Influence of depth-dependent diffusivity profiles in governing the evolution of weak, large-scale magnetic fields of the Sun

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Abstract

We study the influence of various diffusivity profiles in the evolution of the large-scale, diffuse magnetic fields of the Sun. After noting that we only have an estimate of the diffusivity value at the surface (from a mixing-length argument), and that we do not know much about how it should vary as a function of depth down to the base of the convection zone or below it, we mathematically construct various theoretical profiles of the depth-dependent diffusivity. We study the effect of each profile, by using an advective-diffusive flux-transport model, in producing certain magnetic features at the surface. We compare the model output with observed solar magnetic features and discuss the successes and drawbacks of each profile. We comment on which ones among these depth-dependent diffusivity profiles can be considered as the most relevant for the Sun.

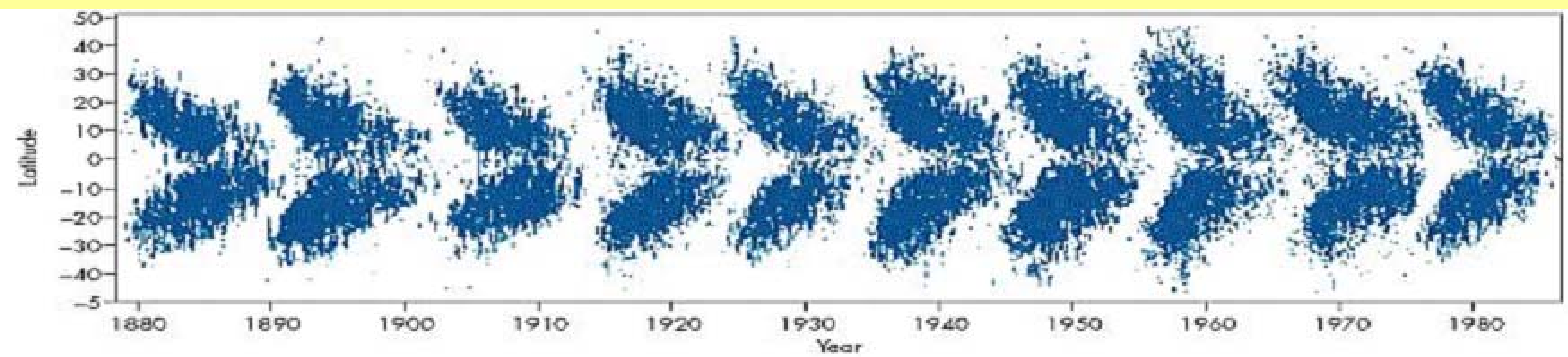
Outline

- Observations of solar cycle
- Solar dynamo processes: questions, model
- How magnetic diffusivity η affects field evolution
- Goals and methods
- Test runs of model with variable diffusivity
- Preliminary results constrain profile and magnitude of magnetic diffusivity
- Future work

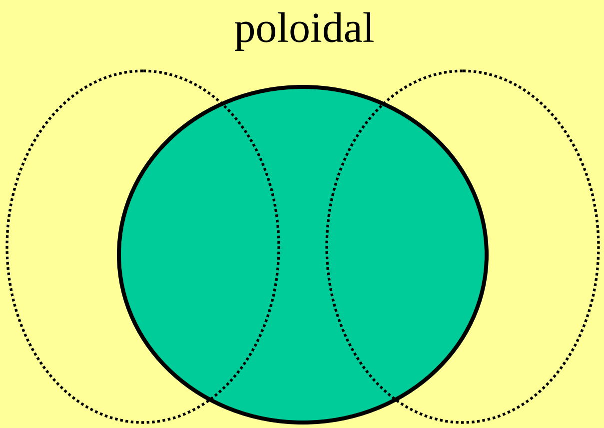
Observations of solar cycle

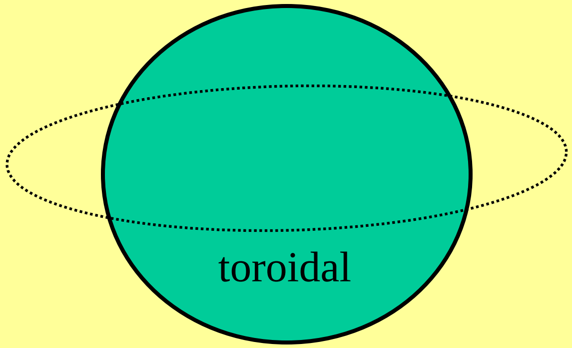
- Sunspots migrate equatorward
- Diffuse poloidal field migrates poleward as the mean solar field reverses

- Solar mean field reverses every 11 years
- Sunspots peak during reversal (“solar max”)



Solar dynamo terms

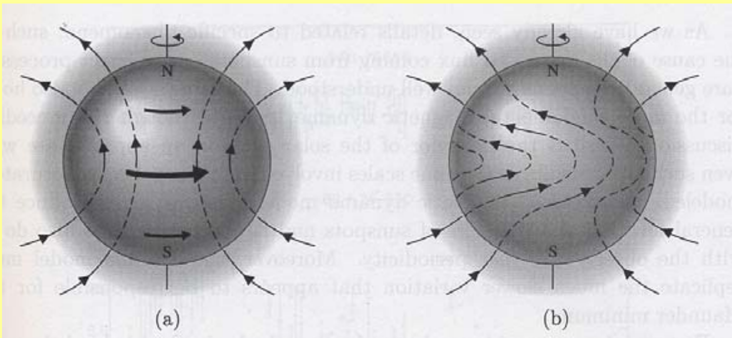


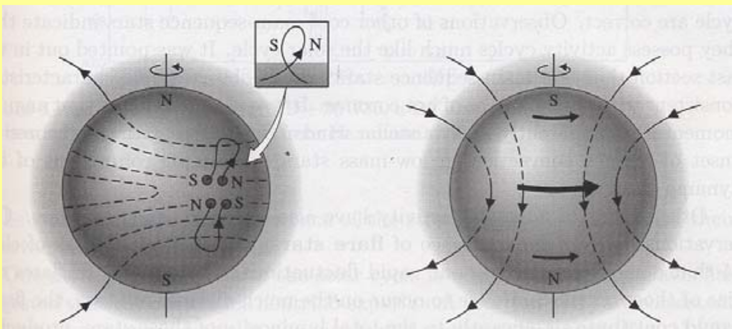


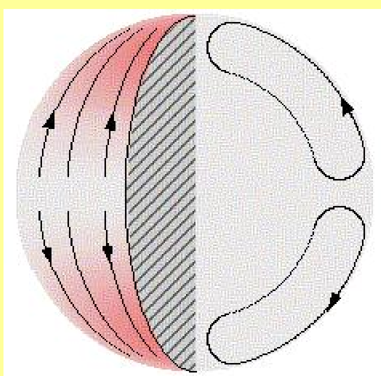
- The sun has a bipolar magnetic field
- Called the **poloidal** field

- Field is stretched out through differential rotation
- Wraps around the sun to create a **toroidal** field

Solar dynamo processes







Ω-effect: Differential rotation creates toroidal field from poloidal field

α-effect: Helical turbulence twists rising flux tubes, which can tear, reconnect, and create **reversed** poloidal field

Meridional circulation: surface flow carries reverse poloidal field poleward; equatorward flow near tachocline is inferred

Poloidal magnetic field evolution

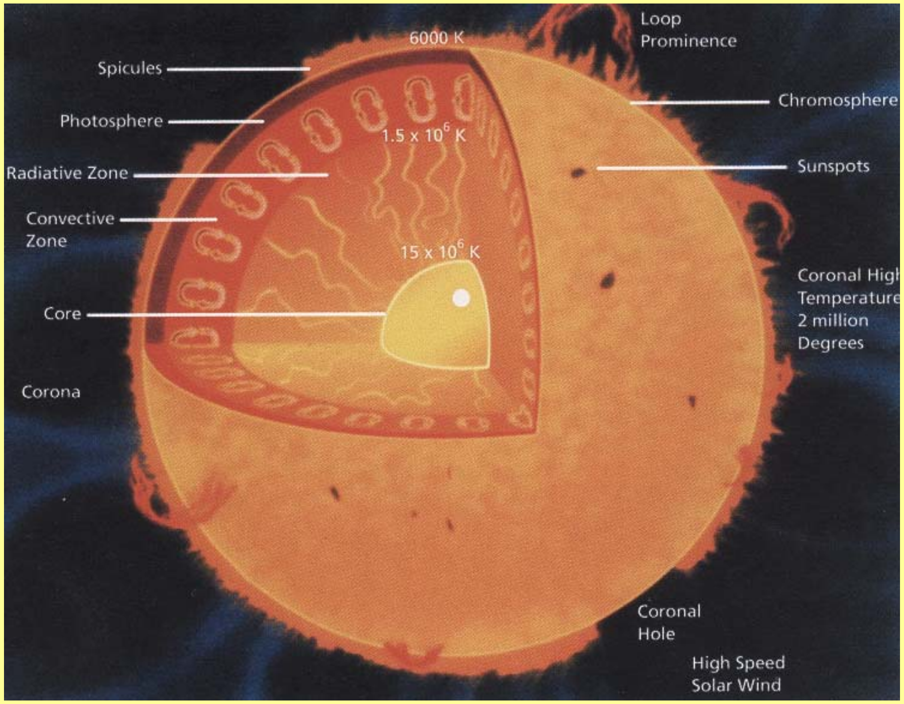
- 2 sources for the poloidal field

  1) α **effect at the tachocline**

  2) α effect at the surface

- Evolution of poloidal field is governed by **diffusivity** and meridional circulations
- Pole reversal takes place when enough new flux reaches the poles to cancel the remnant field

Solar dynamo questions…



How does poleward flow of surface poloidal field contribute to mean field reversal?

How does the magnetic diffusivity $\eta(r)$ vary across the convection zone?

2D kinematic dynamo model

- "Evolve" code by Mausumi Dikpati et al.
- Uses set flow rates v(r,θ,t)
- Equatorward propagating dynamo wave is the source for poloidal magnetic field
- Calculates evolution of magnetic field B(r, θ, t) with induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[(\mathbf{v} \times \mathbf{B}) - \eta \nabla \times \mathbf{B} \right]$$

- where magnetic diffusivity η = resistivity/permeability
- Model reproduces observations of recent solar cycles

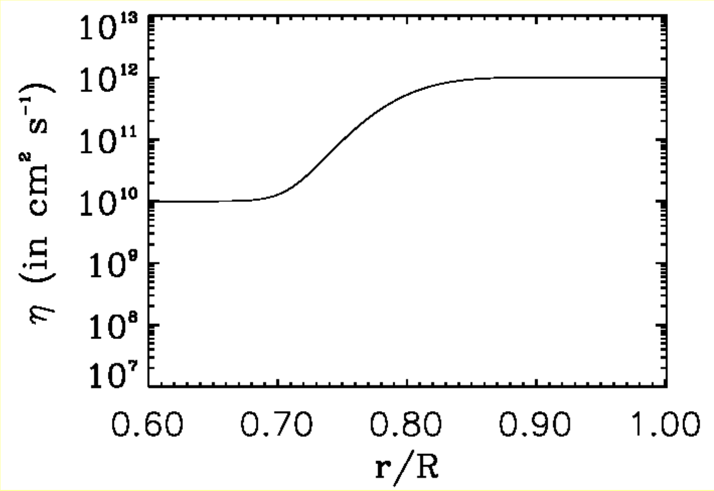
Magnetic diffusivity depends on plasma properties and dynamics

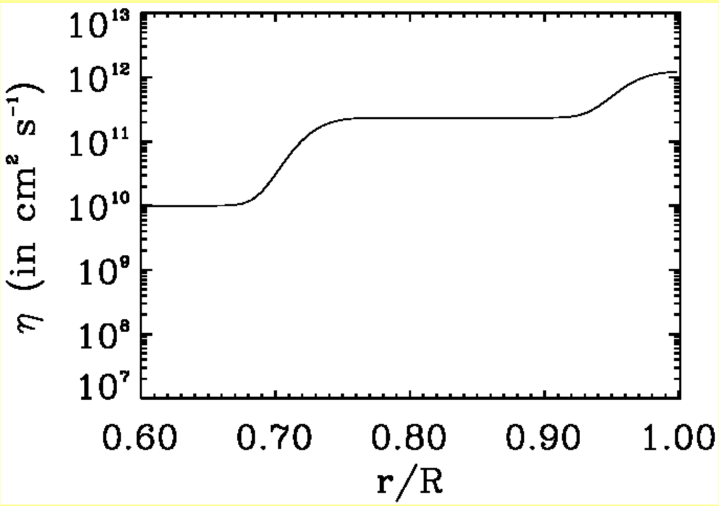
- Resistivity depends on temperature ($\sim T^{-3/2}$)
- Convective turbulence near surface enhances resistivity and therefore diffusion
- Estimate ranges for magnetic diffusivity

  $\eta_{surface}$ (10^{12}- 10^{14} cm^2 s^{-1}) and $\eta_{tachocline}$ (10^8 cm^2 s^{-1})

- Lower η : higher conductivity: slower field changes
- Higher η : higher resistivity: faster field changes

How does magnetic diffusivity change across the convection zone?



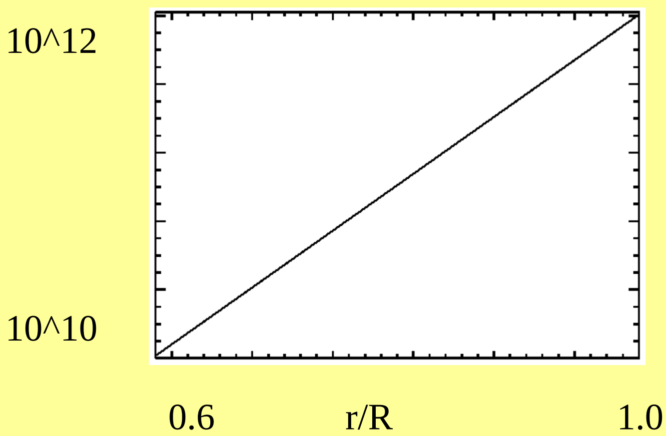


- Shape of solar diffusivity profile η(r) is unknown
- We tested three shapes of η(r)

Single-Step .../dynamo/ss/var/etasurf1/etacor01/ieta1/etaplt.eps

Double-Step .../dynamo/ss/var/etasurf1/etacor01/ieta2/etaplt.eps

Linear (http://download.hao.ucar.edu/pub/green/dynamo/all/dynamo/all/etaplt.eps



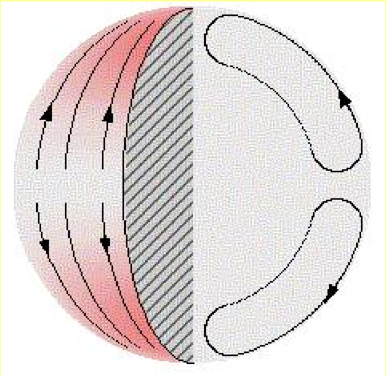
GOALS and methods

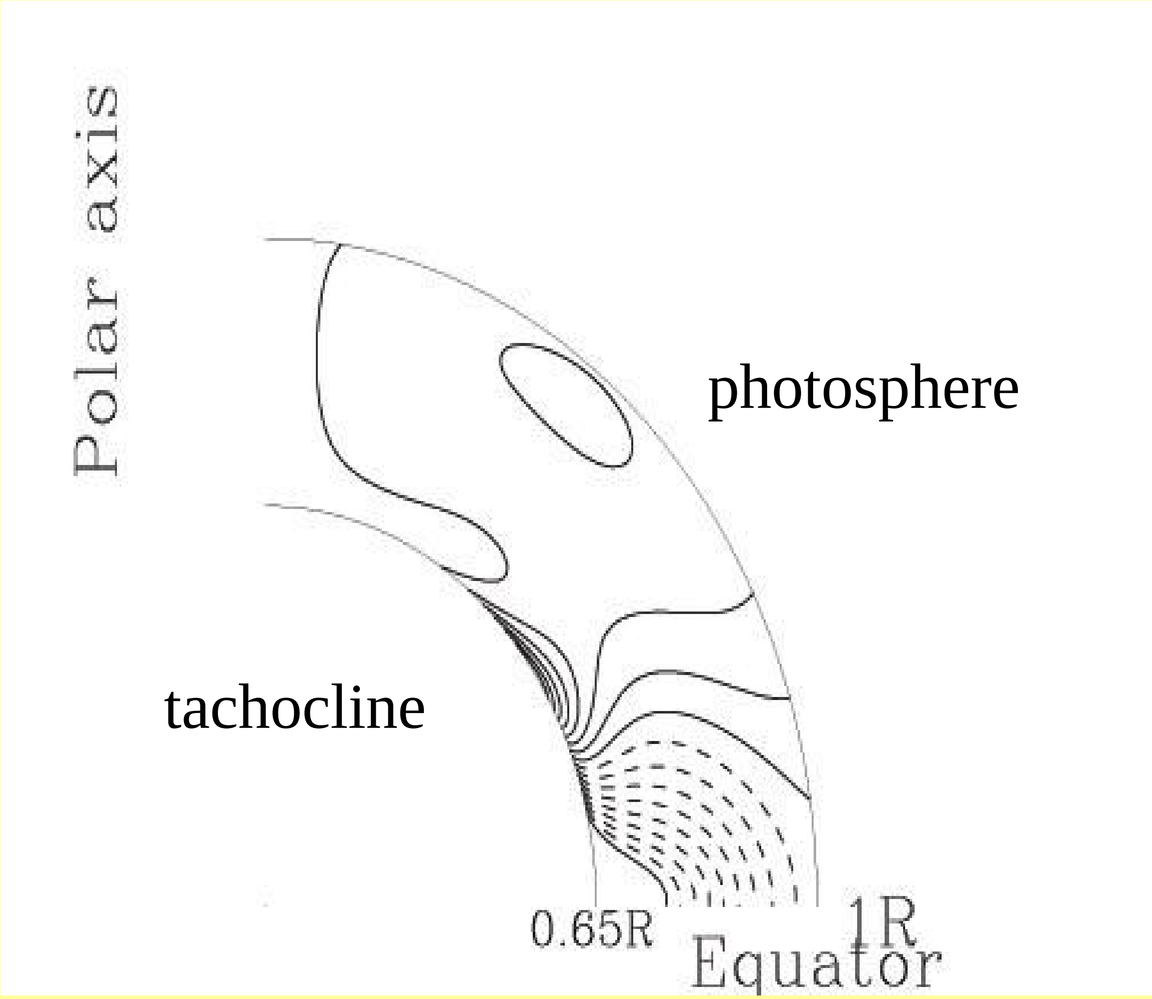
- Find how evolution of diffuse poloidal field depends on $\eta(r)$
- Constrain both magnitude and shape of $\eta(r)$ for better understanding of structure and dynamics of convection zone $\rightarrow$ better dynamo models

METHODS:

- Write "evolveta" to include variable $\eta(r)$ profiles in evolution of magnetic fields in convection zone
- Analyze evolution of fields with new $\eta(r)$ profiles.

Plotting poloidal field lines in a meridional plane





The magnitude of diffusivity shapes the evolution of the poloidal field

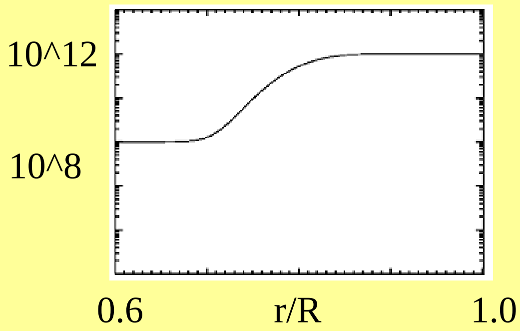
- Value at tachocline η_{tach} is unknown
- We let $\eta(r)$ be uniform and change its magnitude
- Higher η : 10^{12} cm^2 s^{-1}
  Field leaks out of the plasma at the surface
- Lower η: 10^{11} cm^2 s^{-1}
  Field is still carried by meridional circulation

dynamo/pcfast/etacor0001/ieta0/poster/ssplt3.eps

dynamo/pcfast/etacor0001/etasurf01/ssplt3.eps

Bad runs constrain the magnitude of η

- Single-step η(r) with a range in diffusivity from 10^8 - 10^{12} $cm^2\ s^{-1}$
- Diffusion is too low near the tachocline
- Field is too concentrated



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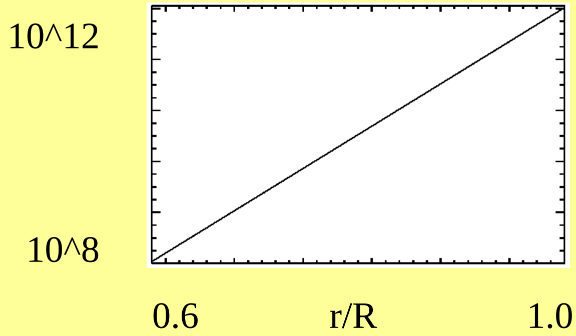
Bad runs constrain the shape of η(r)

- Linear η(r)
- Same magnitude as previous single-step η(r)
- Diffusion looks reasonable



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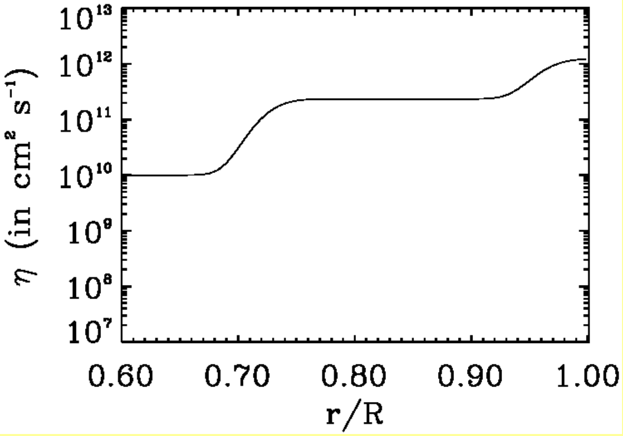
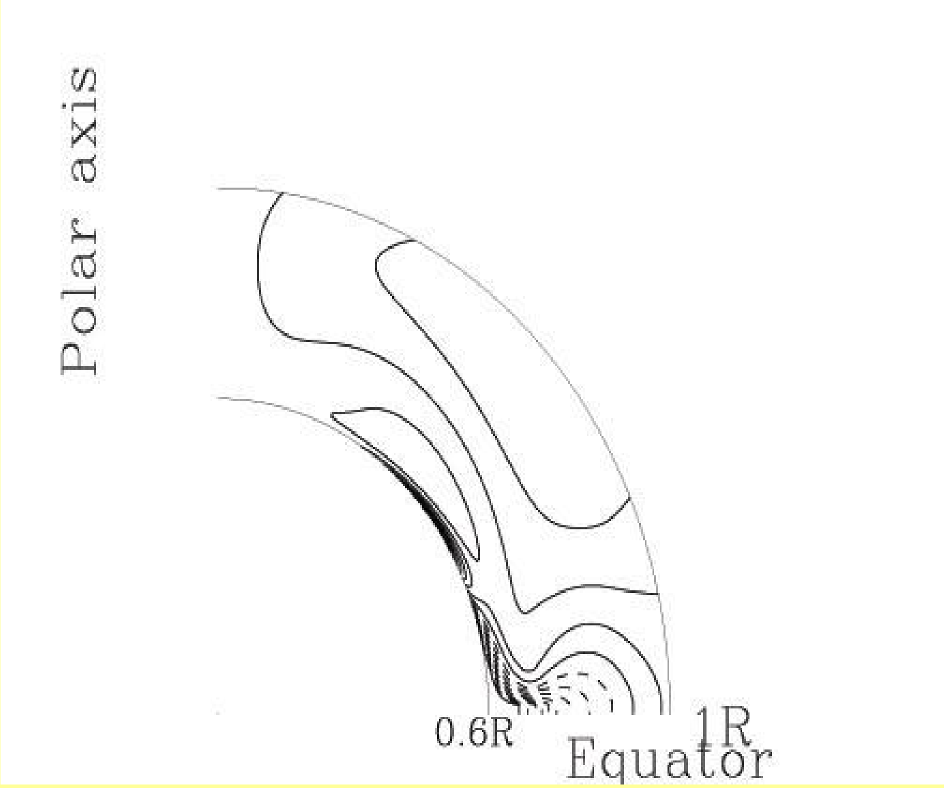
Good runs shed light on role of η(r) in solar dynamo process



Double-step η(r)



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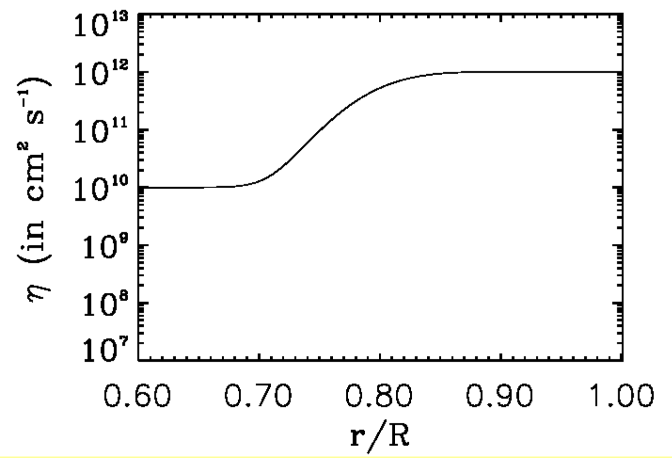
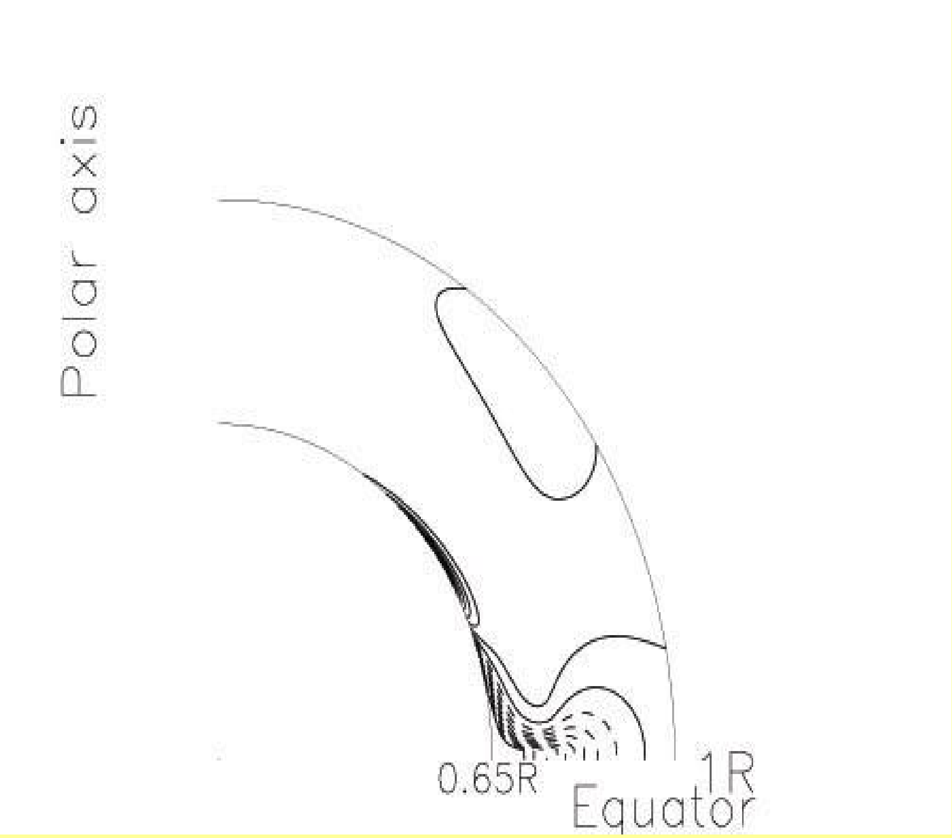
Single-step η(r) shows field line bunching near the gradient in η(r)





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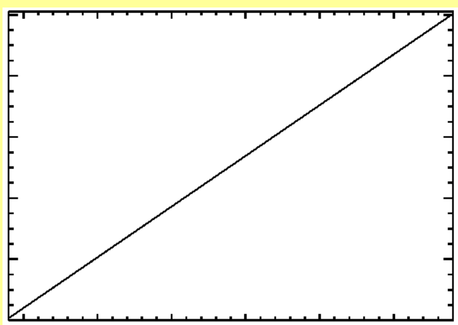
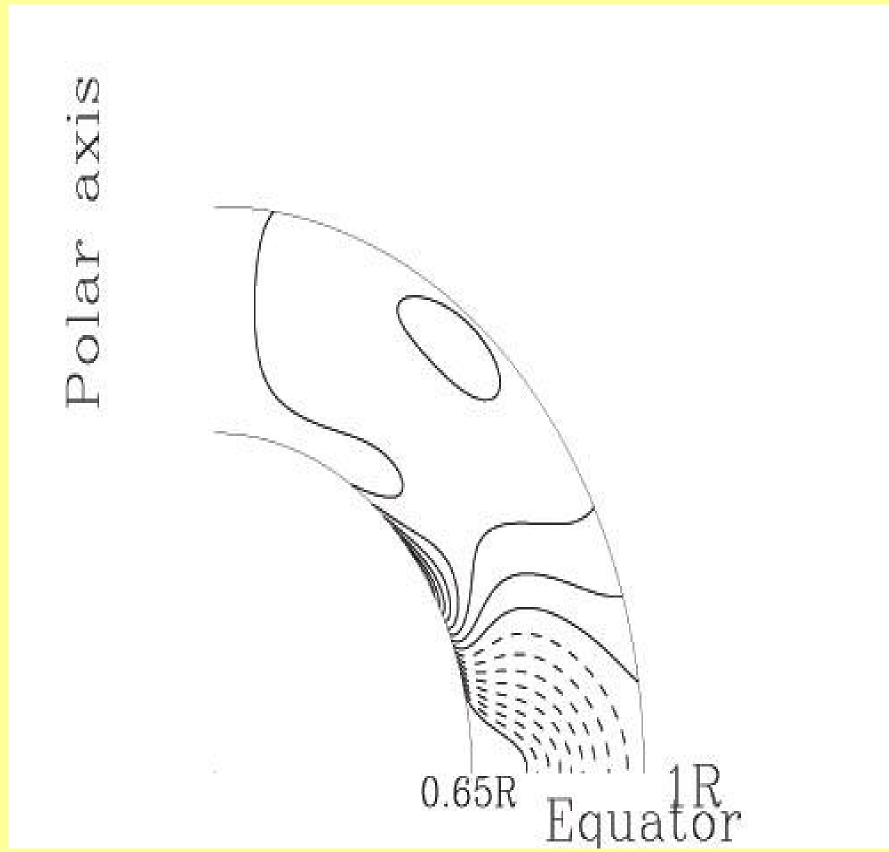
Linear η(r) doesn't bunch up field lines
(constant η(r) gradient)

10^12

10^10



0.6 r/R
1.0



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Preliminary results of numerical experiments

Diffusivity$_{\textbf{surface}}$:

- If η is too low at the surface, the field becomes concentrated there – particularly at the poles
- If η is high the field diffuses too much

Diffusivity$_{\textbf{tachocline}}$:

- If η is low near the base of the convection zone, then the field is frozen near the equator and tachocline

Shape:

- Linear $\eta(r)$ can handle the greatest range of diffusivity

Outstanding questions

- What is a reasonable range for diffusivity in the convection zone?
- How will a greater understanding of diffusion affect modeling flux transport?
- How does equatorward flow of field at tachocline contribute to the solar dynamo?

Possible future work

- Generate butterfly diagrams and time depth plots from our data
- Try new runs with different meridional flow patterns
- Compare results of these diffusion profiles with observations

References and acknowledgements

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Sources of figures

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Solar structure: Kenneth Lang, *The Cambridge Encyclopedia of the Sun,* Cambridge: Cambridge UP, 2001.

Butterfly diagram: http://www.mhhe.com/physsci/astronomy/fix/student/chapter17/17f35.html

Our runs are available at http://download.hao.ucar.edu/pub/green/dynamo/

This talk is available at http://academic.evergreen.edu/z/zita/research/summer2004/dynamo/NightHAO2.ppt