Exploring the Sun and its effects on the
Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

Solar Convection Zone Dynamics

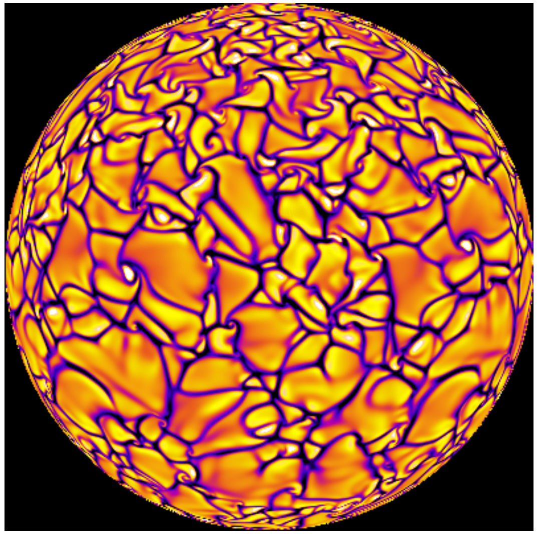
What could we learn from Solar-C?

Matthias Rempel
HAO/NCAR

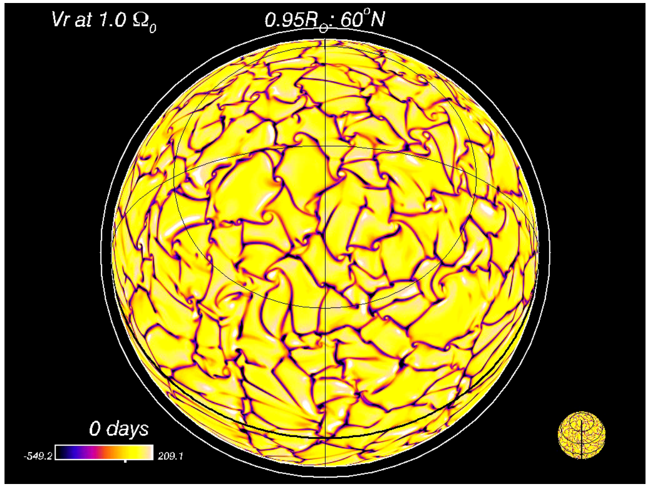
Outline

- Our current understanding of large scale flows and magnetic fields
  - Large scale convection flow (> supergranulation)
  - Differential rotation and meridional flow
  - Large scale cyclic dynamo
  - Cyclic variations of diff. rot. and merid. Flow
  - Magnetically induced flows at base of convection zone
- What is the current state of the field?
- What are the key questions?
- How can Solar-C help?

Large scale convection patterns



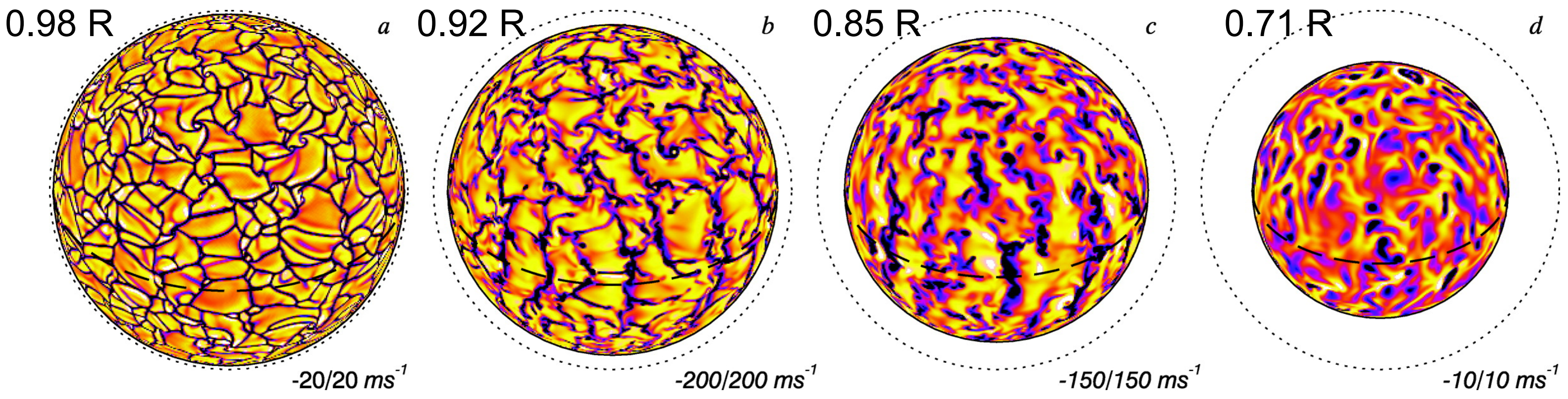
Miesch et al.

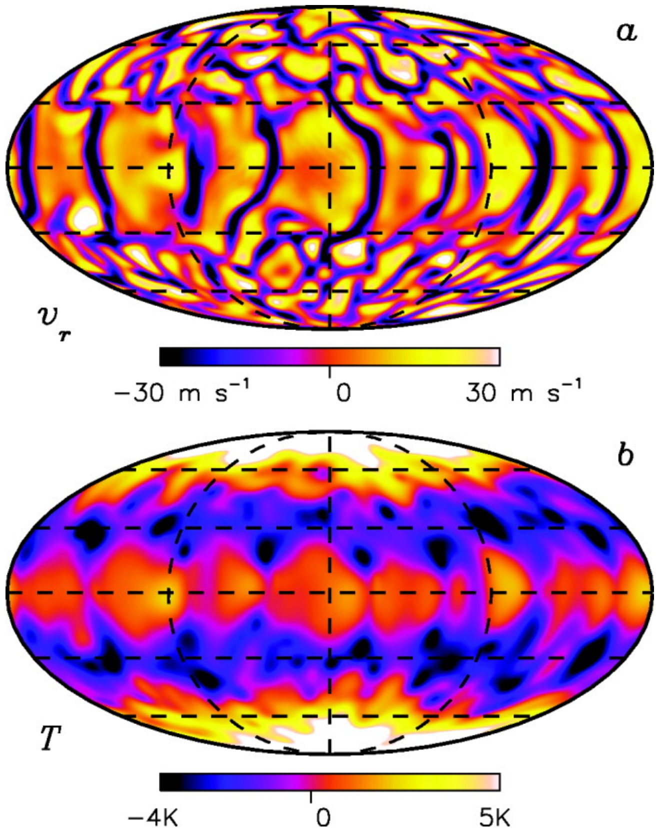


B. Brown

- Influence of rotation changes with latitude and depth
- Is this influence visible in near surface flows?
- Flow structure near poles
  - Polar vortex?
  - Rossby waves?
  - Any unexpected surprise?
- View on pole allows to track features for several rotations
  - Study temporal evolution instead of snapshots
  - Less distortion by differential rotation

Large scale convection patterns



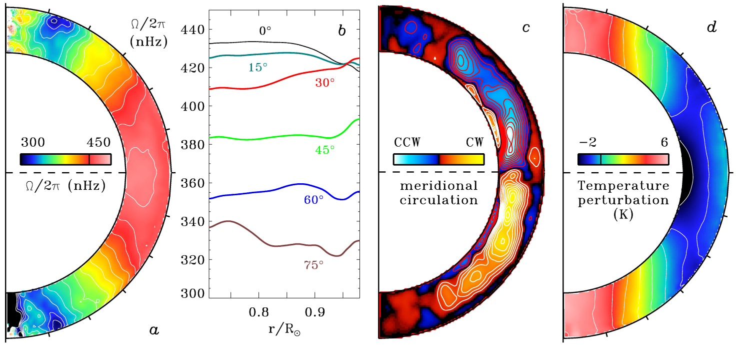


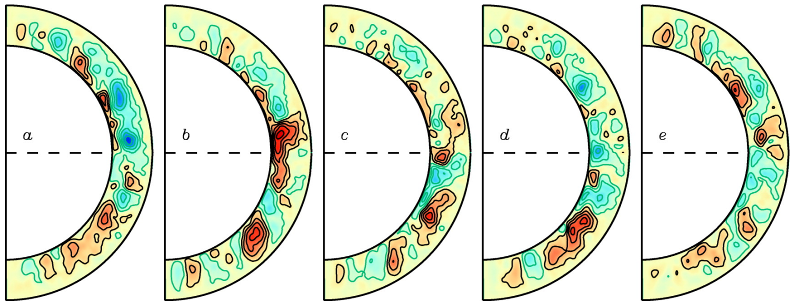
- Preferred alignment of convection cells with respect to axis of rotation in low latitudes (outside tangent cylinder
- Co-rotation of convection pattern
- Thermal transport toward poles ~ 5 – 10 K difference between pole and mid latitudes
- Some indication of longitudinal alignment of supergranulation?
- Primarily theoretical prediction, no observational constraints!

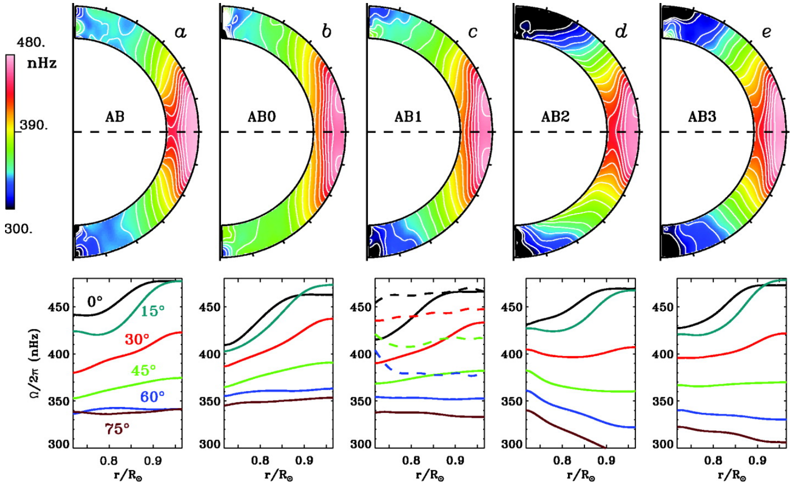
Large scale flows, magnetic fields, some general remarks

- Two different modeling approaches
  - 3D MHD simulations from ‘first principles’
    - No ‘free’ parameters
    - Limited in degree of turbulence reached
    - Computationally very expensive (most recent runs ~1536^3)
  - 2D axisymmetric mean field models
    - Computationally inexpensive
    - Not from first principles, strongly dependent on parametrizations
- Potential role of observational constraints
  - 3D MHD: Determine if models are on right track (resolution and related to that diffusivities are the primary free parameters)
  - 2D meanfield: Too many degrees of freedom, need to be able to rule out certain models

Results from 3D simulations: DR and MC



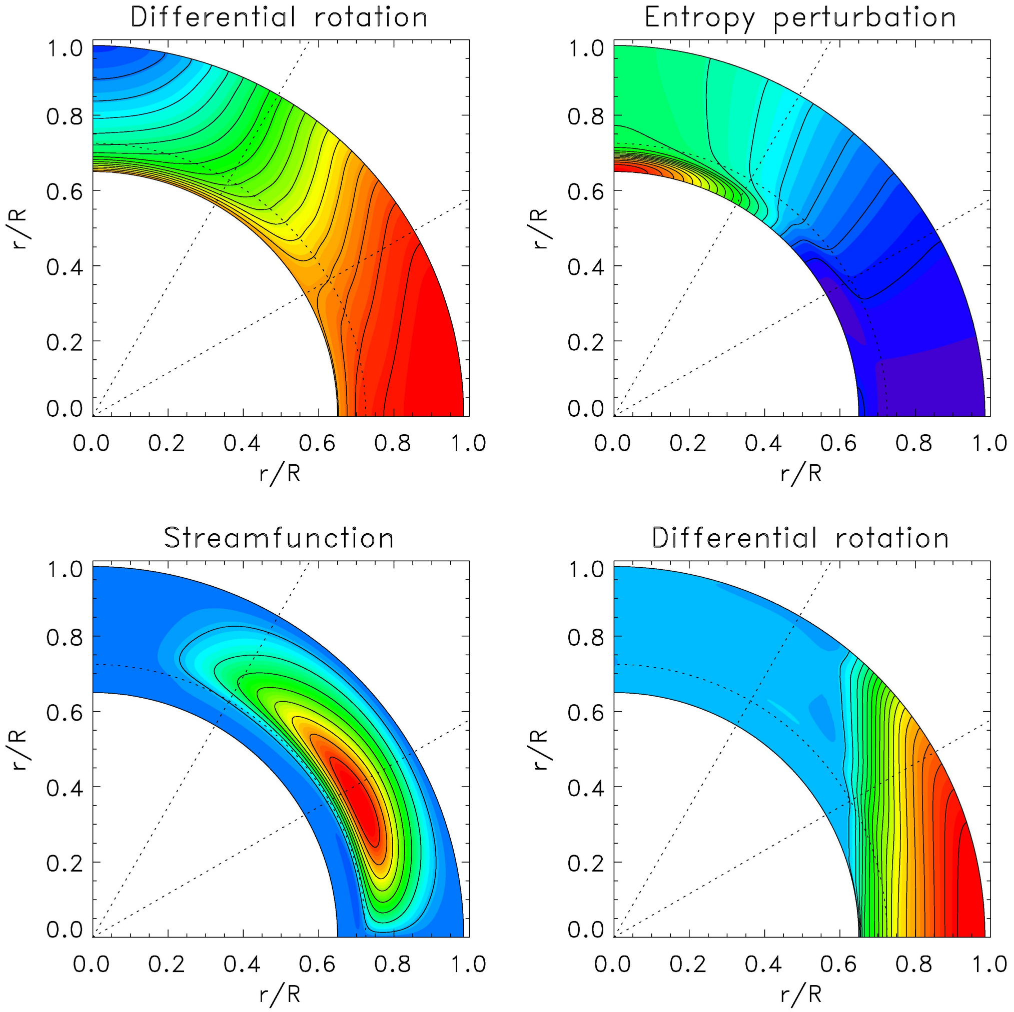




- ➢ Strong Reynolds stresses drive differential rotation and meridional flow
- ➢ Equatorial acceleration with solar like amplitude (almost always)
- ➢ Single celled meridional flow in highest resolution case, multiple cells in lower resolution case (no converged results yet)
  - – Meridional flow always shows strong temporal variability
- ➢ Solar-like rotation profiles require equator pole entropy differences, origin debated
  - – Anisotropic energy transport
  - – Coupling to tachocline

Miesch, Brun, Toomre et al. 2006, 2008

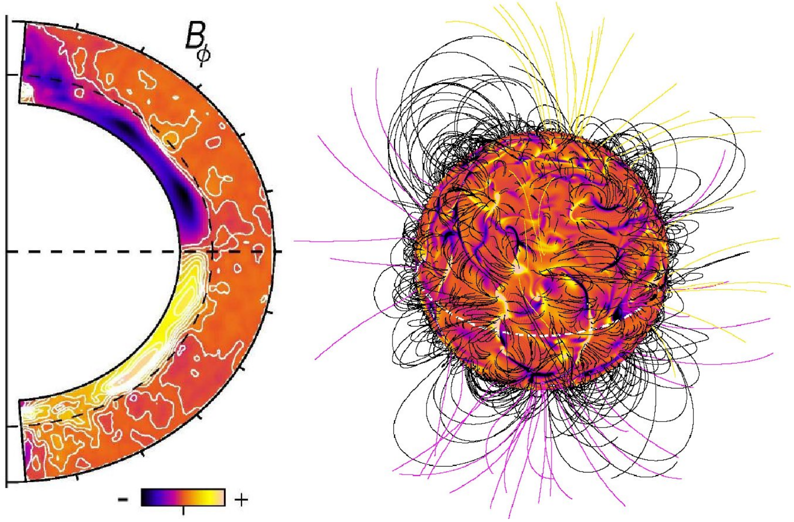
Results from 2D mean field models



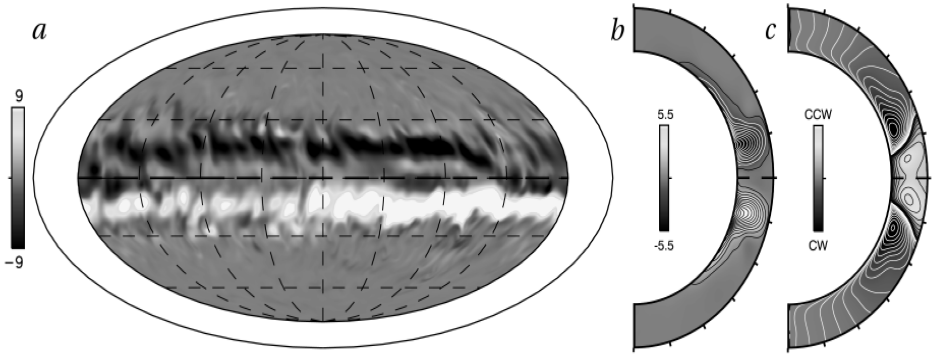
Rempel, 2005

- Solar-like diff. rotation requires latitudinal entropy variation
- Entropy variation originates self-consistently from coupling to tachocline
- Counter-clockwise meridional flow if inward directed angular momentum transport (expected in limit of fast rotation according to models by Rüdiger & Kitchatinov)
- Meridional flow structure and latitudinal temperature variation in convection zone so far not constrained
- Theoretical controversy regarding origin of temperature perturbation (anisotropic energy transport vs. tachocline)

3D dynamo simulations



Browning et al. (2006)



Brown et al. (2008)

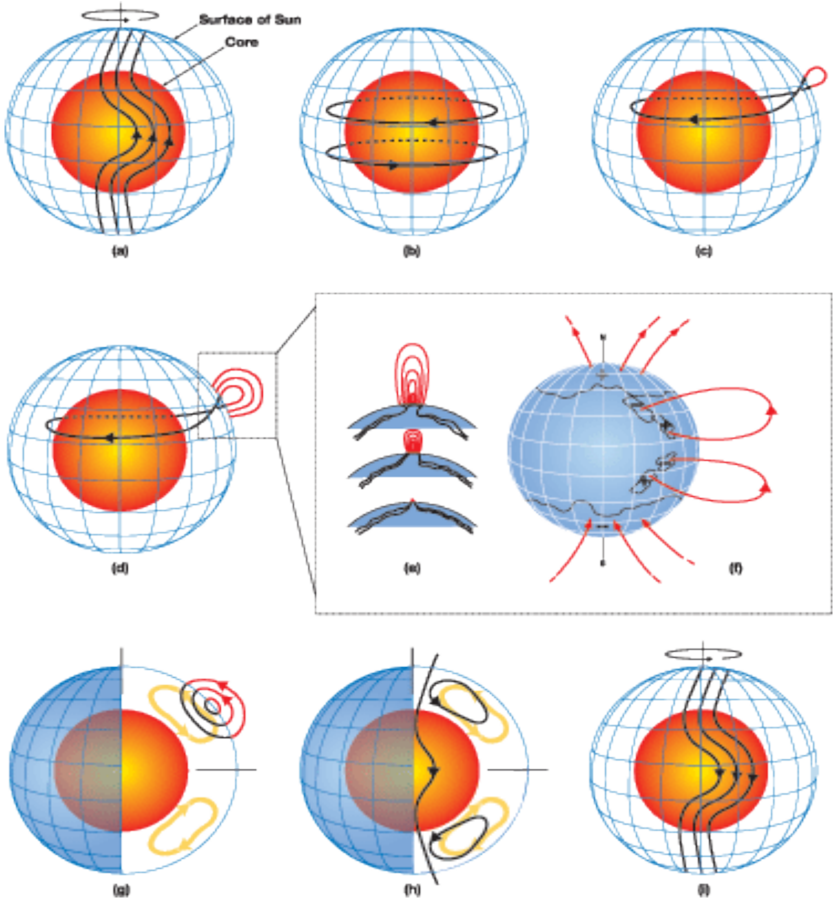
- Convection zone dynamo
  - Turbulent field, meanfield < 0.03%
- Tachocline
  - Strong mean field ~10 kG
- Faster rotators (3x)
  - Strong (~ 5 – 10 kG) field in convection zone
  - Antisymmetric over equator
  - Activity confined to low latitudes
- No cyclic dynamo yet
  - Difficult to evolve 3D runs for > 10 years
- No 3D dynamo model yet available that can be directly compared to observations

2D mean field dynamo models

- Main challenge
  - Not models from first principles, rely heavily on parameterizations
  - Ingredients known, but not relative importance
  - Variety of different models (tachocline, interface, distributed dynamos) with cyclic behavior
  - Progress means ruling out certain models!
  - Difficult since most of the action is happening in the deep convection zone!
- Potential ways to discriminate between different models
  - Meridional flow measurements in deep convection zone
  - Cyclic variations of meridional flow and differential rotation
  - Magnetic field (direct / indirect)

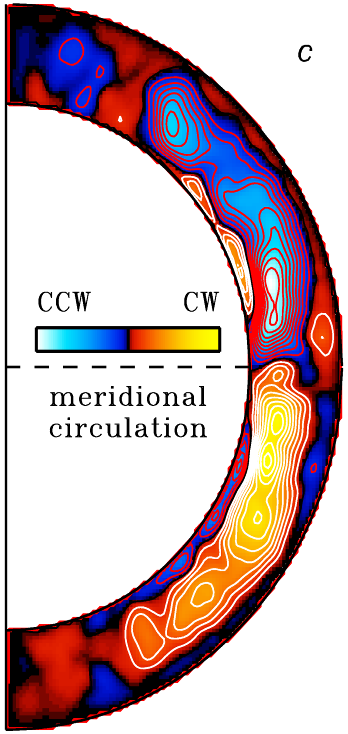
Why is the meridional flow important

- Flux-transport dynamo
  - Turbulent transport weak (strong assumption these models are based on!)
  - Meridional flow primary transport mechanism
  - Meridional flow at base of CV responsible of equtorward propagation of activity
- Does the solar meridional flow have the right topology to achieve this?



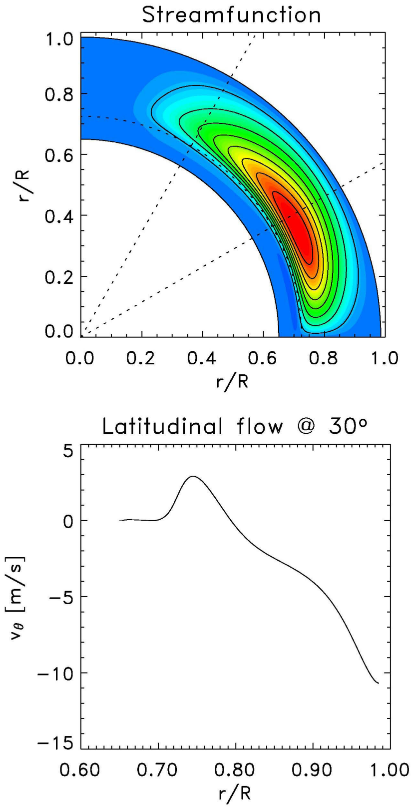
M. Dikpati

Meridional flow structure



3D simulation
Miesch et al.
(2008)

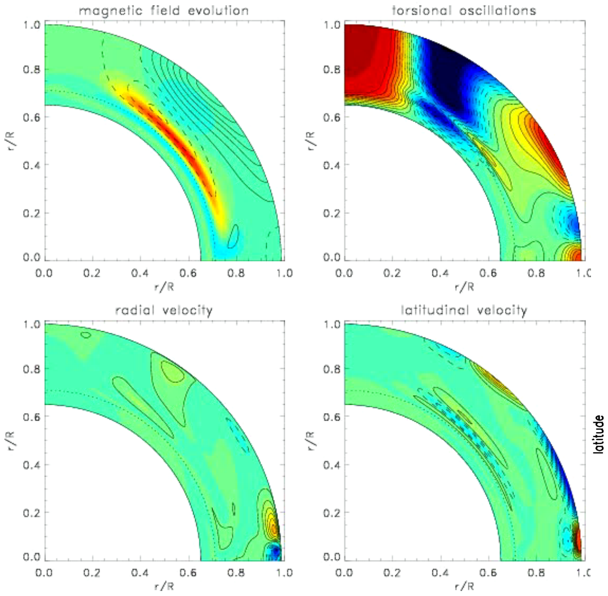
- Poleward at surface (observed)
- Return flow not observable through helioseismology
  - 50 Mm depth still poleward (Gizon & Rempel 2008)
- Mass conservation
  - Equatorward at base
- Theory:
  - Meanfield models: equatorward
  - 3D simulations
    - Equatorward (high resolution)
    - Multiple flow cells (low resolution)
- Overall: Equatorward flow at base of CZ very reasonable, observational confirmation needed (speed of a few m/s)!
- Turbulent transport remains major uncertainty: We can potentially rule out a flux-transport dynamo, but we can't confirm it!



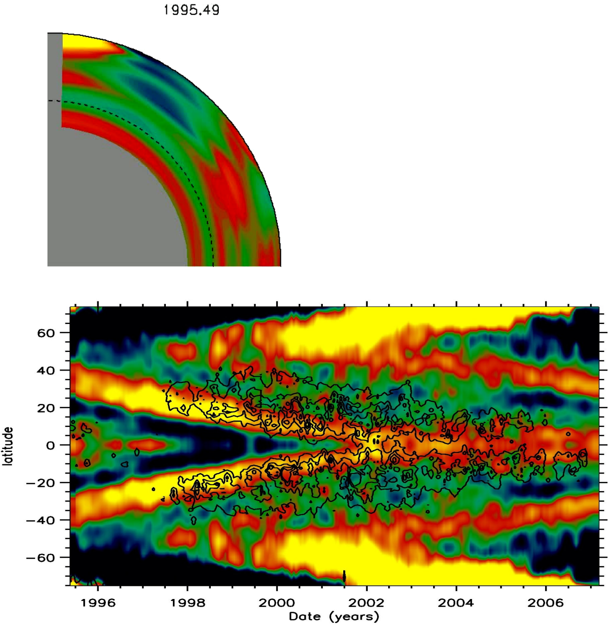
Meanfield model
Rempel (2005)

Cyclic flow variations

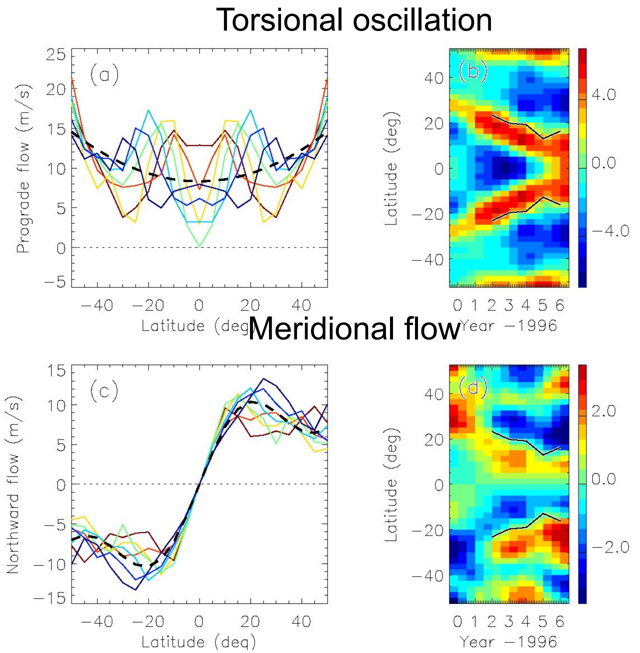
Simulation, Rempel (2006)



(R. Howe, global)



(L. Gizon, local)

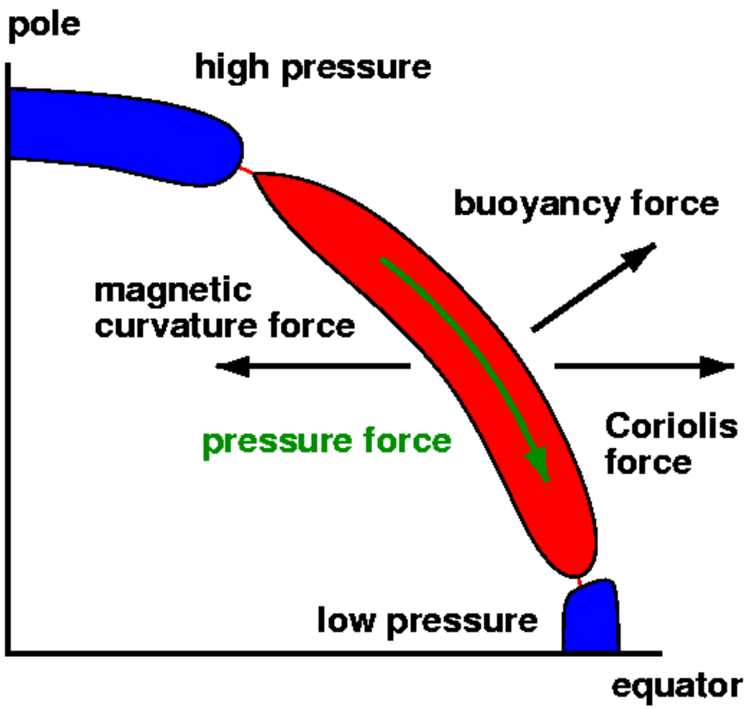


- Torsional oscillations most likely linked to dynamo, provide information about global energy budget
- Global inversions loose sensitivity in high latitudes
- Global inversions less sensitive to meridional flows
- Origin of torsional oscillations can only be understood if zonal and meridional flow variations are observed at same time (required to disentangle Lorentz force and thermal forcing)
  - High latitude local helioseismic observations required

Structure of magnetic field at base of convection zone

- In most dynamo models base of convection zone is essential for organization of large scale toroidal field
- Disagreement regarding field strength
  - Rising flux tube models require ~ 100 kG
  - Differential rotation can energetically produce up to ~10 kG
  - Meridional flow can transport field of up to 30 kG
  - 3D simulations with tachocline ~ 10 kG
- Observational constraints on field strength very helpful, but can we tell the difference between a 100 kG intermittent and a 10 kG homogeneous field?
  - Direct magnetic effect ~ 10^{-7} - 10^{-5}
  - Possibility of detection through zonal flow variations?

Equilibrium and instability of magnetic field at the base of the convection zone

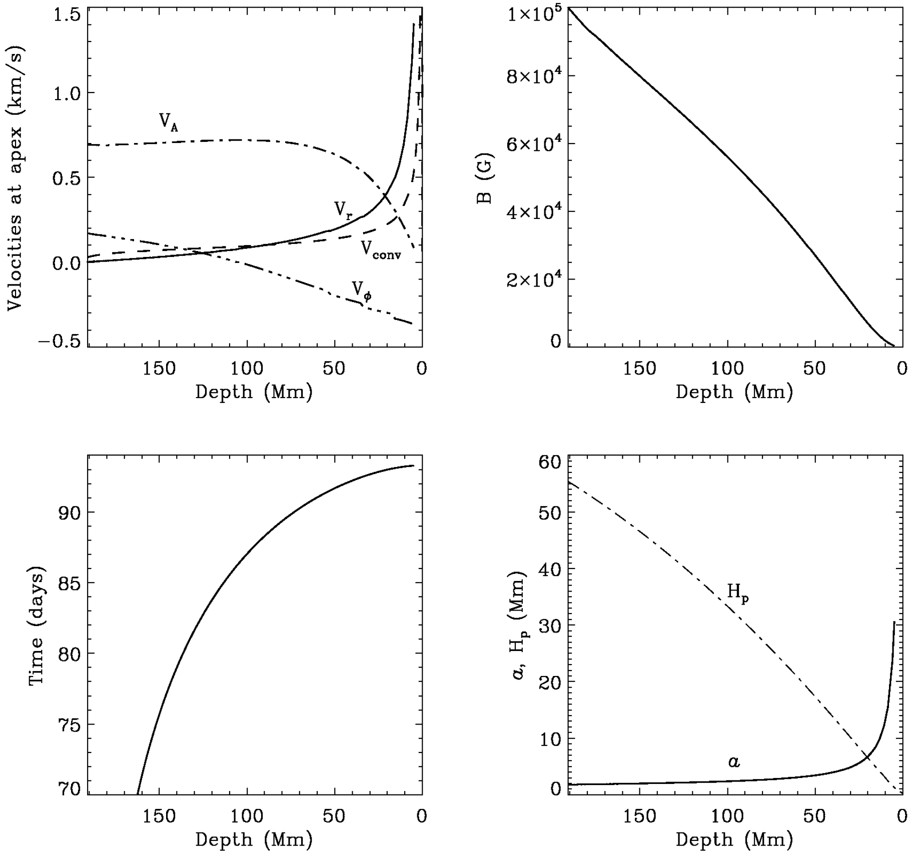


- Force equilibrium requires balance of magnetic curvature force by pressure, buoyancy and Coriolis force
- Low filling factor field preferentially in balance between tension, buoyancy and Coriolis force:
  - Prograde jets in strong field regions

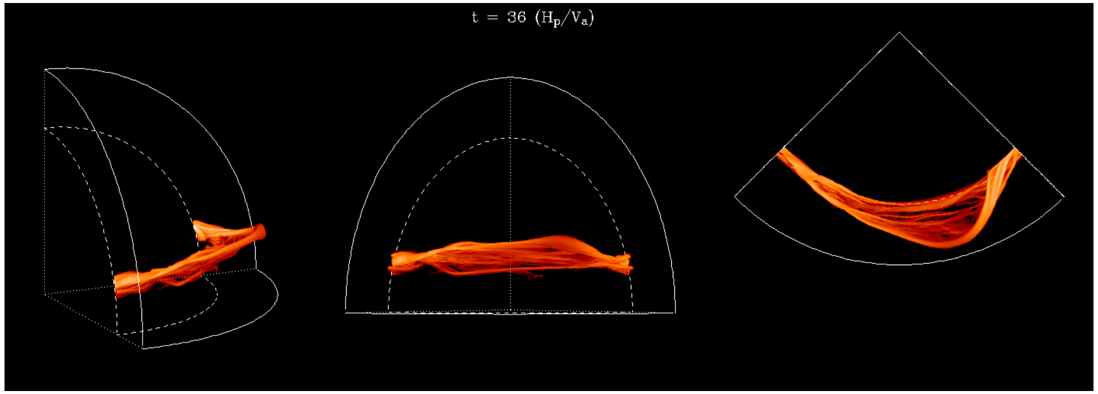
$$\Delta v \approx 200 \ \ \mathrm{m/s} \ \left(\frac{\mathrm{B}}{100 \ \ \mathrm{kG}}\right)^2$$

  - Potentially observable if B~100 kG
  - If B~ 100 kG filling factor most likely small (0.1)

Flow variations during rise of flux tubes



- ➢ Zonal flow changes from prograde to retrograde in middle of convection zone (angular momentum conservation)
- ➢ Large rise velocities (~ km/s) in upper most 10-20 Mm, however, timescale short

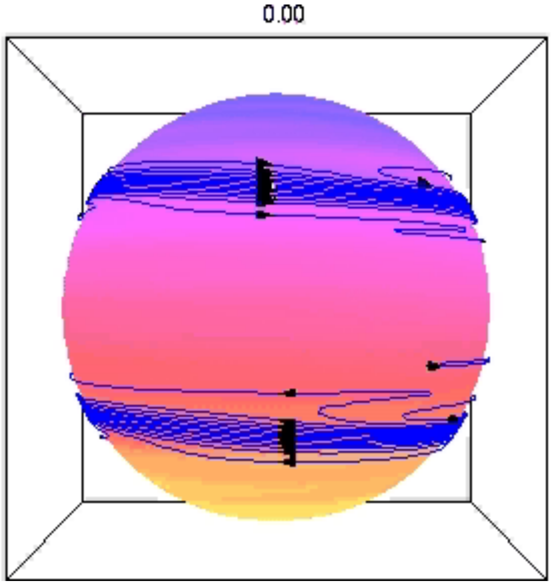


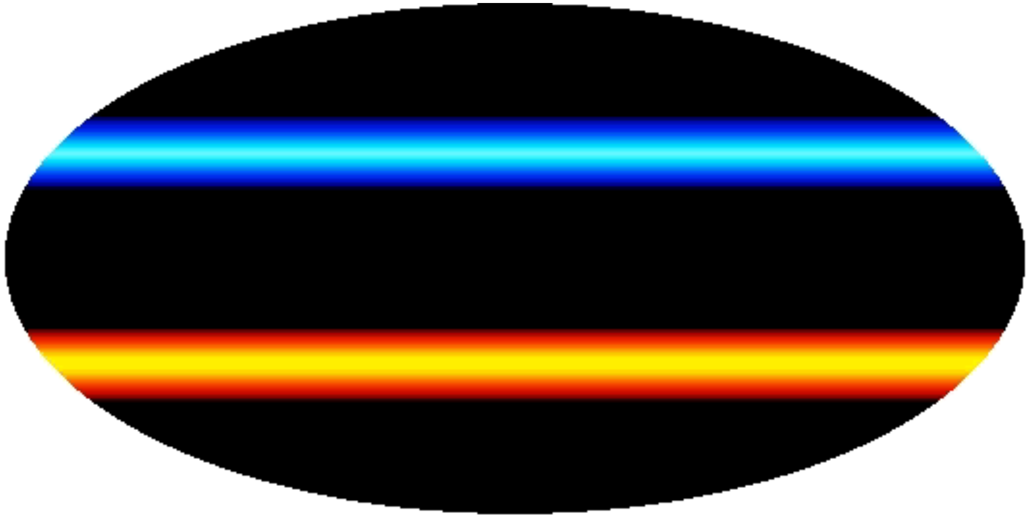
Thin/thick flux tube simulation (Y. Fan)

HD/MHD tachocline instabilities produce non-axisymmetric flow

2D MHD model of tachocline shows tipping & deformation of a toroidal band; flows channeled through the magnetic fields produce large-scale non-axisymmetry in the flow field

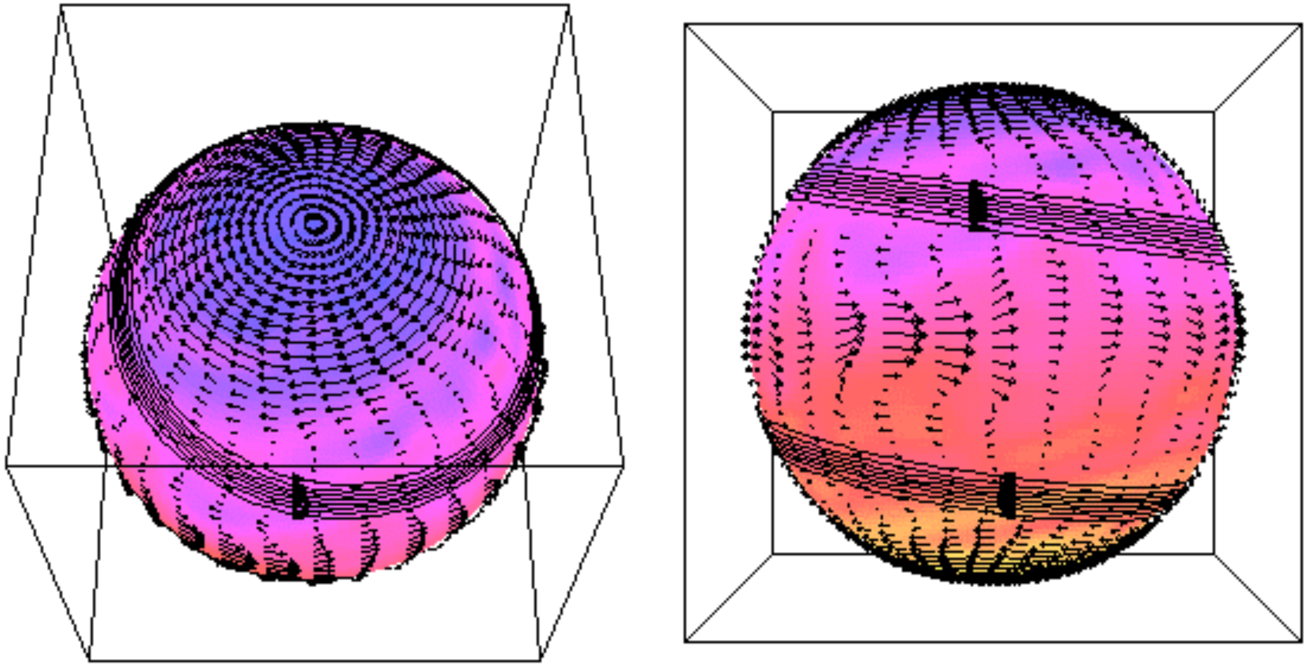
(Cally, Dikpati and Gilman, 2003)





3D models also produce tipping (Miesch et al. 2007a, 2007b)

A snap-shot of the non-axisymmetric flow



- Global inversions show that axisymmetric variations at the base of the convection zone with ~ 5 m/s amplitude are detectable
  - Can we detect jet-like feature at the base of the convection zone?
  - Can we constrain non-axisymmetric variations of the zonal flow with similar accuracy?

Summary

- Helioseimic measurements of flows
  - Influence of rotation on convection (latitude/depth)
    - Constraint on global convection models
    - Long term tracking of temporal evolution
  - Structure of meridional flow
    - Constraint on global convection models (constrains turbulent angular momentum flux parallel to axis of rotation)
    - Constraint of flux-transport dynamo models
      - ‘unfavorable’ flow can rule out flux transport dynamo
      - ‘favorable’ flow is not sufficient due to uncertainty of role of turbulent transport processes
  - High latitude zonal and meridional flow pattern
    - Better understanding of the origin of torsional oscillations and their relation to the dynamo process
    - Unknown territory, polar vortex, Rossby waves?

Summary

- Helioseismic measurements of flows at base of CZ
  - Zonal jets at base of convection zone/tachocline
    - Indirect detection of strong magnetic field? (100 kG is a 10^{-5} change in pressure, but a 10% change in flow speed)
  - Non-axisymmetric flows
    - Tachocline instabilities?
    - Indirect detection for strong magnetic field?
- High precision photometric measurements
  - Pole equator temperature variation
    - Predicted by most convection models
    - Essential ingredient for solar-like differential rotation in current models

Summary

- Photospheric flow/field measurements
  - Better understanding of flux-transport and dispersial, point of return of meridional flow
  - Detailed measurements of low order non-axisymmetric field components needed for non-axisymmetric dynamo models under development
  - Quantification of magnetic helicity fluxes potentially very important for operation of dynamo
  - Detailed structure of photospheric field might be less important for large scale dynamo since dynamo region about a factor of 10^5 in density stratification away from photoshpere

Conclusion

- Understanding the large scale dynamo is strongly linked to understanding convection and large scale flows
  - All of our current knowledge on structure of convection is based on numerical simulations
  - Strong need for observational constraints (a lot can be learned from measurements in the upper half of the convection zone)
- Dynamo theory is a field that suffers strongly from insufficient observational constraints, but the observations we need are very challenging:
  - Can we differentiate between a 10 kG (f~1) and a 100 kG (f<0.1) field at base of CZ
  - Can we measure ~1-5 m/s meridional flow at base of convection zone?
  - Can we see signatures of the flux emergence process?
- A mission such as Plan A combined with a major effort in numerical modeling (and also further investigation of the solar stellar connection) is the only path I see we can make progress in this field
  - The question is not if, but when we should do it?