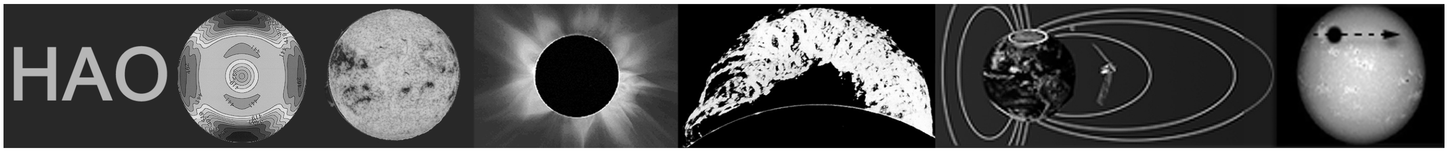


The Solar Dynamo

Peter A. Gilman

High Altitude Observatory

National Center for Atmospheric Research

SHINE 2002 Summer Workshop

NCAR

High Altitude Observatory (HAO) – National Center for Atmospheric Research (NCAR)

The National Center for Atmospheric Research (NCAR) is operated by the University Corporation for Atmospheric Research (UCAR) under sponsorship of the National Science Foundation. An Equal Opportunity/Affirmative Action Employer.

Layers of the Sun

Layer	Properties
core (r = 0 to ~.15)	Thermo nuclear reactions
radiative interior (r ~ .15 to 0.7)	Radiative diffusion, subadiabatic temperature gradient
tachocline (r ~ 0.7)	Strong DR, also TF?
convection zone (r ~ 0.7 to 1.0)	Convective heat transport
photosphere (r = 1.0)	Source of visible light, also where velocities measured
chromosphere, corona (r = 1.05 ~3 or 4)	Magnetically dominated
solar wind interplanetary medium	High speed streams

Solar Cycle Model "Tracks"

"Classical" Track	**"Heuristic, Semiempirical" Track**
Parker 1955 Dynamo Waves	Babcock Model
"Mean Field" Dynamo Theory	Leighton Random Walk Model
3D Spherical Convection Dynamos (*failed for Sun*)	
Interface Dynamos (*Parker*)	"NRL School" Models (*surface flux transport*)
Flux Transport Dynamos	

Where Next?

- Longitudinal Wave Number m > 0 (*non axisymmetric models*)
- Predictions of Subsequent Cycles

What is a Hydromagnetic Dynamo?

A conducting fluid in which the flow maintains the magnetic field "permanently" against ohmic dissipation.

Some General Requirements:

- Dynamos must be 3D in space. "Cowling's theorem" precludes 2D dynamos (proved 1934)
- Irony: Most solar dynamos ARE 2D; circumvents Cowling's theorem by parametric representation of 3D induction processes
- Simple estimates of ohmic decay time for, say, a star, are not enough to determine whether will have dynamo action (primordial fields are sometimes proposed)
- Why? Because **turbulence** can greatly enhance dissipation.
- Magnetic Reynolds number R_m must be sufficiently large

Properties that Promote Dynamo Action

(inferred from observation, verified by theory)

1. Rotation
2. Convection *(energy conversion)*
3. Size *(hard to make an MHD dynamo in the lab - R_m's too small)*
4. Complexity of flow pattern (Cowlings theorem). A particularly interesting flow property is its

KINETIC HELICITY

$$\vec{V} \cdot \nabla \times \vec{V}$$

- Is large when flow has spiral structure
- Would cause lifting & twisting of initially straight field line in highly conducting fluid.
- Combination of rotation and convection can lead to a lot of kinetic helicity, but can get it by other means also

Magnitude of Solar Dynamo Problem

Range of observed spatial scales in magnetic field & flow pattern: Factor of 10^5

Range of density variation from bottom to top of convection zone: Factor of 10^6

Density scale height $\sim 10^2$ top ($R_{sun}=7 \times 10^5$ km)
$\sim 3 \times 10^4$ km bottom

Dominant historical strategy:

- Stick to kinematic problem – specify velocities and solve for magnetic fields
- Keep problem global, parameterize all smaller scale effects

---

Advantage:

Avoids all of scale problems listed above

Disadvantage:

Need to know how to parameterize, and how to specify velocity fields

Observational Constraints on Solar Dynamo Theory

Structure & Velocities

- § Differential rotation with latitude, depth, time
- § Meridional circulation with latitude, depth, time
- § Convection zone depth
- § Existence of solar tachocline
- § Other motions from helioseismic interferences *(synoptic maps)*

Magnetic Properties

- § Butterfly diagram for spots
- § Hales polarity laws
- § Field reversals
- § Phase relation in cycle between toroidal & poloidal fields
- § Field symmetry about equator
- § Field “handedness” (*current helicity, magnetic helicity)*
- § Solar cycle envelope
- § Cycle period – cycle amplitude relation
- § Active longitudes
- § Sunspot group tilts *(Joy’s Law)*, asymmetries between leaders & followers
- § Others???

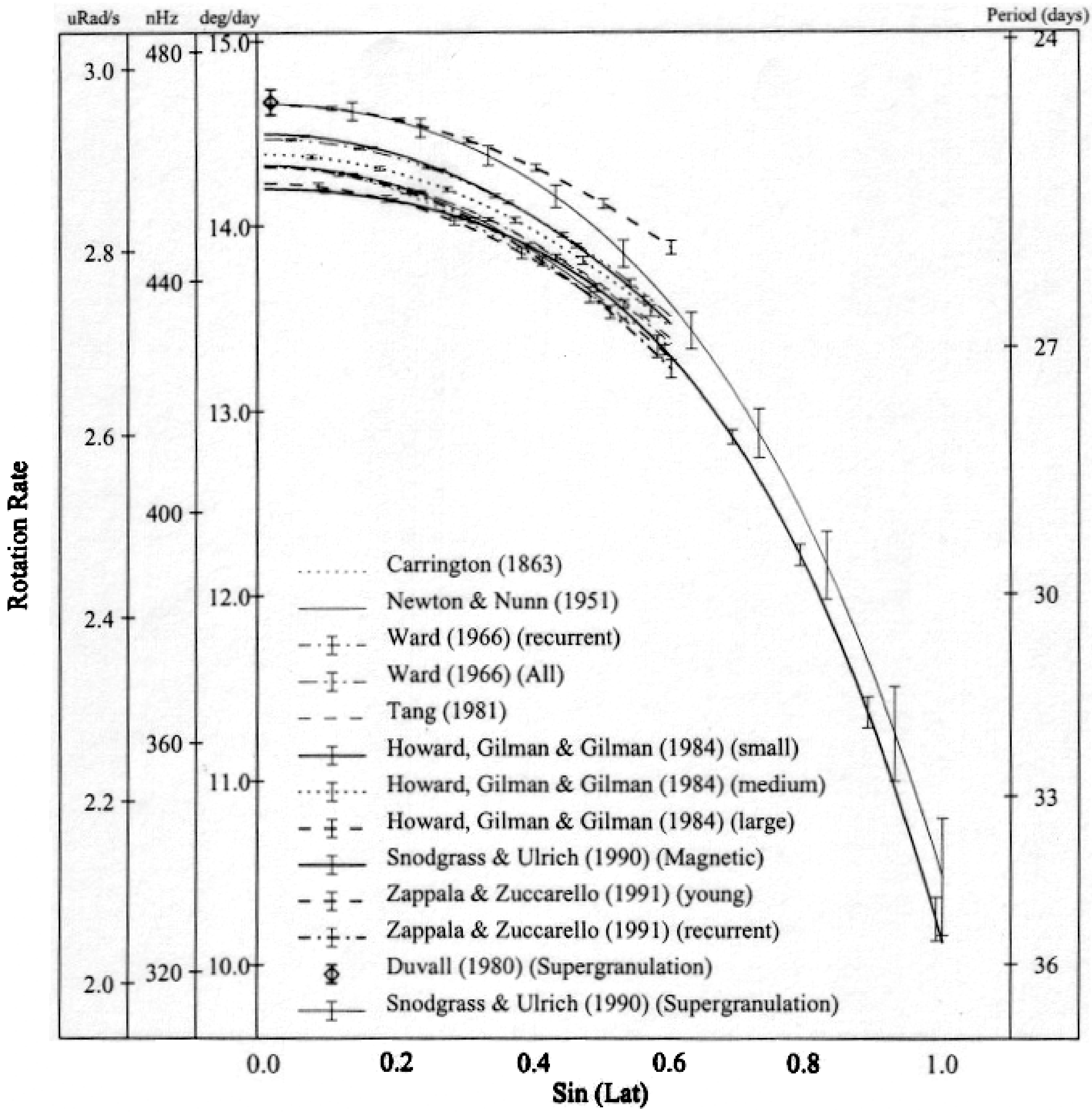
Physical Processes That May Be Important in the Solar Dynamo

Inclusion in dynamo models:
Explicitly-**E**; *Parameterized*-**P**; A*bsent*-**N**

- **E** Shearing of poloidal fields by differential rotation
- **E** §Flux transport by meridional circulation
- **P** Lifting & twisting of fields by helical motions *(_-effect)*
- **P** §Rising of magnetically buoyant flux tubes *(effect of Coriolis forces)*
- **P** §Turbulent diffusion of fields *(all directions)*
- **P** Random walk of surface fields *(across photosphere)*
- **P** §Turbulent pumping of fields *(downward)*
- **P** §Field reconnection in convection zone
- **P** §Joint instability of differential rotation & toroidal field in the tachocline
- **N** §Flux transport by other near surface flows
- **N** §Ejection of flux by CMEs
- **N** §Field reconnection in chromosphere, corona
- **N** §Flux injection into convection zone by instability of toroidal field to rising loops

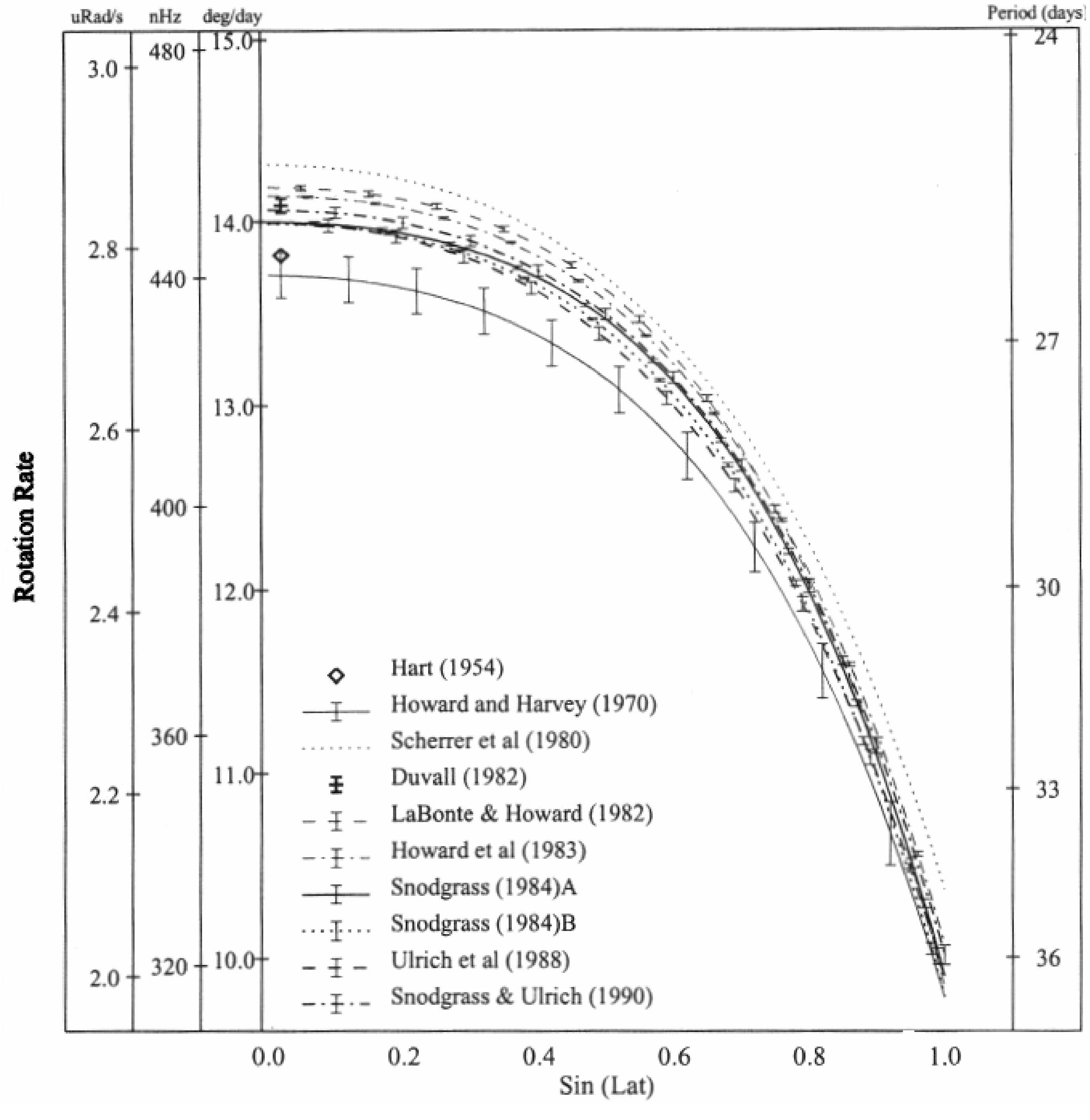
Others???

Tracer Rotation



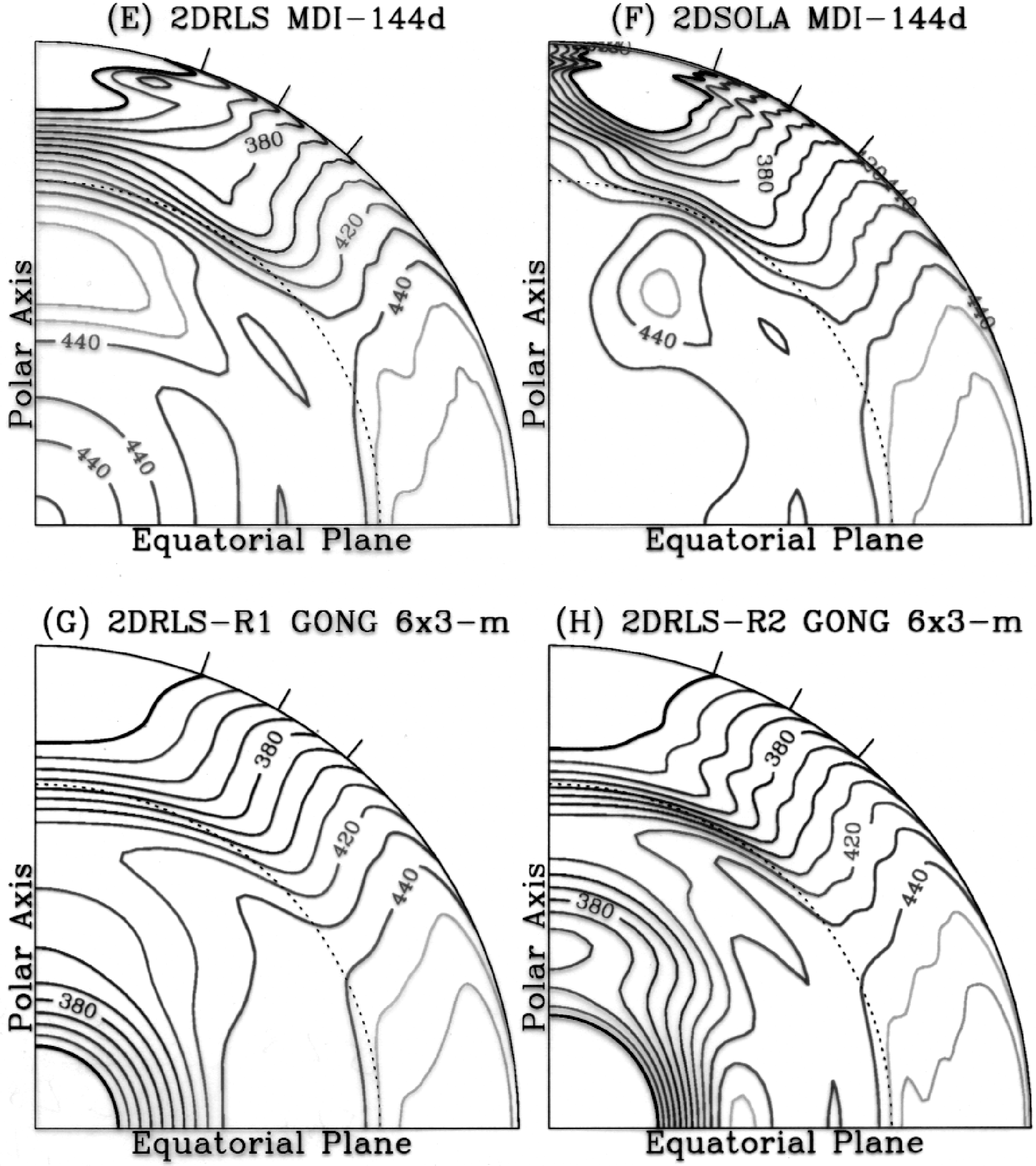
(*Reprinted from Beck, John G., A Comparison of Different Rotation Measurements , Solar Physics, 191: 47-70, 1999.*)

Spectroscopic Rotation



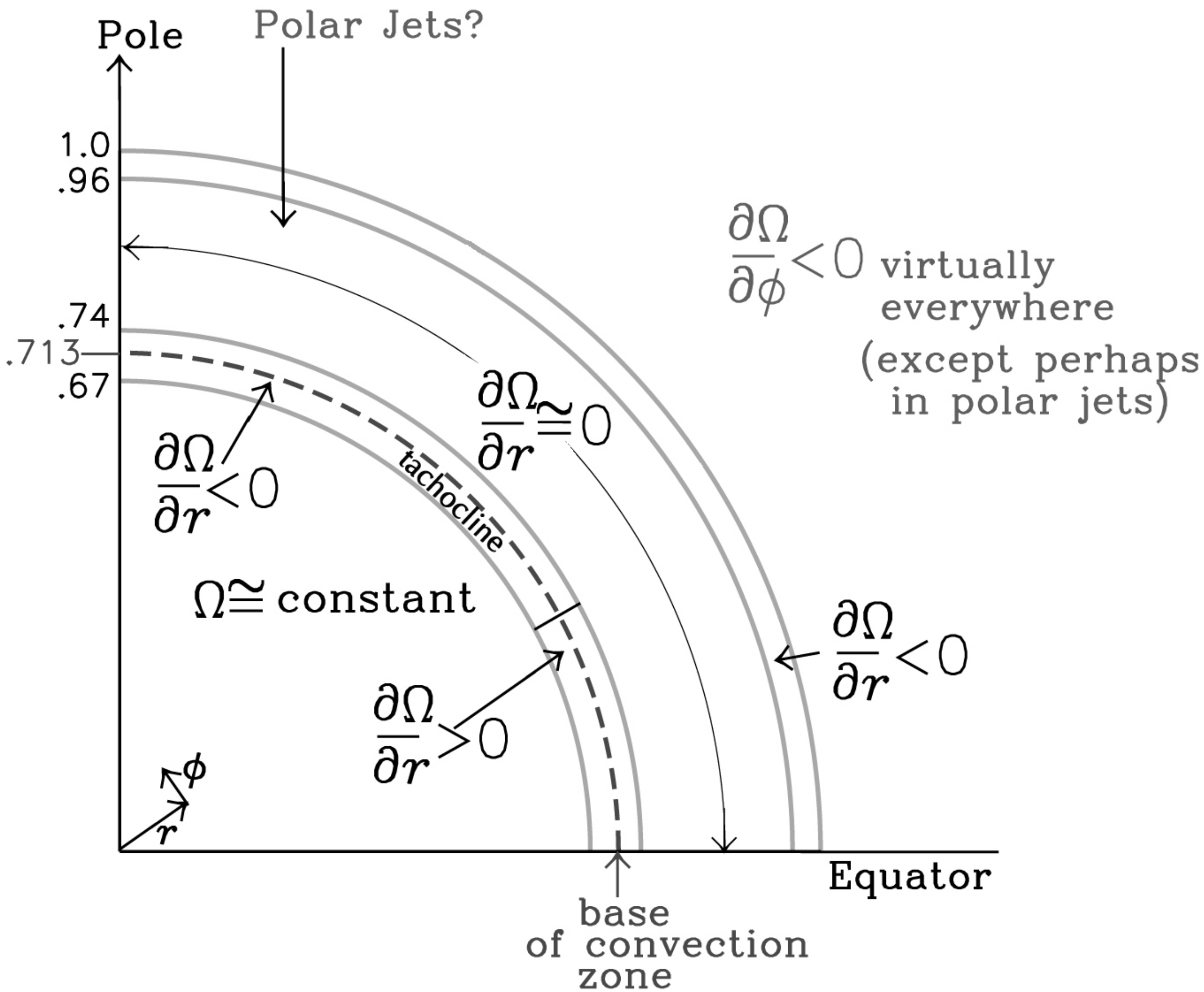
(*Reprinted from Beck, John G., A Comparison of Different Rotation Measurements , Solar Physics, 191: 47-70, 1999.*)

Differential Rotation from Helioseismic Analysis



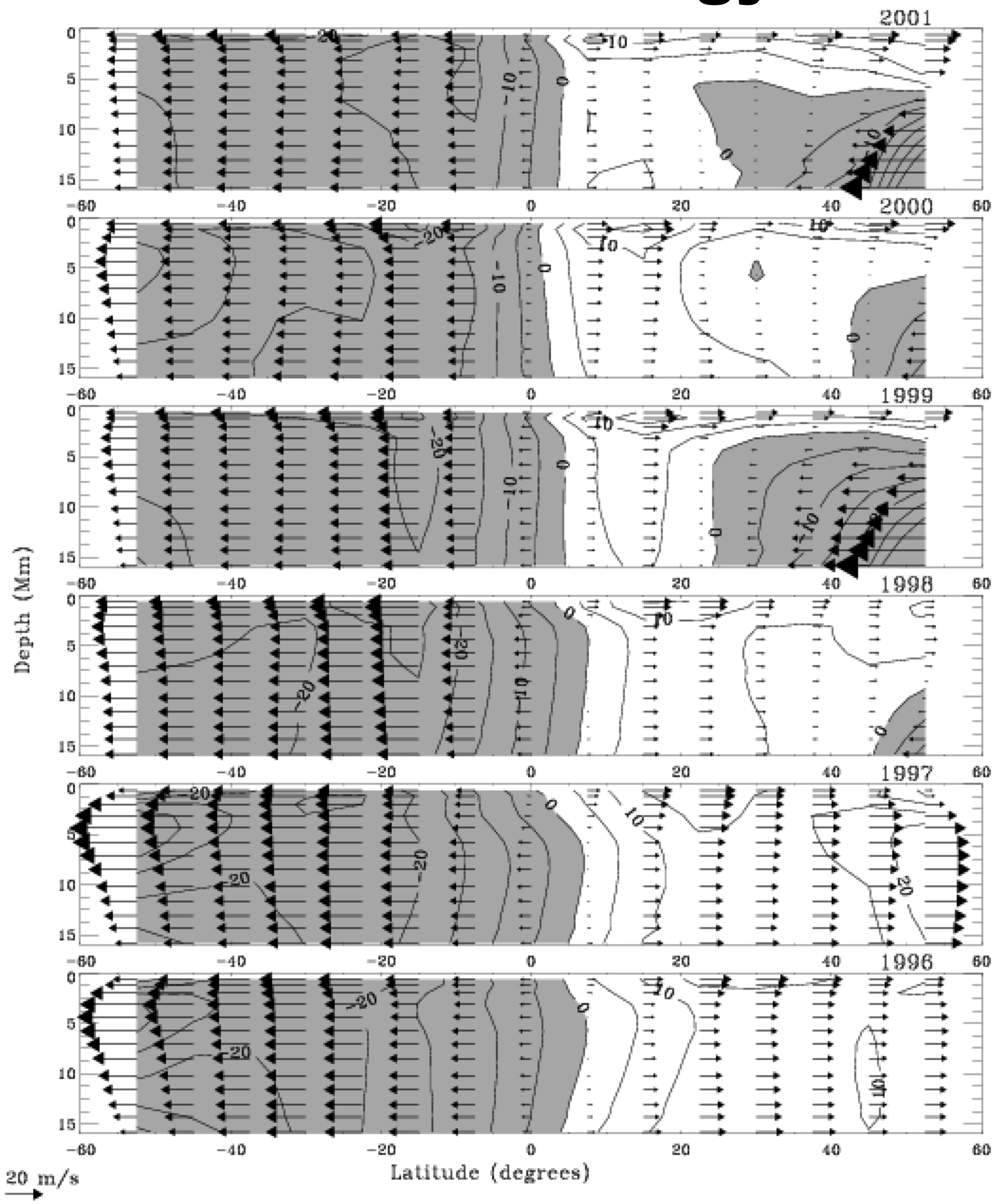
(*Used with permission from Paul Charbonneau*)

Angular Velocity Domains in Solar Convection Zone and Interior, from Helioseismology



Peter A. Gilman

Meridional Circulation from Helioseismology



(Courtesy of JILA, University of Colorado)

Observed and Inferred Characteristics of Meridional Circulation

(from a variety of sources)

- Usually poleward flow in each hemisphere ~20m/sec.
- Surface variations with the time 50-100%.
  (how much real, how much noise?)
- One circulation cell replaced by two at times.
- North & South hemispheres can look quite different.
- Cell in one hemisphere can extend several degrees latitude to the other.
- Surface Doppler & helioseismic results often do not agree. Spots as tracers show much smaller drift.
- Flow amplitude likely determined by small differences among large forces *(Coriolis, pressure gradients, turbulent stresses, and buoyancy?)*, so significant fluctuations likely.
- Most mass transport well below photosphere, because flow speed observed to change slowly with depth.
- Must be return flow near bottom of convection zone, but not observed yet.
- Return flow amplitude should respond quickly *(sound travel time?)* to poleward flow changes above *(has implications for cycle prediction).*

Mean Field Dynamo Equations

(Steenbeck, Krause, Radler, et al.)

$$\frac{\partial B}{\partial t} = \nabla \times \left(\mathrm{U} \times \mathrm{B} + \alpha B - (\eta + \beta) \nabla \times B \right)$$

Turbulent diffusion

Molecular diffusion

Differential rotation and/or meridional circulation

~ Kinetic helicity of lifting and twisting (“_-effect”)

on sphere, solve for axisymmetric magnetic field

$$\mathrm{B}(\mathrm{r},\theta,\mathrm{t}) = \underbrace{\nabla \times \left(\mathrm{A}(\mathrm{r},\theta,\mathrm{t})\hat{\mathrm{e}}_\phi \right)}_{\text{“Poloidal” Field}} + \underbrace{\mathrm{B}_\phi(\mathrm{r},\theta,\mathrm{t})\hat{\mathrm{e}}_\phi}_{\text{“Toroidal” Field}}$$

Axisymmetric Dynamo Evolution

	Mean Field (70s – 80s)	Interface (early-mid 90s)	Flux Transport (late 90s – present)
Velocity Constraints	Surface Differential Rotation →	DR with latitude & radius; Tachocline properties →	DR with latitude & radius; meridional circulation; Tachocline properties
Velocity Constraints	α-effect assumed →	α-effect assumed →	α-effect from observations of Babcock-Leighton process, and/or tachocline global instabilities
Magnetic Constraints	Hales Laws Butterfly Diagram Toroidal/Poloidal phase difference →	Same + Strong TF in tachocline →	Same + Current helicity or "handedness"; cycle period amplitude correlation; Field symmetry about equator

Some Major Effects of Observational Constraints on Dynamo Models

- Differential rotation with radius contradicted assumption in 1970s mean field models; led to putting dynamo at base of convection zone. Also contradicted 3D global convection models.

- Sunspots only in low latitudes led to requirements of ~100 kG fields at base as source, because magnetic buoyancy must overcome Coriolis forces.

- Tachocline differential rotation allows induction of strong toroidal fields at location where they can be held in storage until erupt as active regions.

- Observed meridional circulation strong enough to determine dynamo period (*correctly*), over-powering combination of radial differential rotation and α-effect.

First Solar Dynamo Paradox

- Mean field dynamo theory applied to sun required rotation increase inward
- Global convection models predicted rotation approximately constant or cylinders, but with equatorial acceleration ~30%

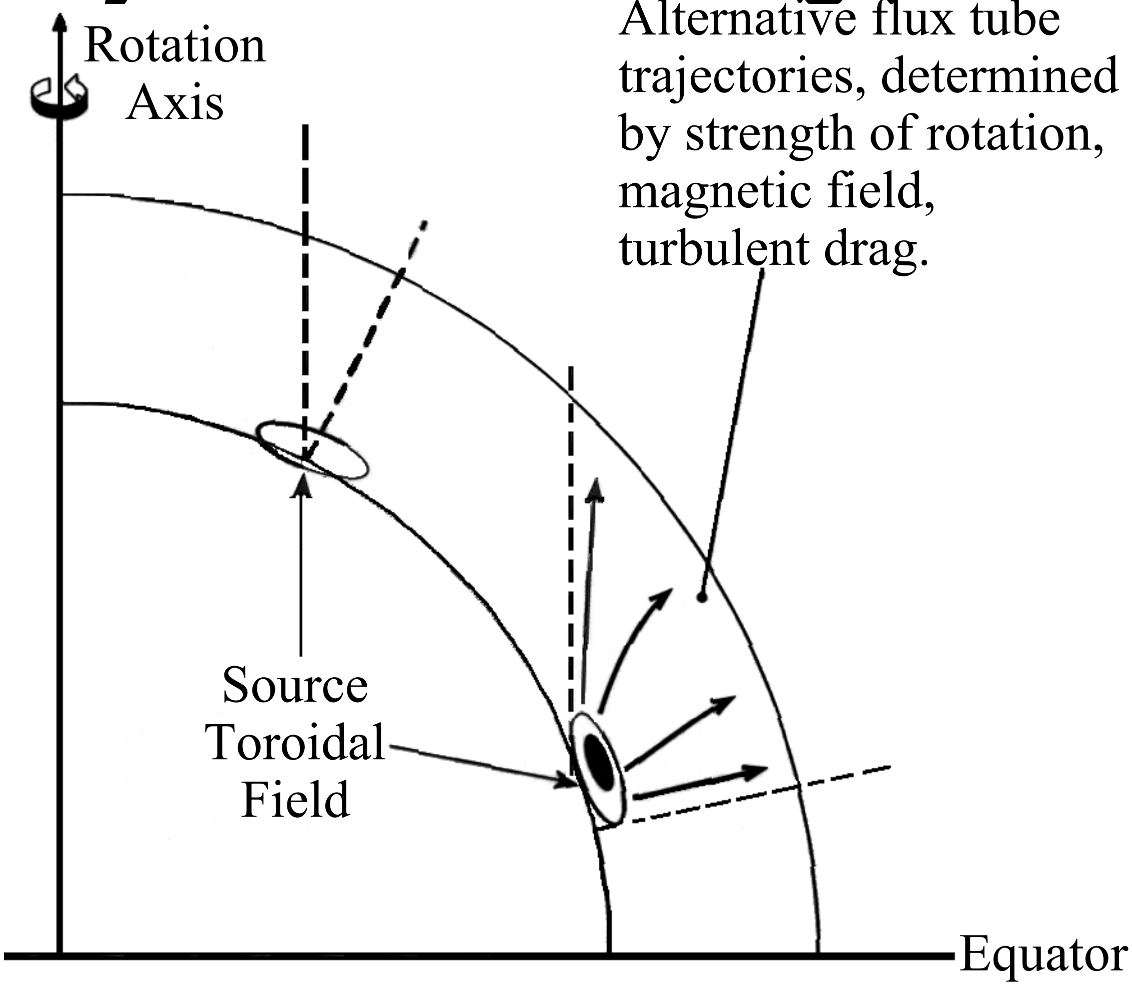
In 1970s prevailing view was that global convection theory must be wrong (I never shared that view).

In 1980s helioseismic inferences proved both were wrong, but dynamo theory more wrong than convection theory.

Conclusion

Move dynamo to base of convection zone

Schematic of Range of Trajectories of Rising Tubes



Limiting Cases:

Strong Rotation	Weak Rotation
Weak Magnetic Fields	**Strong** Magnetic Fields
Weak Turbulence	**Strong** Turbulence

Œ
Trajectory Parallel to the Rotation Axis

Œ
Trajectory Radial

*Choudhuri and Gilman, 1987, ApJ., **316**, 788.*

Second Solar Dynamo Paradox

- To produce sunspots in low latitudes requires toroidal fields ~10^5 gauss at the base of the convection zone (influence of Coriolis forces on rising tubes)

- 10^5 gauss fields very hard to store – must be below convectively unstable layer (overshoot layer subadiabatic?)

- 10^5 gauss fields are 10^2 x equipartition – won't that suppress dynamo action? (but apparently does not in geo case!)

Resolution

Interface Dynamos

Flux Transport Dynamos

Interface Dynamos

(Introduced by Parker ApJ. 408, 707, 1993)

Elements:

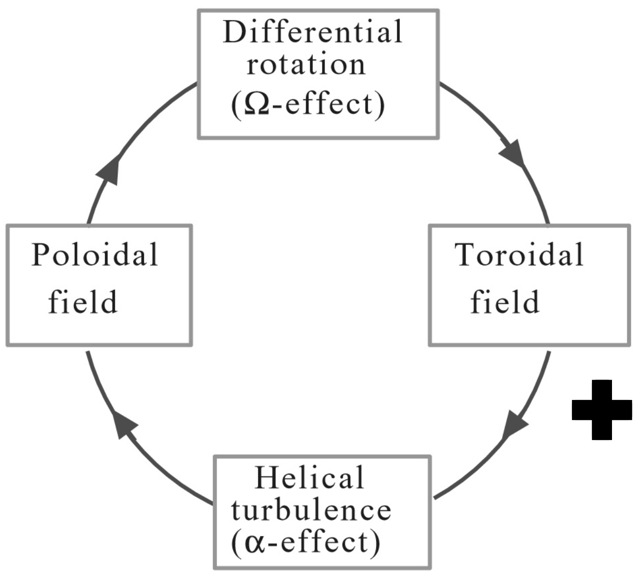
Interface at base of convection zone (at tachocline)

Below interface:	helicity or α small turbulent diffusivity small radial differential rotation **large**
Above interface:	helicity or α small turbulent diffusivity **large** radial differential rotation small

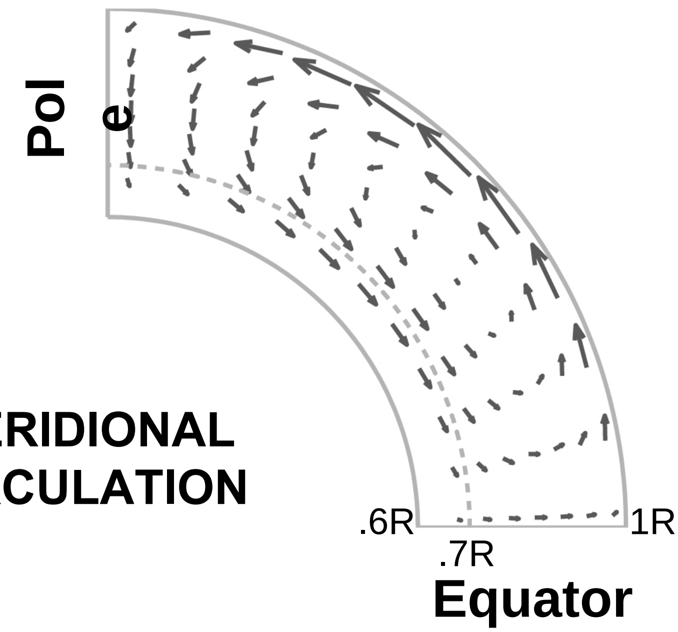
Weak diffusion across interface crucial.

Solutions work:

Below interface:	Toroidal field **large** Poloidal field small
Above interface:	Toroidal field small Poloidal field **large**



✚ MERIDIONAL CIRCULATION



⇒ FLUX-TRANSPORT DYNAMO

(Dikpati & Choudhuri, 1994, A&A, 291, 975.)

(Choudhuri, Schüssler, & Dikpati, 1995, A&A, 303, L29.)

(Durney, 1995, SolP, 160, 213.)

Flux Transport
Mean Field Dynamos

Solved Including:

- Meridional circulation *(single celled, with surface flow toward poles)*

- Nonlinear and nonlocal α-effect arising from twist acquired by rising buoyant flux tubes acted upon by Coriolis forces

- α-effect from global HD/MHD instabilities in tachocline

Successes:

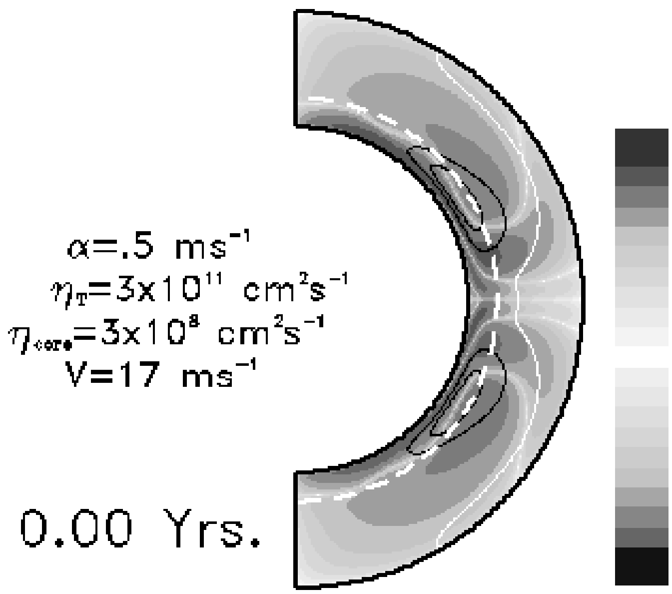
- Reversal frequency determined by amplitude of meridional circulation

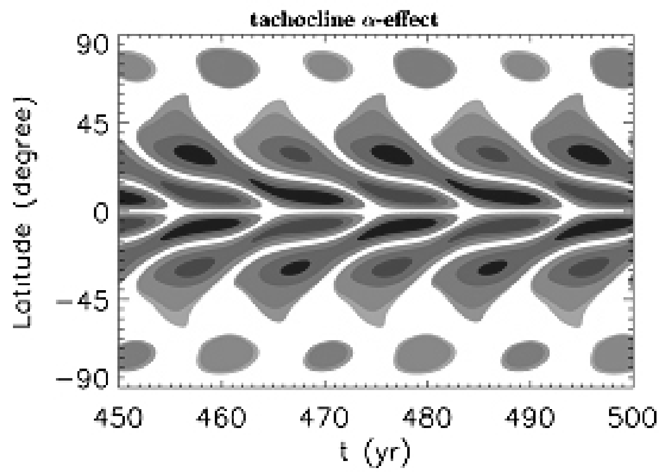
- Observed meridional circulation leads to observed solar cycle period! *(Relatively independent of α magnitude, profile)*

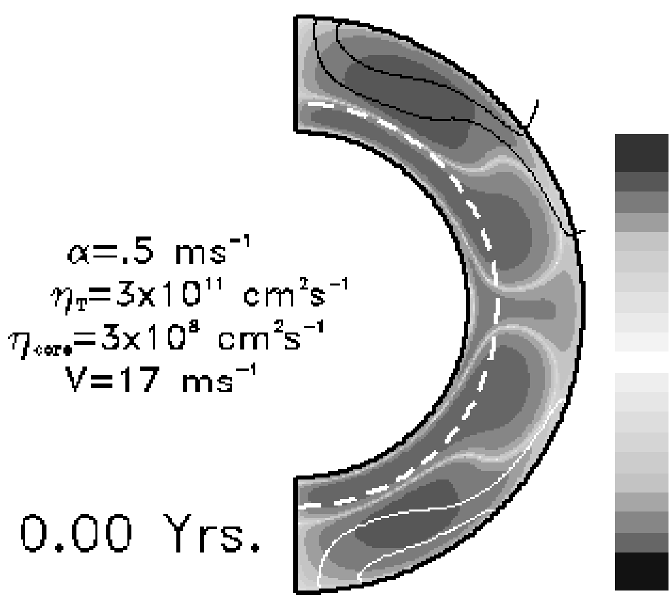
- α-effect near bottom from global HD/MHD instability in tachocline leads to correct magnetic field symmetry about equator *(Hales Law)*

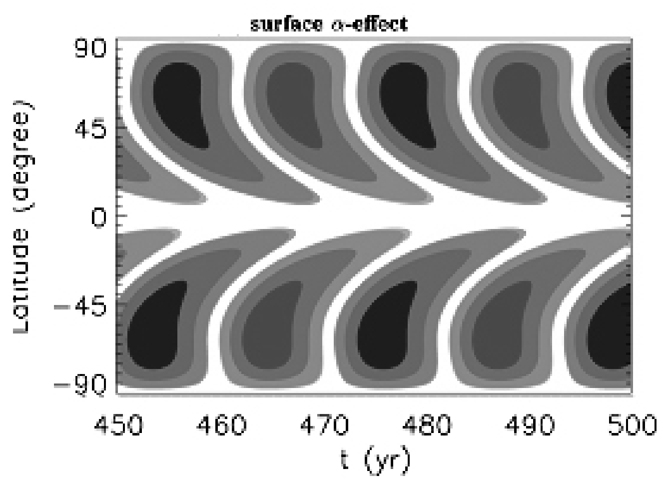
Evolution of Magnetic Fields In Flux-Transport Dynamos

(Dikpati Model)









How Much Solar Rotation, Meridional Circulation Theory is Needed to do Solar Dynamos?

Kinematic Axisymmetric Dynamos:

NONE - Just need enough observational detail of rotation, meridional circulation

Ultimate MHD Dynamo:

- Full theory for solar differential rotation, meridional circulation, convection and magnetic fields including convection zone & tachocline;
- Early attempts were dynamos, but got wrong radial rotation gradient and butterfly diagram;
- Same problem today

A Promising Intermediate Step:

- Combine a global MHD theory of the tachocline with kinematics of the convection zone
- Requires focus on theory of coexisting toroidal field and differential rotation in the tachocline *(this is tractable)*

What Would Happen Now if we did Full MHD Dynamo Simulations with the Best Available Global Convection Model?

- Would still get wrong butterfly diagram (migration towards poles rather than equator)
- Toroidal fields probably much too weak, diffuse
- Would not be able to handle both storage of flux at the bottom, as well as bulk convection zone dynamics.
- Fields too diffuse, partly because of resolution limits. Means flow in model cannot “get around” magnetic flux the way it can in real sun.
- Answer may be to have hybrid dynamo, with full MHD in tachocline, but kinematic in convection zone above.

Hybrid Nonaxisymmetric Dynamo With Some MHD

Properties:

- 2D or 3D global MHD in the tachocline
- Flux transport model for bulk convection zone, with assumed DR and MC from observations
- DR from convection zone imposed on tachocline
- Global $m \neq 0$ patterns generated in tachocline diffuse into convection zone

Hybrid Nonaxisymmetric Dynamo With Some MHD

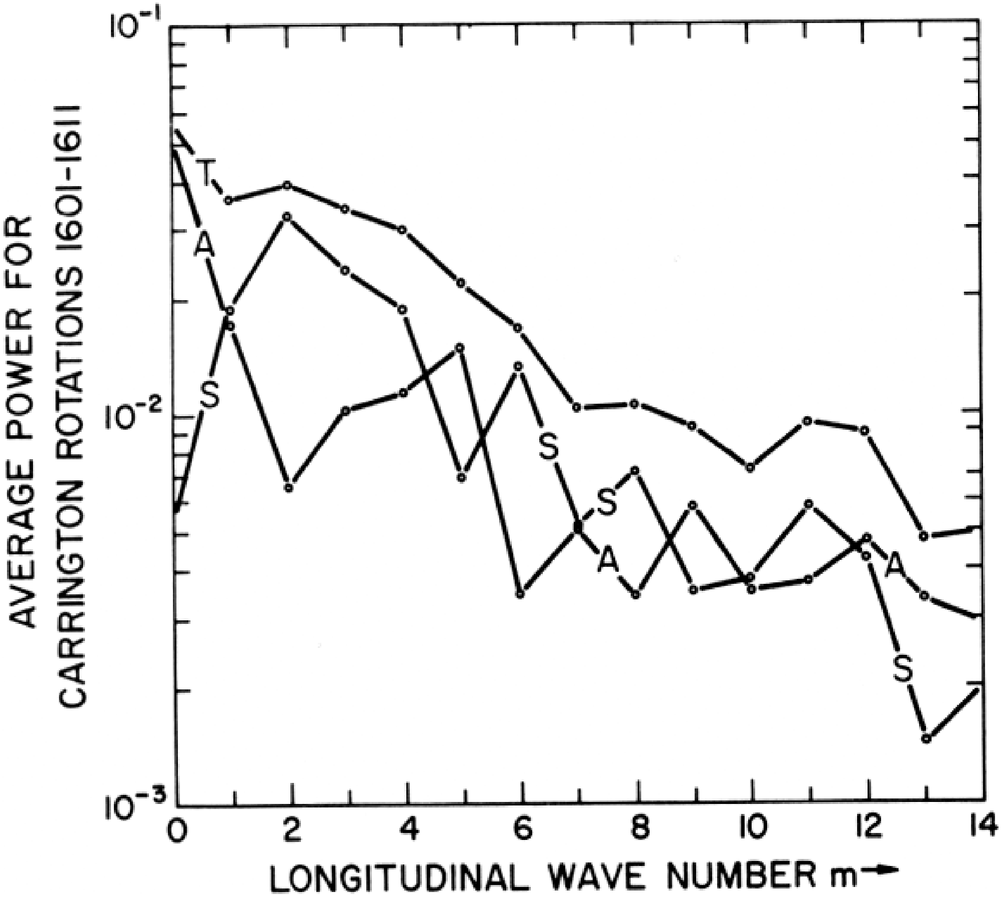
Advantages:

- Avoids use of global theory of convection and differential rotation and meridional circulation that we know from previous calculations will give dynamo results in conflict with solar observations, i.e., wrong butterfly diagram

- Can extend flux transport dynamos to physics-based modeling of $m \neq 0$ magnetic patterns

- Can directly assess the relative roles played by meridional circulation and tachocline dynamics in determining dynamo properties

Power Spectrum of the Magnetic Field

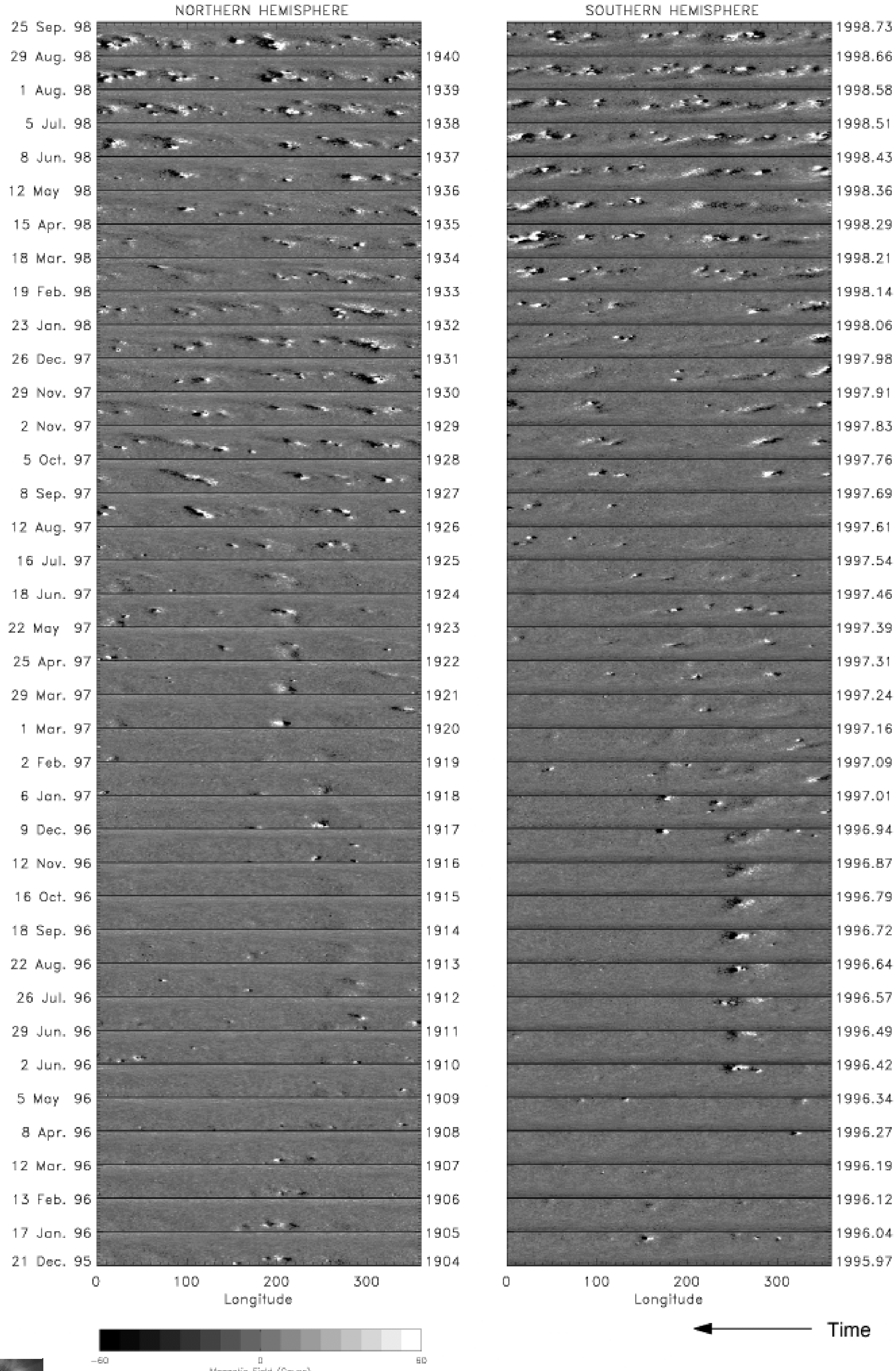


Power in lowest longitudinal wave numbers, integrated over all latitudes, of the observed photospheric radial magnetic field (from Kitt Peak magnetograms), averaged over Carrington rotations 1601-1611.

- The segmented curve **T** represents the total power in each wave number
- The curve **S** represents power in that part of the field which is symmetric about the equatorial plane
- The curve **A** the antisymmetric part
- **T** is simply the sum of **S** and **A**.

(Reprinted from Coronal Holes and High Speed Wind Streams, edited by J. B. Zirker, c. VIII, p. 340,1977.)

deToma et al. Active Region Plots in Time



Global, Quasi 2D MHD of the Solar Tachocline

Ingredients:

- Differential Rotation
- Subadiabatic Stratification
- Strong Toroidal fields

- MHD analog to classical GFD problems of barotropic & baroclinic instability
- Magnetic field can make unstable differential rotations that are stable without it
- If allow some variation in radial direction, instability can generate kinetic helicity.
- Subject of continuing long term study by: Gilman, Fox, Dikpati, Cally, Miesch
  (in order of first involvement)

Global Quasi-2D MHD Instability of Tachocline Results

(Gilman, Fox, Dikpati, Cally)

- DR and TF generally unstable to global waves, particularly longitudinal wave number m = 1, sometimes also m = 2 or higher.

- efolding Growth Times: few months – few years.

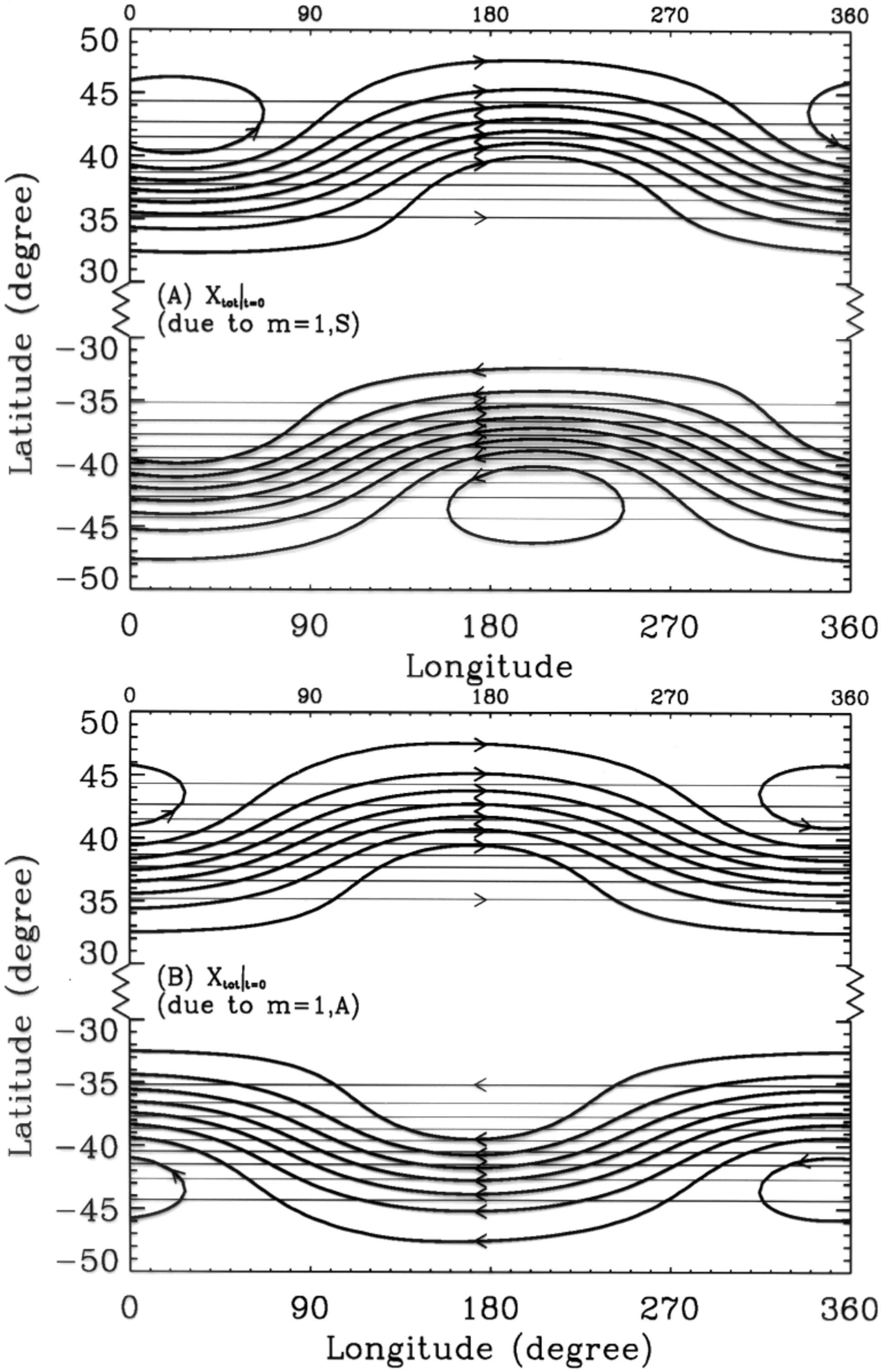
- Longitudinal Propagation Speeds: between minimum and maximum rotation rates (Ł max for strong fields)

- Nonlinear growth leads to "tipping" of toroidal field rings *(can be same or opposite in NH and SH)*

- Allowing even weak radial motions leads to unstable modes with kinetic helicity Ł α-effect

- Global disturbances in tachocline could set "template" for surface magnetic features.

Tipped Toroidal Ring in Longitude-latitude Coordinates Linear Solutions with Two Possible Symmetries



(Cally, Dikpati, & Gilman, 2002 ApJ, submitted)

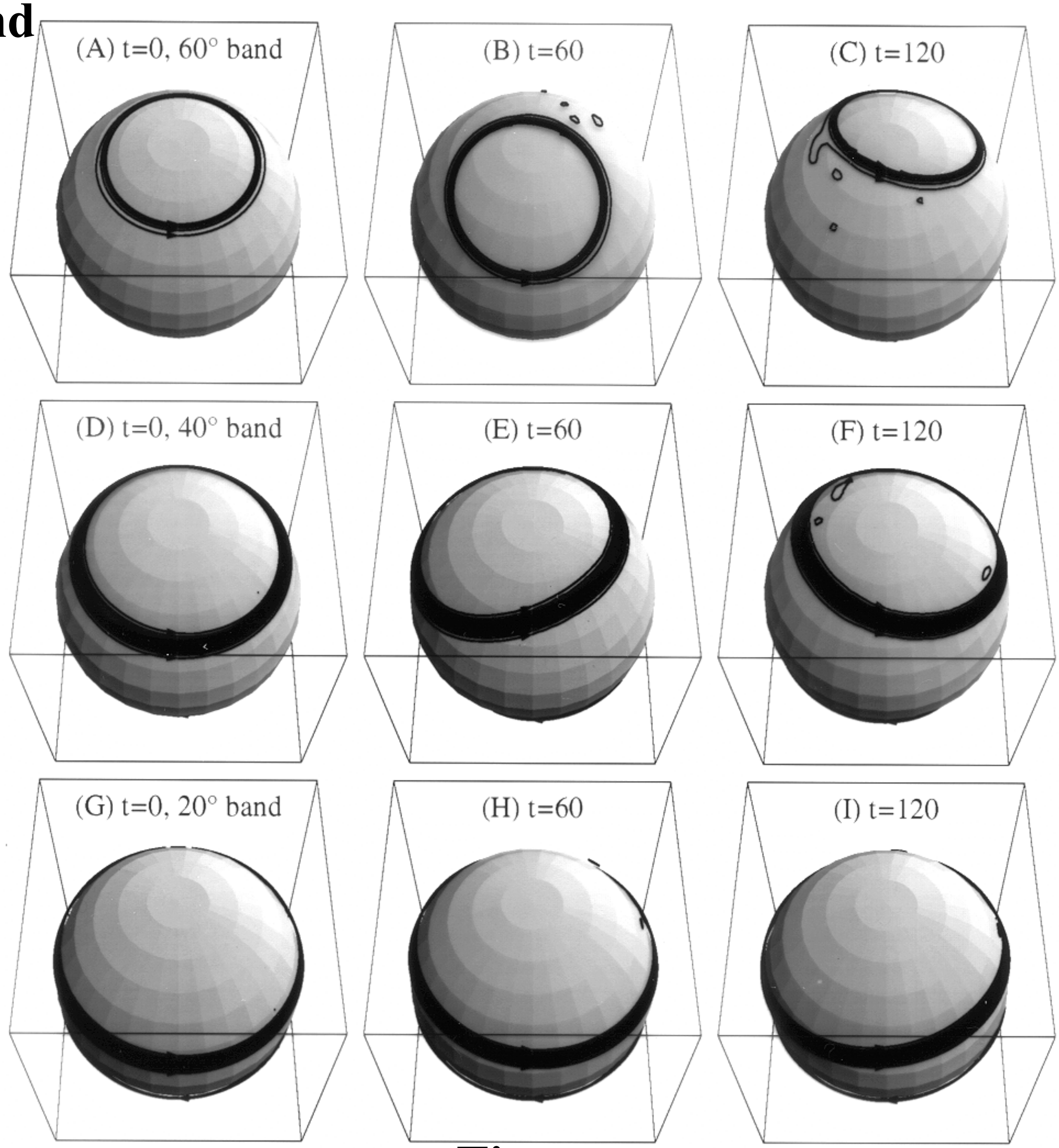
Nonlinear Evolution of Tip of Toroidal Rings Due to 2D MHD Instability

Latitude of band

60º

40º

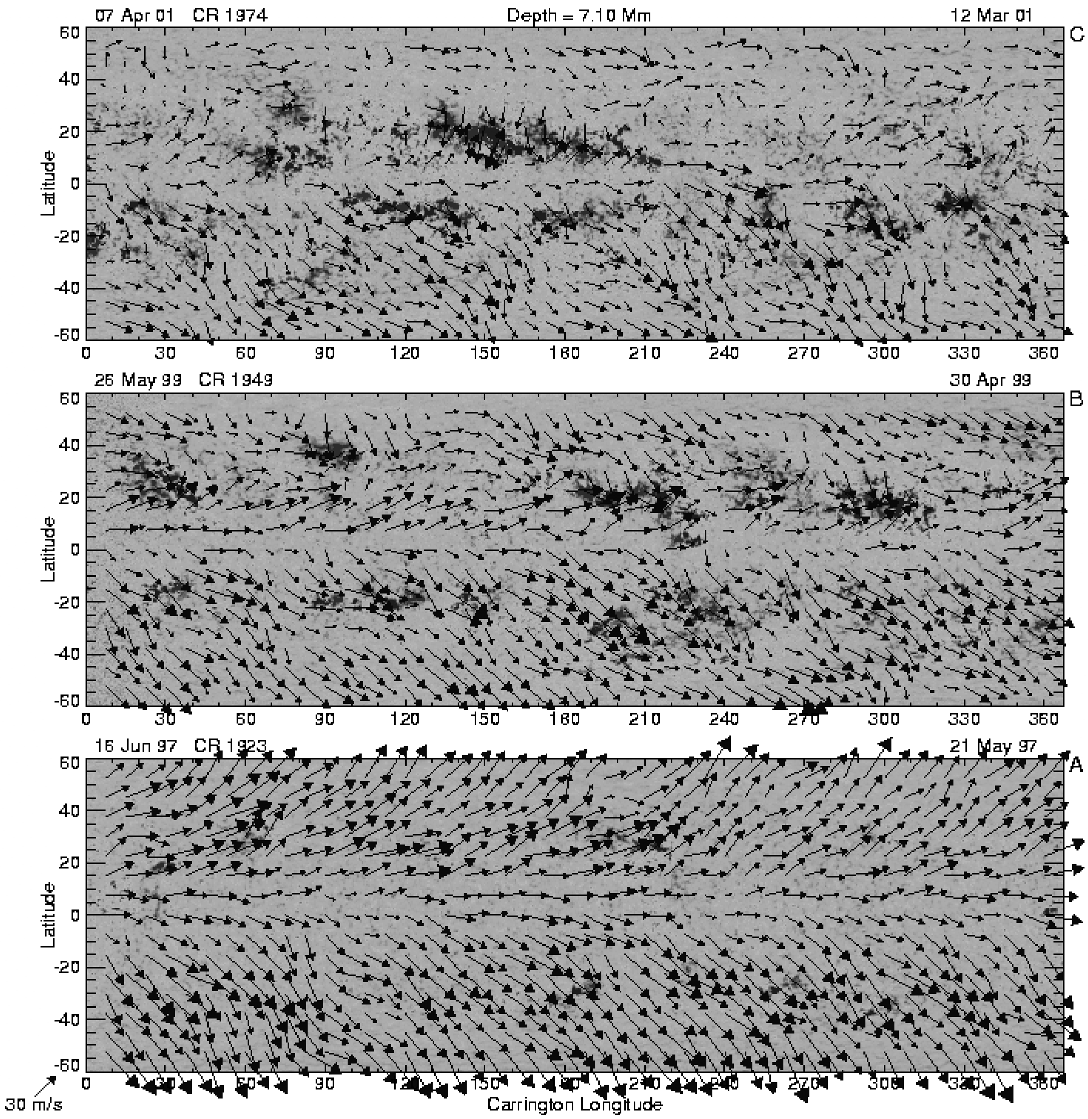
20º



Time Ł

(Cally, Dikpati, & Gilman, 2002, ApJ, submitted)

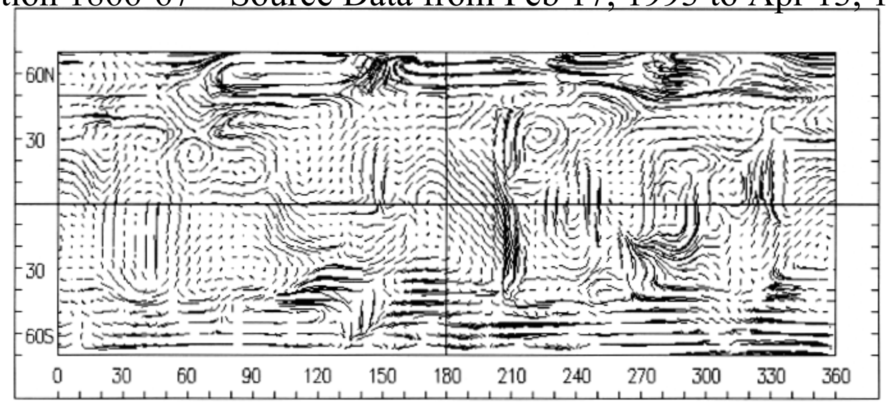
Solar Subsurface Weather (SSW) (*JILA/CU*)



Solar Subsurface Weather (SSW) JILA / University of Colorado

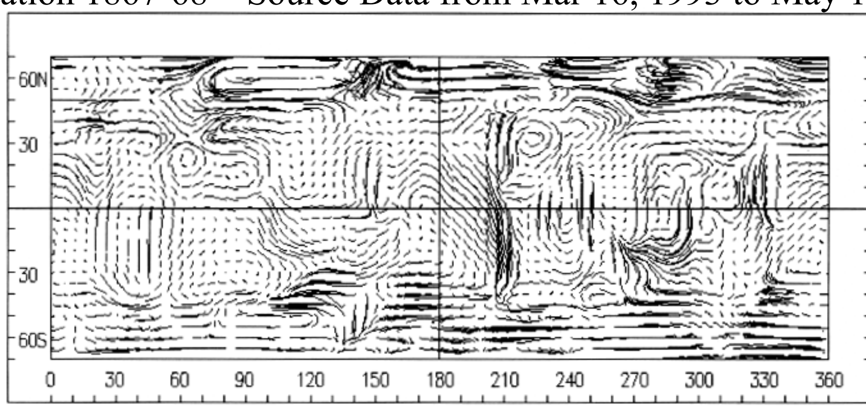
Synoptic Flow from Magnetic Patterns

Rotation 1866-67   Source Data from Feb 17, 1993 to Apr 13, 1993



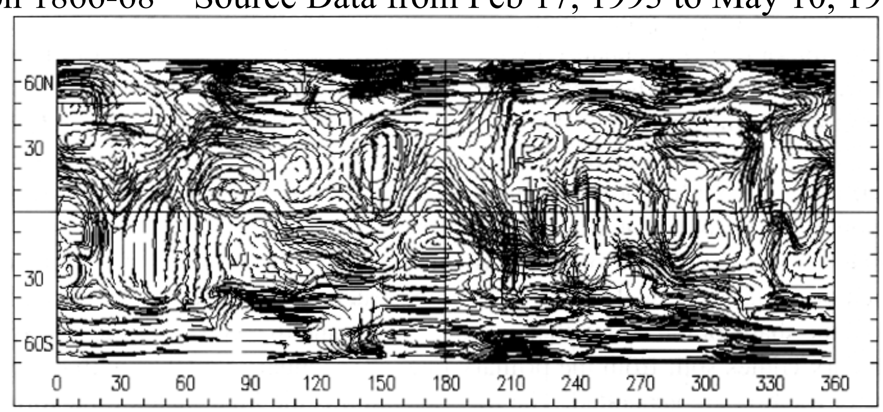
CARRINGTON LONGITUDE

Rotation 1867-68   Source Data from Mar 16, 1993 to May 10, 1993



CARRINGTON LONGITUDE

Rotation 1866-68   Source Data from Feb 17, 1993 to May 10, 1993



CARRINGTON LONGITUDE

*P. Ambro_from Solar Physics, **199**: 251-266, 2001.*

Possible Causes of Dominance of (1) Dipole Symmetry & (2) N-S Asymmetries

(1) Location of kinetic helicity or "α-effect" (*top versus bottom)*

Others?

(2) Asymmetries in differential rotation and/or meridional circulation

(3) Stochastic fluctuations

What Should Affect Cycle Strength?

- Differential rotation amplitude
  (*doesn't vary much*)

- Meridional circulation amplitude
  (*varies a lot*)

- Storage time for toroidal magnetic fields below convection zone
  (*in tachocline*)

- Threshhold for magnetic flux injection into convection zone

- Stochastic variations

- Others?

What Should Affect Polar Field Reversals?

- Random walk rate
  (*variations unknown*)

- Meridional circulation
  (*variability large fraction of mean value*)

- Meridional transport by nonaxisymmetric motions
  (*not studied yet*)

- In-situ magnetic flux emergence
  (*hard to estimate*)

- In-situ magnetic flux submergence
  (also hard to estimate)

Sources of Departures from Equatorial Symmetry

- Random fluctuations in flux eruption
- N/S asymmetries in meridional circulation
- N/S asymmetries in differential rotation
- N/S asymmetries in other synoptic-scale motions

A Case-Study Thought Experiment

Meridional circulation was weaker, or reversed, in NH in years leading up to cycle 23 reversal, so might expect reversal later there. But in fact it was apparently earlier or the same

---

Possible reasons:

- NH less eruption of new flux?
- NH cycle phase already ahead of SH?
- NH polar flux weaker to start with?