Dynamos with feedback of jxB force on meridional flow and differential rotation

M. Rempel, M. Dikpati & K. MacGregor

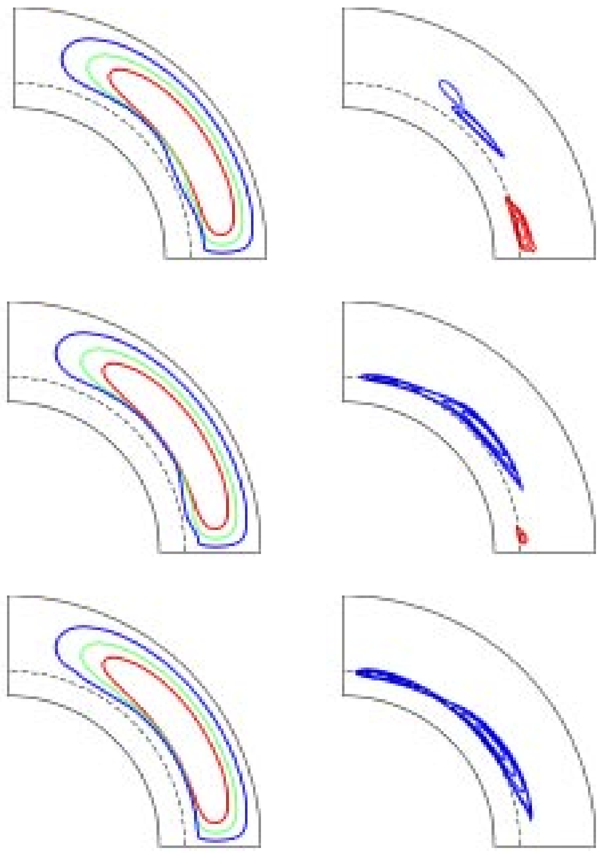
HAO/NCAR, 3450 Mitchell Lane, Boulder, CO-80301

Introduction

Recently, flux-transport dynamos have been successful in reproducing various observed features of the large scale solar magnetic fields. However, these studies addressed the transport of magnetic fields by the meridional circulation in a purely kinematic regime. The toroidal field strength at the base of the solar convection zone inferred from studies of rising magnetic flux tubes is around 100 kG and thus orders of magnitude larger than the equipartition field strength estimated from a meridional flow velocity of a few m/s. Therefore it is crucial for flux-transport dynamos to address the feedback of the jxB force on the meridional flow. In this paper we present two approaches: 1) A kinematic approach in which we parametrize this feedback in terms of a non-linear quenching of the meridional flow in regions of strong field. 2) A MHD approach in which we solve the full set of hydrodynamic equations together with the dynamo equations.

Kinematic dynamo model

We use the kinematic dynamo model developed by Dikpati et al. (1999), which solves the axisymmetric dynamo-equations for a prescribed differential rotation and meridional flow. We incorporate a feedback of the Lorentz force on the meridional flow in terms of a 'quenching' of the stream function, which deflects streamlines from regions of strong magnetic field.



Three frames at the left show the variation in flow pattern (stream function) during a sunspot cycle, and the corresponding right frames, the toroidal field configurations. In the top frame, the flow is quenched at two latitude zones (one high and the other low), at the beginning of the cycle. The toroidal field configuration reflects that old cycle (red contours) ends near the equator and the new cycle (blue) starts at high latitude. With progress of the solar cycle, the toroidal field belt migrates equatorward and the flow becomes quenched in the corresponding latitude of strongest toroidal fields (see middle and bottom frames).

MHD model

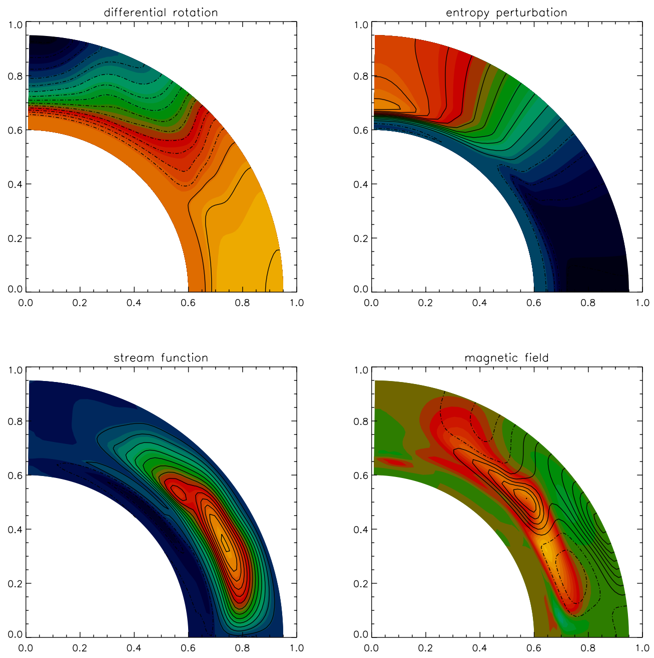
We couple a mean-field Reynolds-stress approach for the differential rotation and meridional circulation with the axisymmetric dynamo equations. This provides a self-consistent model that allows to study the back-reaction of the mean-field Lorentz-force of the dynamo generated field on differential rotation and meridional circulation.

Theory of differential rotation:

- Parametrized Reynolds-stress angular momentum transport as source term for differential rotation. Angular momentum flux mainly parallel to axis of rotation (Λ-effect, Kichatinov & Rüdiger 1993)
- Meridional circulation driven self-consistently by Coriolis force resulting from differential rotation
- Differential rotation in thermal balance (pole about 4K hotter than equator (this avoids the Taylor-Proudman state with Ω contours parallel to cylinders)
- Equator-pole temperature difference originates in the subadiabatic tachocline and spreads into convection zone due to turbulent thermal conductivity

Dynamo theory:

- Axisymmetric dynamo equations with Babcock-Leighton and tachocline α - effect
- No α - quenching; dynamo saturates through Lorentz-force feedback on differential rotation and meridional flow
- Magnetic buoyancy not considered in model



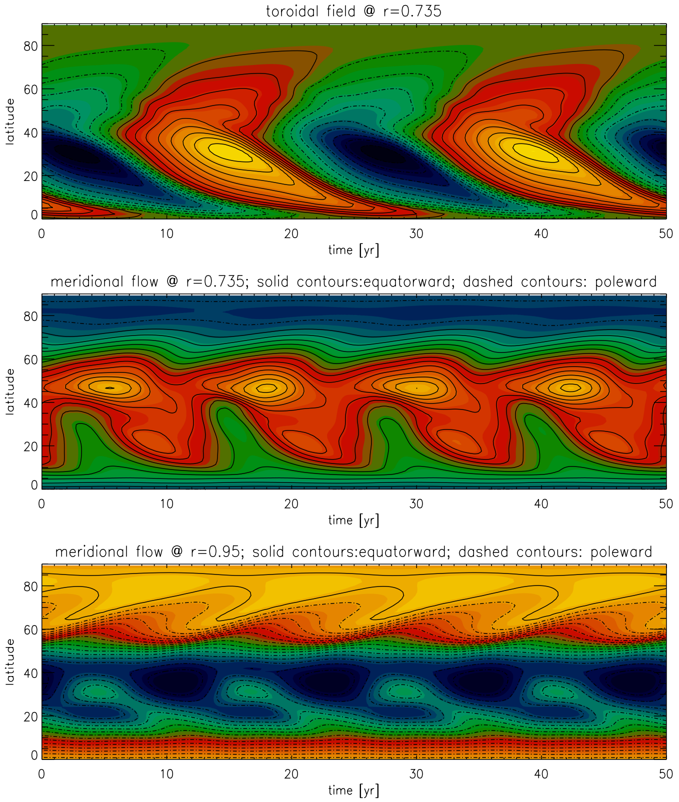
Snapshot of differential rotation, corresponding entropy perturbation, stream function of meridional flow, and magnetic field. In the latter plot the toroidal field is represented by the color shades and the contour lines indicate poloidal field lines. Deformations of the contour lines of differential rotation and the stream function above 45^o latitude originate from the feedback of the Lorentz force. The shown dynamo solution saturates at a toroidal field strength of about 10 kG.

References

M. Dikpati & P. Charbonneau, 1999, ApJ, 518, 508

D. Haber et al. , 2002, ApJ, 570, 855

L.L. Kichatinov & G. Rüdiger, 1993, A&A, 276, 96



Butterfly diagrams of the toroidal field strength at r=0.735 (the range is around -13 kG to + 13 kG), the equator-ward meridional flow velocity (the range is around -0.1 m/s to +1.2 m/s), and the poleward meridional flow at r=0.95 (the range is around -4.5 m/s to + 0.4 m/s). The Lorentz force feedback changes the meridional flow significantly throughout the convection zone. In regions of strong field (around 10 kG) at the base of the convection zone the flow speed is signficantly reduced (by around 50%). Near to the surface the Lorentz force has the tendency to significantly weaken the poleward flow above 50^o latitude. Above 60^o latitude a second cell forms with a reversed flow direction.

Discussion

Flux transport dynamos work even with strong feedback of the Lorentz force on meridional flow and differential rotation for two main reasons:

- The meridional flow avoids regions of strong toroidal field, but still transports the weaker poloidal field that is the source for the toroidal field (via Ω effect)
- The transport capacity of the meridional flow is much larger than estimates based on its energy density suggest, since it is driven by the small difference of large forces (Coriolis force, viscous force, an buoyancy/pressure force)

Further results of the model:

- The dynamo saturates through feedback on differential rotation and meridional circulation at a field strength of about 10 kG (assuming a turbulent viscosity of $2.5 \cdot 10^{12} cm^2/s$ for the differential rotation model)
- The feedback of the Lorentz-force produces a reverse polar cell in the meridional flow that varies with the dynamo phase (a reverse polar cell was found in helioseismic data by Haber et al. 2002)

Acknowledgements

This work is partially supported by NASA grants W-10107 and W-10175. The National Center for Atmospheric Research is sponsored by National Science Foundation.