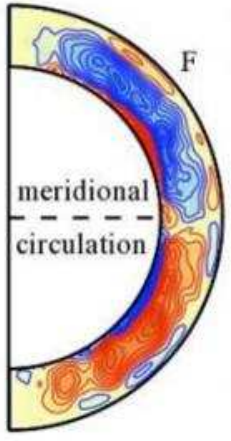
Results from global simulations

From Miesch et al. (2010)

- 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)



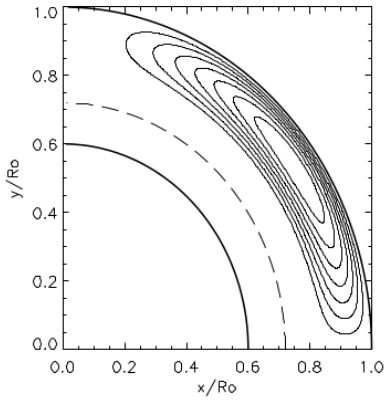
- Red anti-clockwise,
  blue clockwise

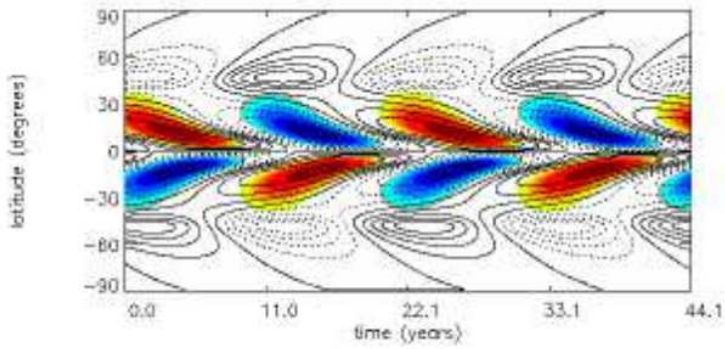


- **We can assume meridional circulation as a free parameter and choose various forms to study their effects on the dynamo.**

From Featherstone et al. (2013)

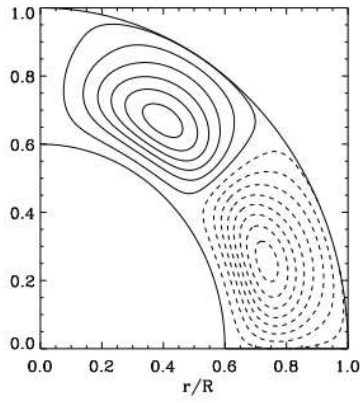
Previous Theoretical Works

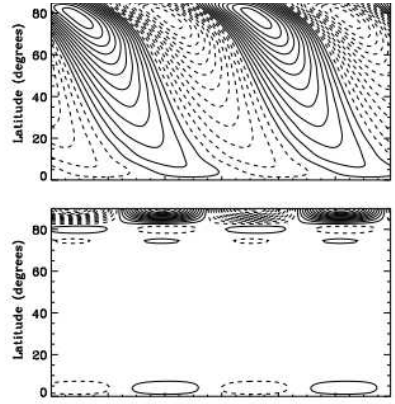


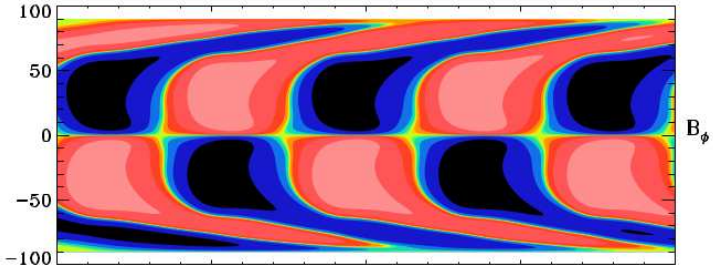


- Guerrero & de Gouveia dal Pino (2008) used strong equatorward pumping to get solar like behaviour

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



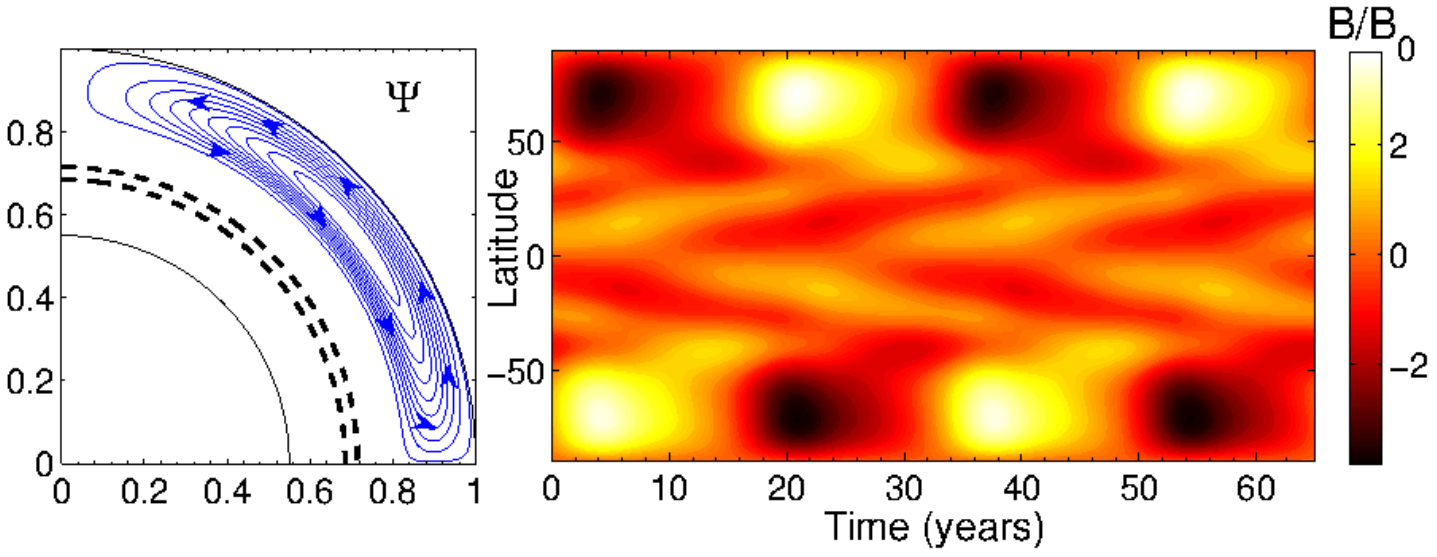




- Jouve & Brun (2007) used radially stacked two cells.
- Poleward propagation.

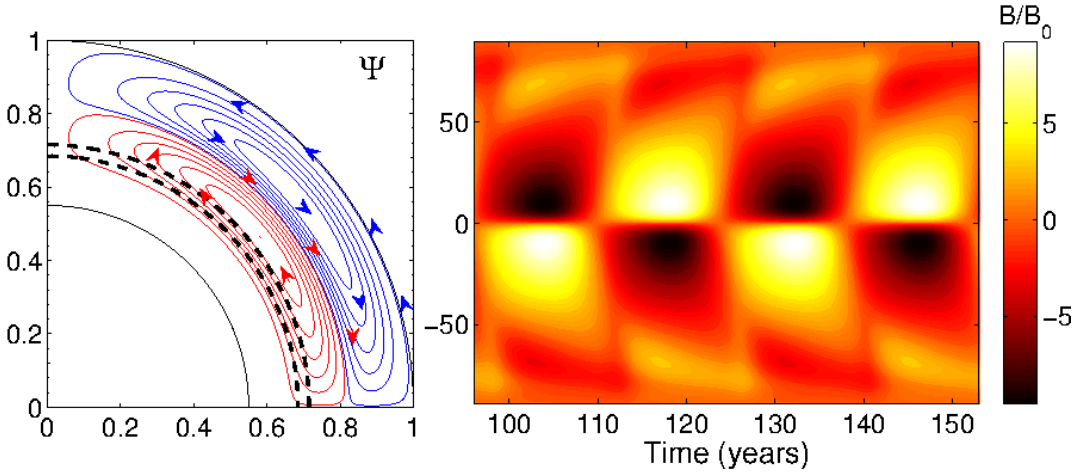
Shallow meridional circulation

We do calculation using shallow meridional circulation.

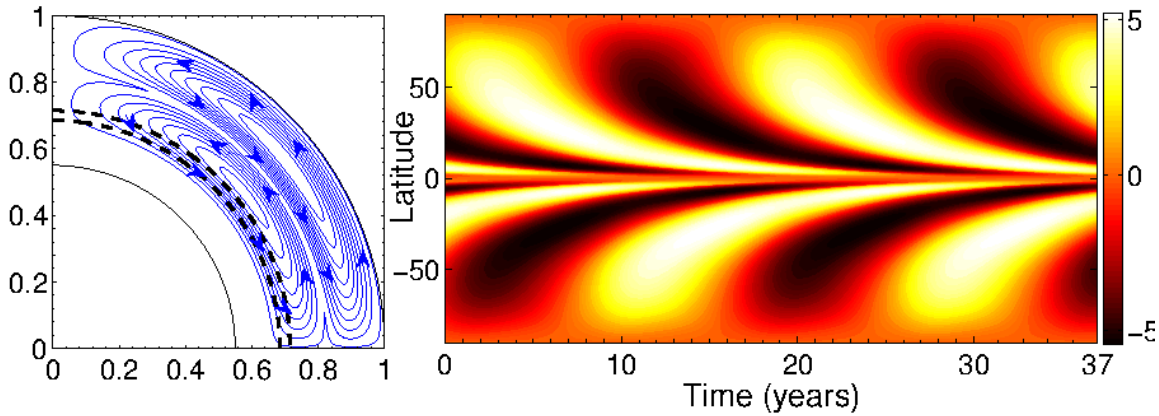


Poleward propagation found in accordance with Parker-Yoshimura sign rule.
Solar like behaviour is not reproduced.

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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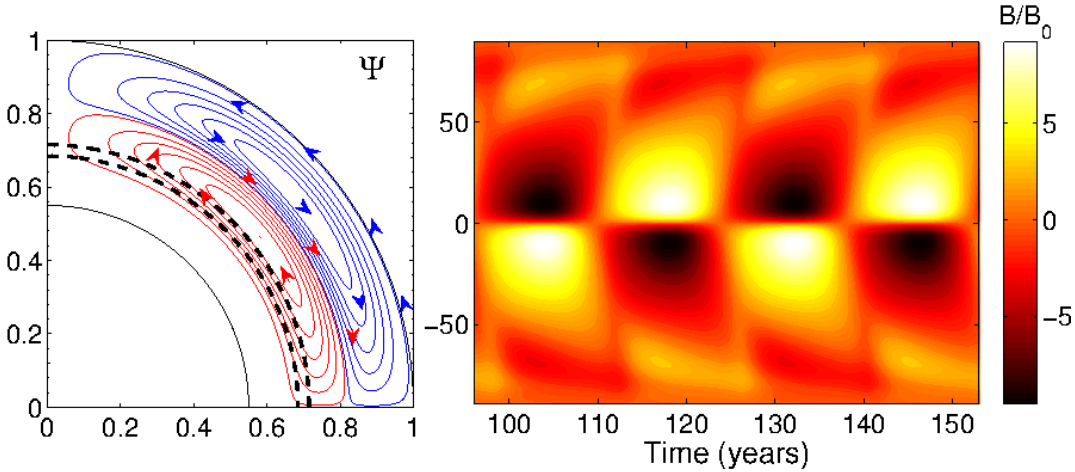
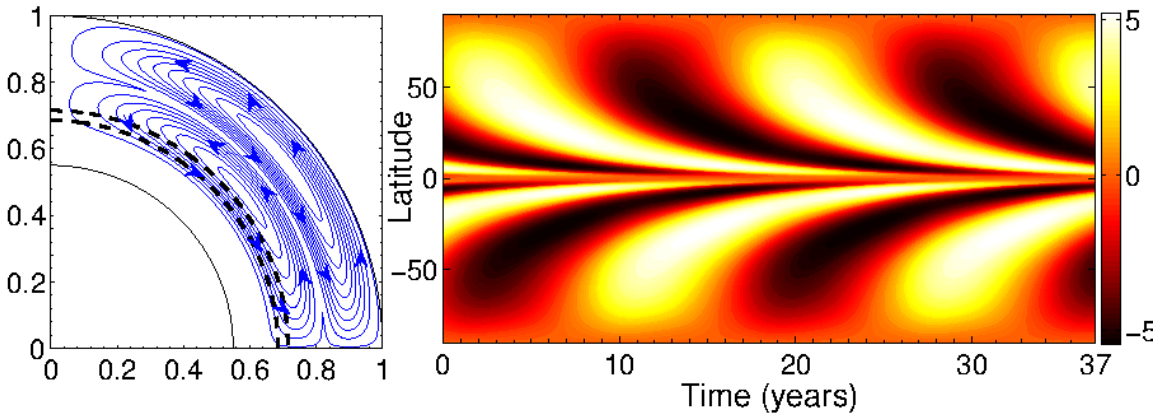
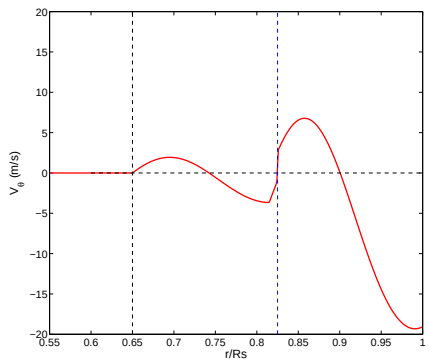


Two-cell circulation with equatorward flow at the bottom gives solar-like butterfly diagram

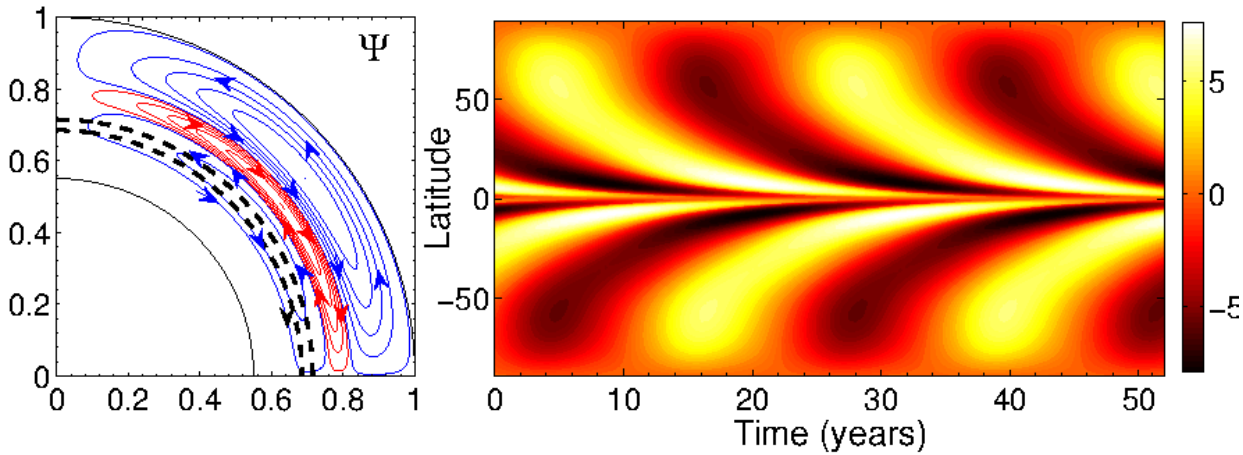
But there is a discontinuity of flow.





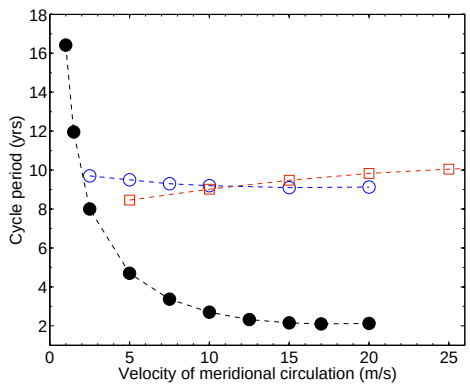
Radially stacked three cells

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



Results:

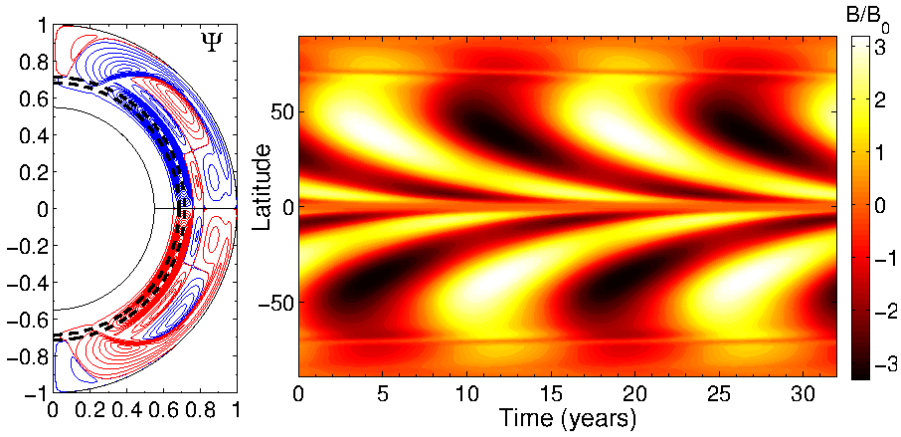
- Solar like behaviour reproduced.
- Period of dynamo depends on the velocity of the lower cell only.($T \sim v_l{}^{-0.72}$)



Hazra, Karak & Choudhuri (2014).

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