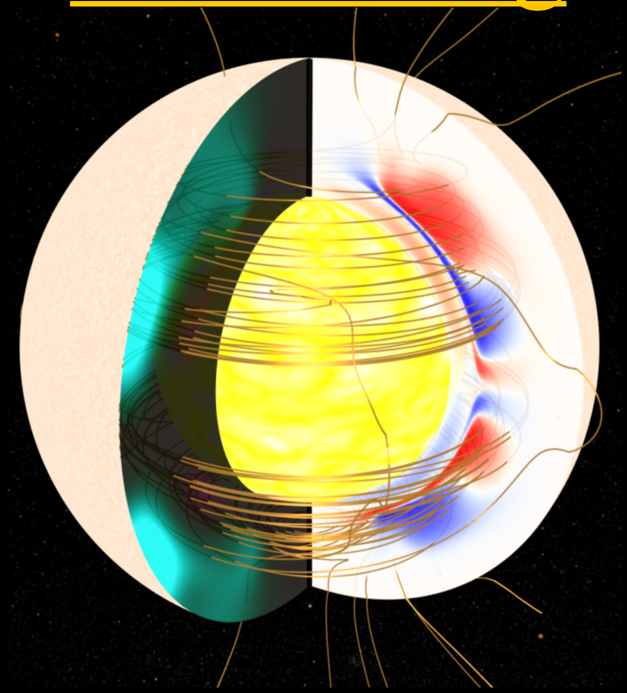
AAS-SPD Karen Harvey Prize Lecture, 12th June, 2012, Anchorage, Alaska

The Solar Cycle: From Understanding to Forecasting



Dibyendu Nandy

Indian Institute of Science Education and Research, Kolkata

IISER KOLKATA

Influences…


CANADA
MONTANA
Havre
Glacier Nat'l. Pk.
Clark Fork
Flathead Lk.
Missouri
Ft. Peck Lake
ROCKY MTS.
Great Falls
Missoula
HELENA
Anaconda
Butte
Billings
Bozeman
Jefferson
Yellowstone Nat'l. Pk.
IDAHO
WYOMING
DAKOTA
enmark)
Indian claim
Chinese line of control
Srinagar
Amritsar
CHINA
Brahmaputra
NEPAL
NEW DELHI
Agra
Kanpur
BHUTAN
Imphal
Ganges
Bhopal
Ahmadabad
Calcutta
Haldia
BANGLADESH
BURMA
Mumbai (Bombay)
Hyderabad
Bay of Bengal
Chennai (Madras)
Bangalore
Pondicherry
Andaman Islands
0 200 400 km
0 200 400 mi
Meet the MSU Solar Physics Group
Read our story

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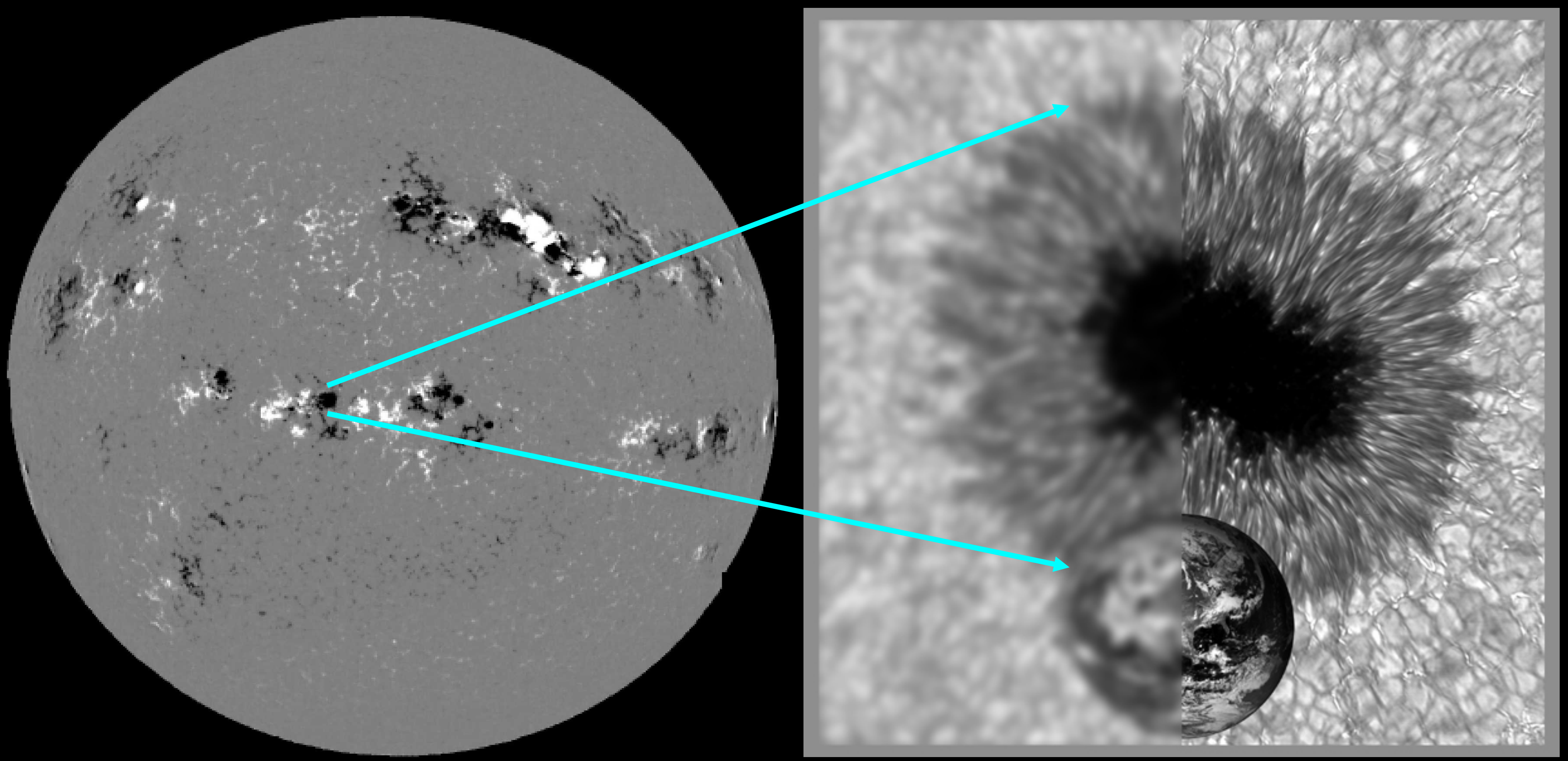
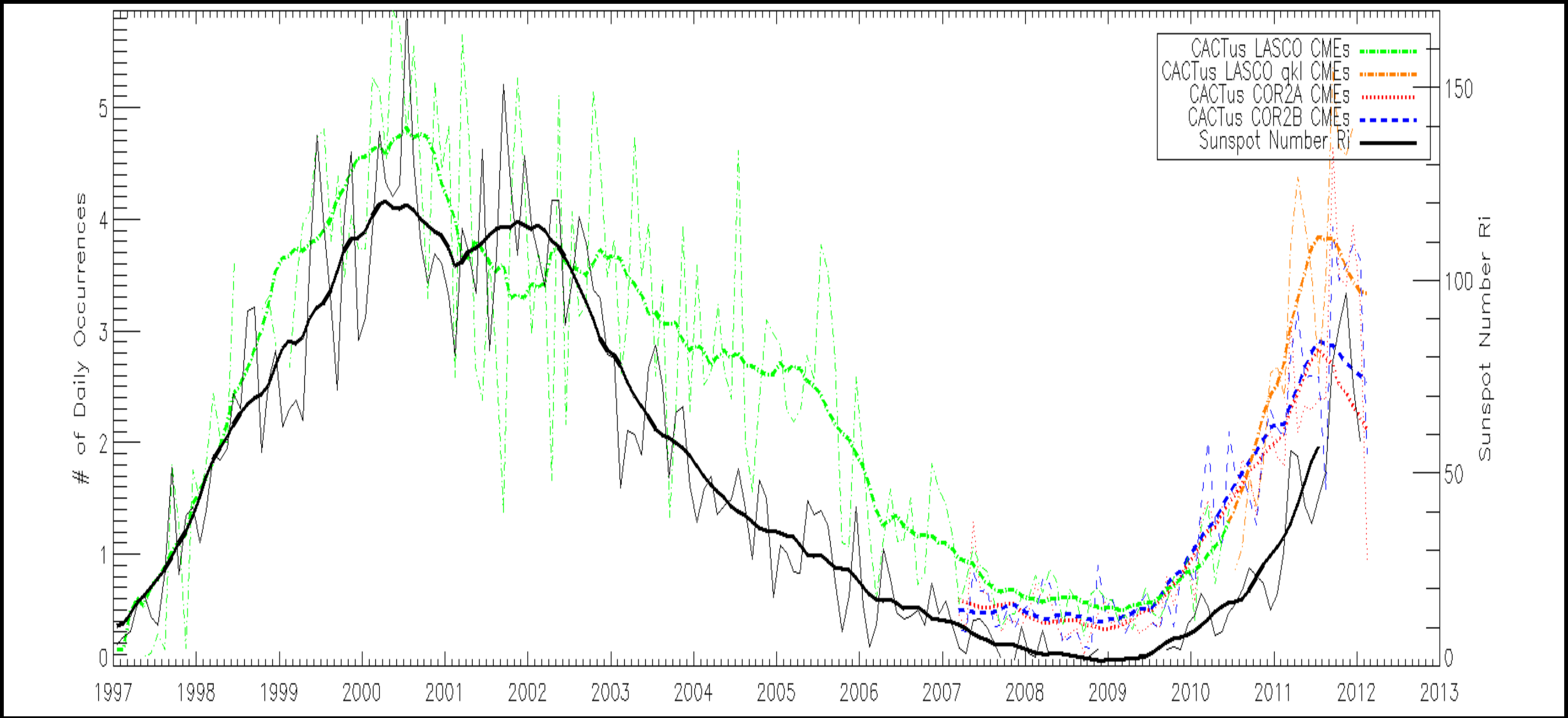
- National Science Foundation, USA

Solar Magnetic Fields: Sunspots



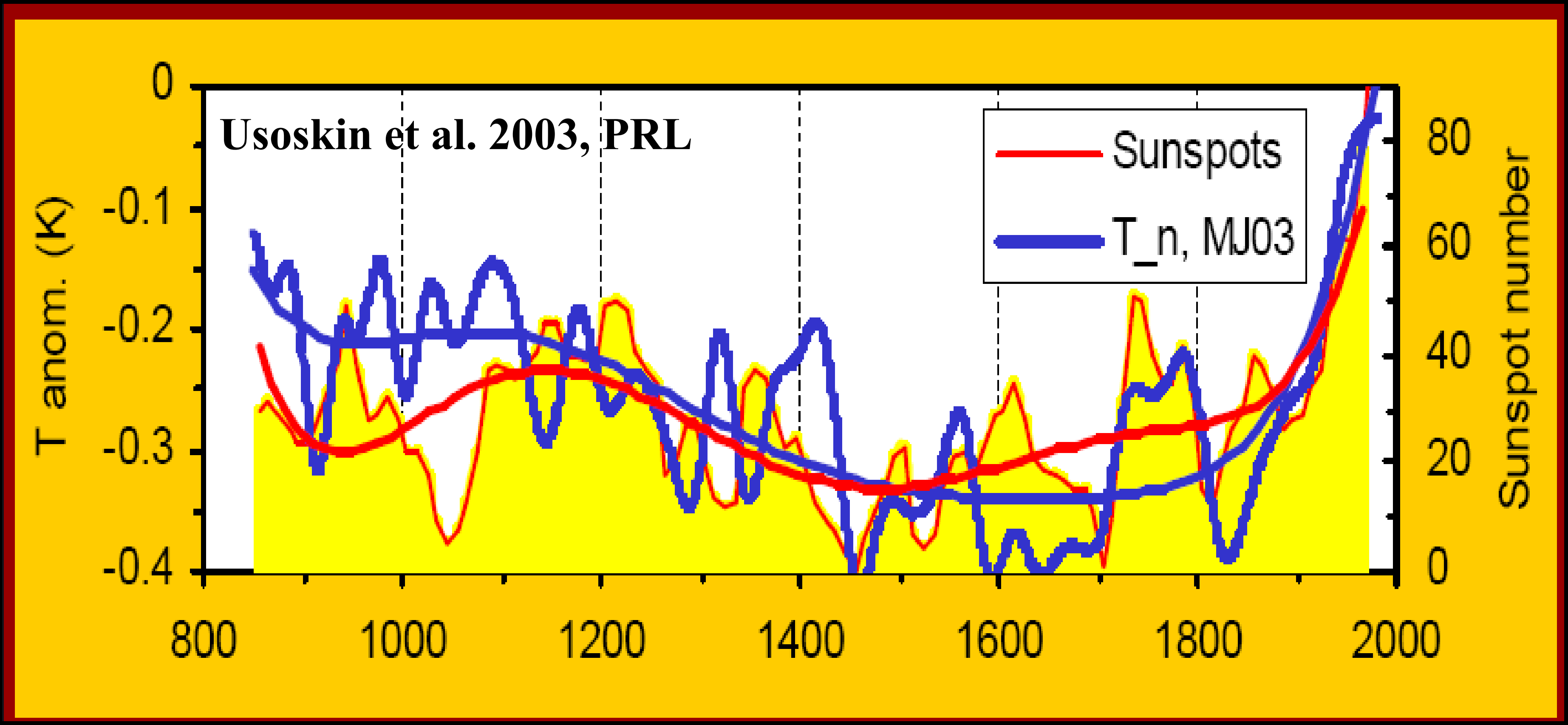
- First telescopic observations by Galileo and Scheiner (1611 AD)
- Size about 10,000 Km
- Sunspots are strongly magnetized ~ 1000 G (Hale 1908,ApJ)
- Appears dark because they inhibit convection

Sunspots are the Seats of Solar Storms



- Solar flares and coronal mass ejections (CMEs) – biggest explosions in the solar system – eject magnetized plasma and charged particles ($m \sim 10^{12}$ Kg, $v \sim 500$-2000 km/s, $E \sim 10^{24}$ Joules)
- Rate of solar storm occurrence correlated with sunspot cycle

The Cycle of Sunspots and its Relevance for Climate



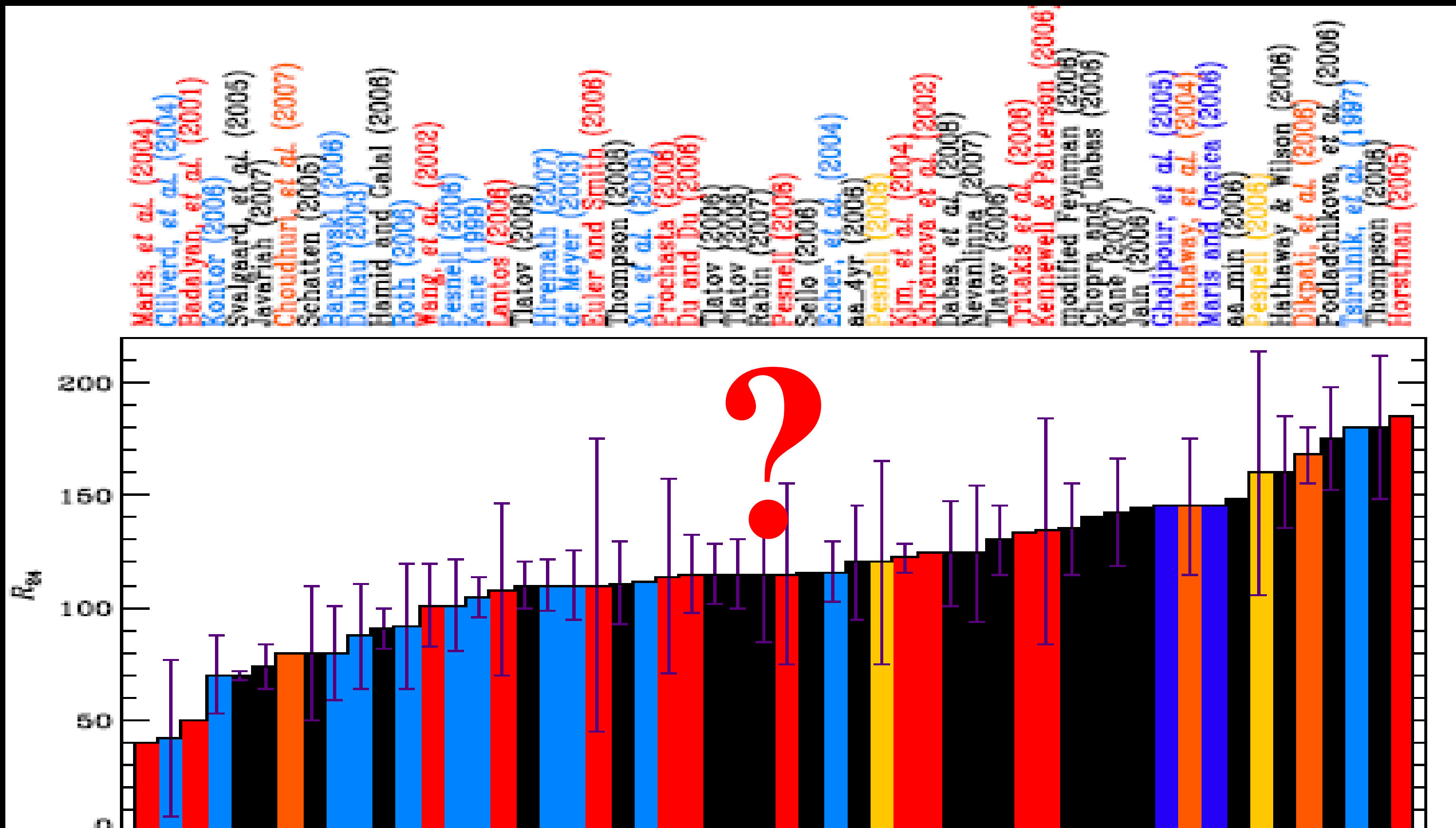
- Number of sunspots observed on the Sun varies cyclically
- Modulates the solar radiative energy output
- Primary natural energy input to the climate system
- Maunder minimum – the "little ice age" – suggestive of link

<u>Understanding & Forecasting Solar Activity Important</u>

Magnetic Fields
Solar Storms
Solar Wind Conditions
Solar Radiation Spectrum

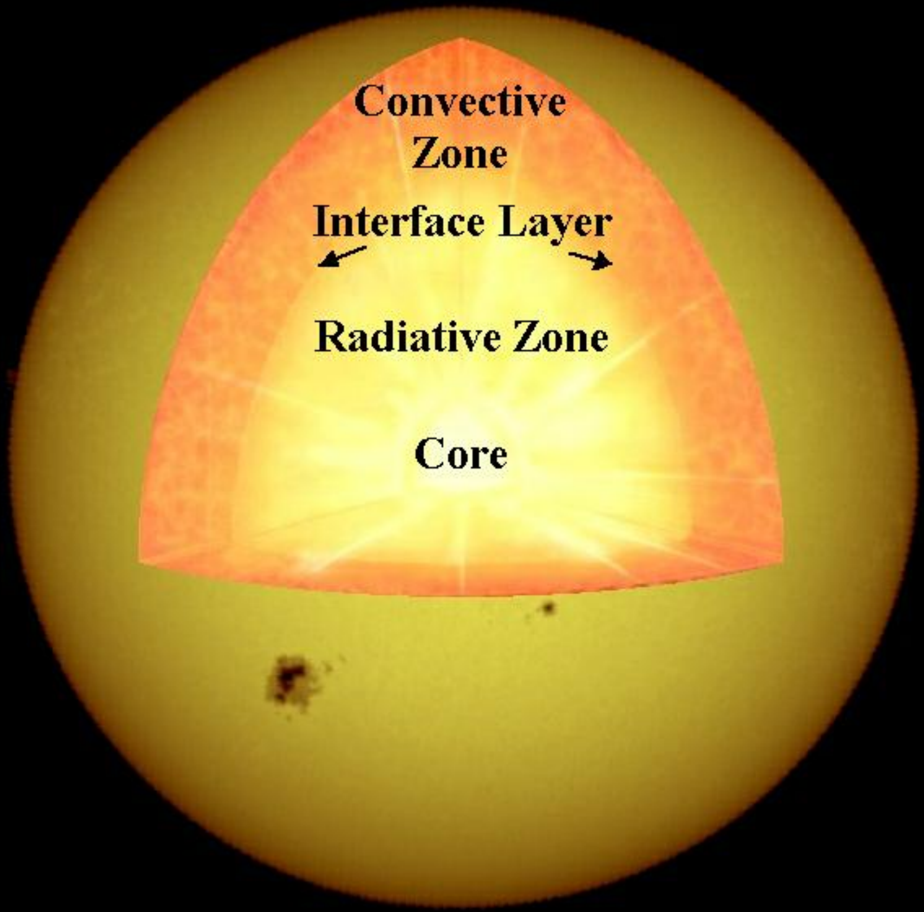
Magnetic field output – the cycle of sunspots,
govern other solar activity parameters

Prediction Target: Sunspot Cycle Amplitude



Range of predictions for one cycle (24)
spans the entire range of all sunspot cycles directly observed!
(Pesnell 2008, Sol. Phys.)

Window to the Solar Interior



- Matter exists in the ionized state in the solar interior
- Convection zone sustains plasma motion and magnetic fields
- Enter magnetohydrodynamics

Basic Physics: Plasma Flows Govern Magnetic Field Generation

- Governing equation: $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

- Magnetic Reynolds Number: $$R_m = \frac{VB/L}{\eta B/L^2} = \frac{VL}{\eta}$$

- In Astrophysical systems, R_M usually high, magnetic field creation possible and fields are frozen with the plasma
  —Diffusion timescale τ_η > Flow timescale τ_v

- In solar interior, plasma β >> 1 (gas pressure higher than magnetic pressure and therefore, plasma flows govern field dynamics
  — Solar Dynamo Models

The Challenges of Direct Numerical Simulation

- Sun's Circumference: 4.39 x 10^9 m

- Sunspot: 10^7 m (typically you need 10 grid points to resolve)
  Horizontal grid size: 10^6 m
  Number of horizontal grids: 4000

- Convective granules (eddies):10^6 m
  Resolving requires grid size of: 10^5 m
  Number of horizontal grids points: 40,000

- Courant-Friedrichs-Lewy condition (with v ~ 100 m/s) demands
  $\Delta t < 1000$ s (0.01 day)

- Huge density stratification, variation in scale heights, high Reynolds number

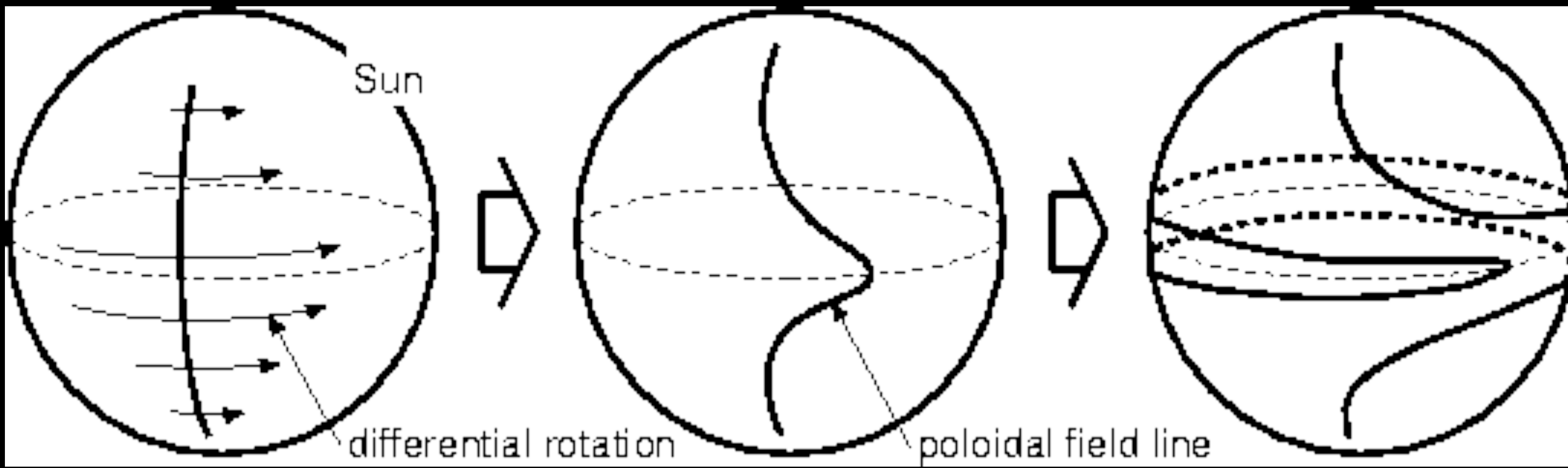
An Alternative Physicist's Approach to Modeling

Understand the micro- and macro-physics of the system;
approximate, parameterize and model this
to simulate the global system

Philosophy

Constrain models with observational data to the extent possible;
generate the understanding necessary to enable predicting

Current Understanding: Toroidal Field Generation (Omega Effect)



Poloidal field

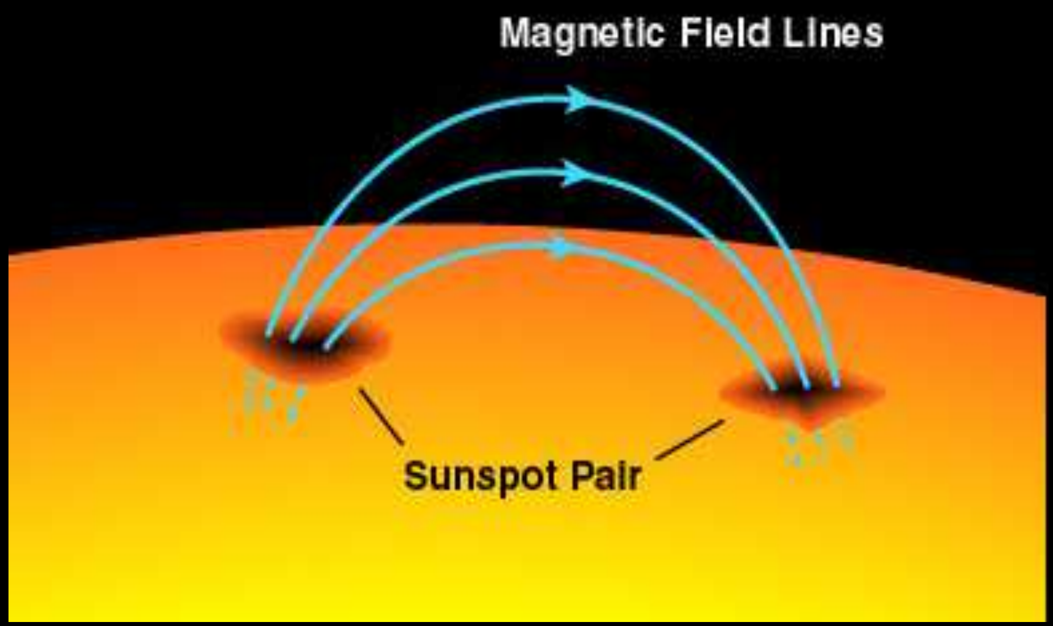
Toroidal Field

- Differential rotation will stretch a pre-existing poloidal field in the direction of rotation – creating a toroidal component (Parker 1955,ApJ)

Magnetic Buoyancy and Sunspot Formation

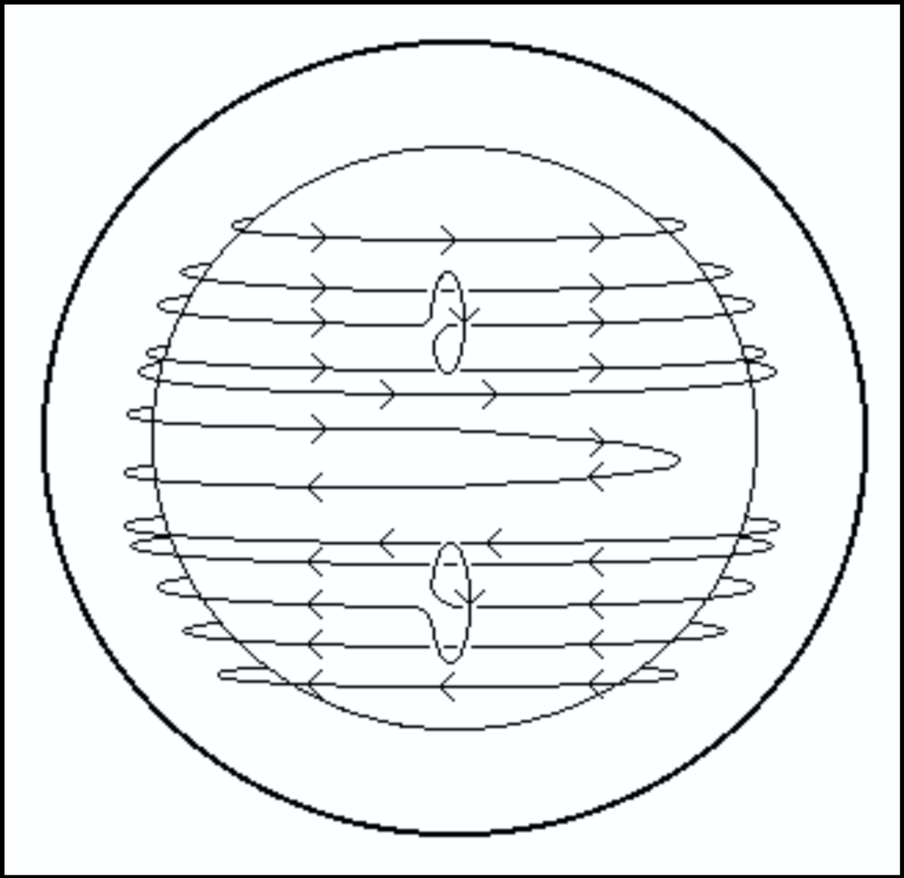
- Stability of Toroidal Flux Tubes – Magnetic Buoyancy (Parker 1955, ApJ)

$\rho_{\text{Internal}} < \rho_{\text{External}}$



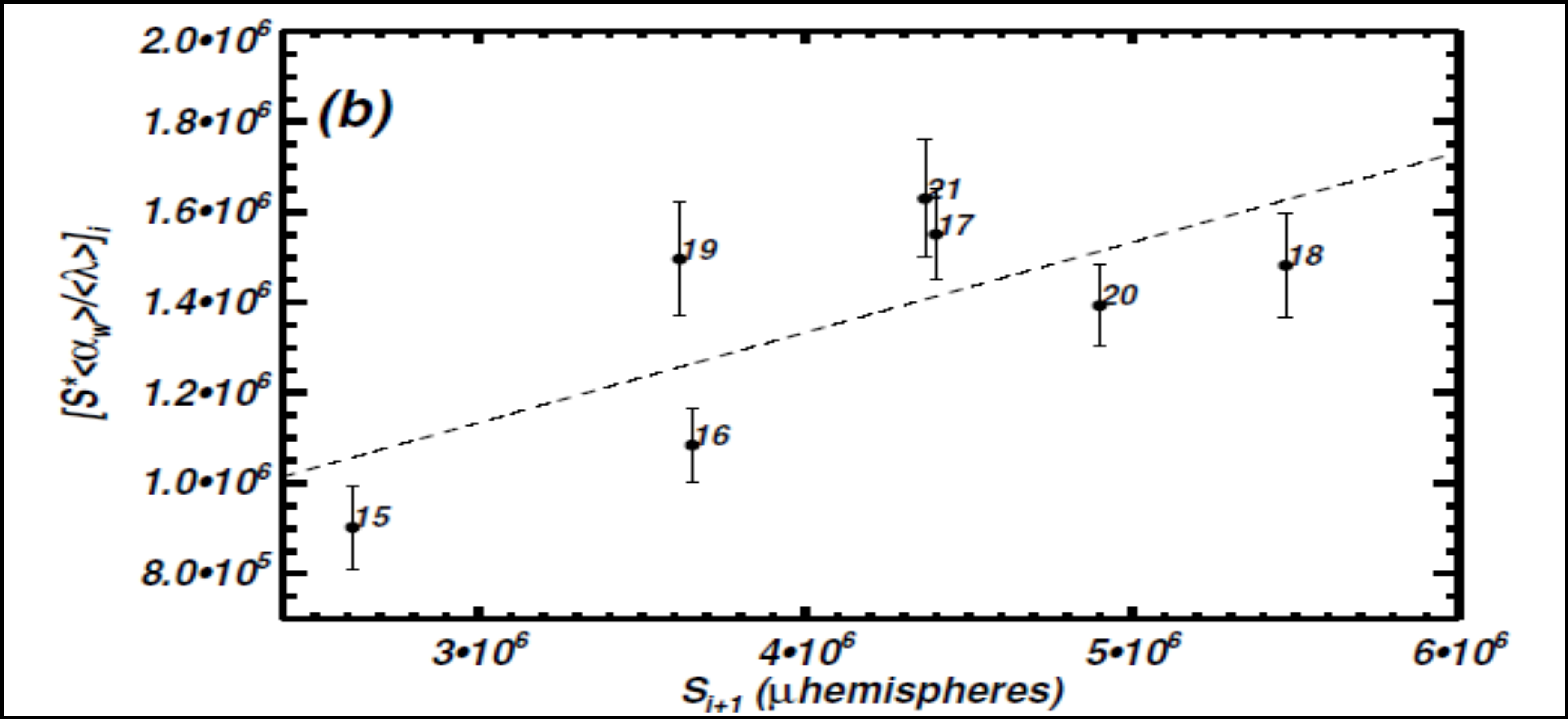
- Buoyant eruption, Coriolis force imparts tilts (sunspots are tilted)

Poloidal Field Generation – The MF α-effect



- Small scale helical convection – Mean-Field α-effect (Parker 1955)
- Buoyantly rising toroidal field is twisted by helical turbulent convection, creating loops in the poloidal plane
- Strong flux tubes will quench this mechanism, alternatives required…

Poloidal Field Generation: Tilted Bipolar Sunspot-Flux Dispersal



- Babcock (1961, ApJ) & Leighton (1969, ApJ) idea: tilted bipolar sunspots pairs decay and disperse near surface – is observed
- Numerous models have been constructed based on the BL idea
  — Strong observational support (Dasi-Espuig et al. 2010, A&A)

Building a Kinematic Solar Dynamo Model

- Axisymmetric Magnetic Fields:

$$\boldsymbol{B} = B\boldsymbol{e}_\phi + \nabla \times (A\boldsymbol{e}_\phi)$$

- Axisymmetric Velocity Fields:

$$\boldsymbol{v} = \boldsymbol{v}_p + \boldsymbol{r} \sin \theta \Omega \boldsymbol{e}_\phi$$

- Plug these into the MHD induction equation:

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathrm{B} - \eta \nabla \times \mathrm{B})$$

And separate the two components to obtain…..

Building a Dynamo Model: The αΩ Dynamo Equations

- Toroidal field evolution:

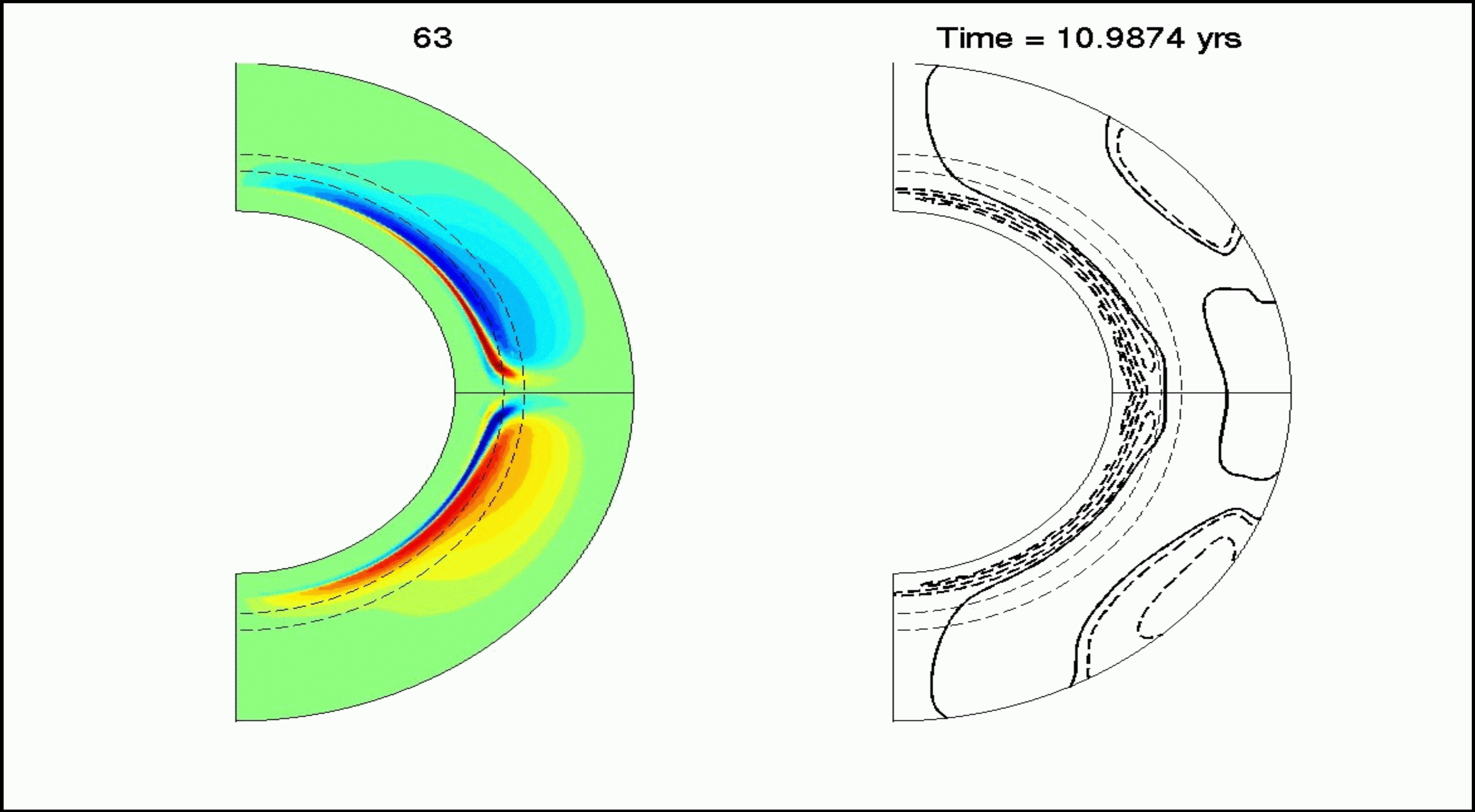
$$\frac{\partial B_\phi}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}\left(r v_r B_\phi\right) + \frac{\partial}{\partial \theta}\left(v_\theta B_\phi\right)\right]$$
$$= \eta\left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right)B_\phi + r\sin\theta\left(B_P.\nabla\right)\Omega - \nabla\eta \times \left(\nabla \times B_\phi\right)$$

- Poloidal field evolution:

$$\frac{\partial A}{\partial t} + \frac{1}{r\sin\theta}\left(v_P.\nabla\right)\left(r\sin\theta A\right) = \eta\left(\nabla^2 - \frac{1}{r^2\sin^2\theta}\right)A + S_\alpha$$

- Poloidal field source is parameterized by S_α
- Often, the alpha-term includes quenching, to limit field amplitude
- Buoyancy algorithm used to represent the emergence of ARs

Simulated Magnetic Fields in the Sun's Interior

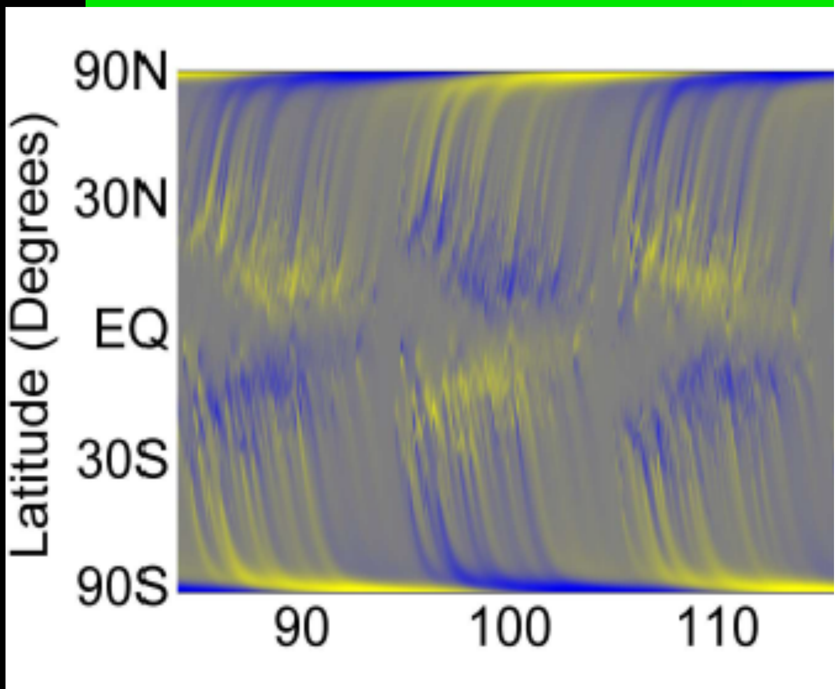


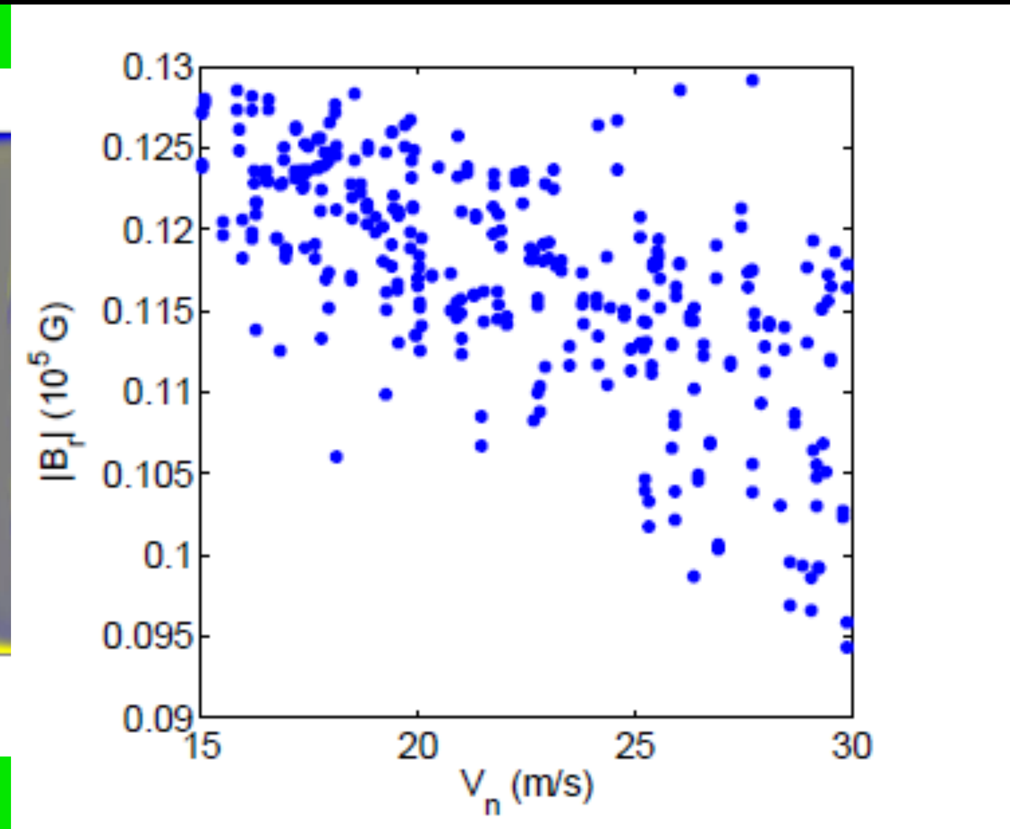
Toroidal Field Evolution

Poloidal Field Evolution

Chatterjee, Nandy and Choudhuri (2004, A&A)

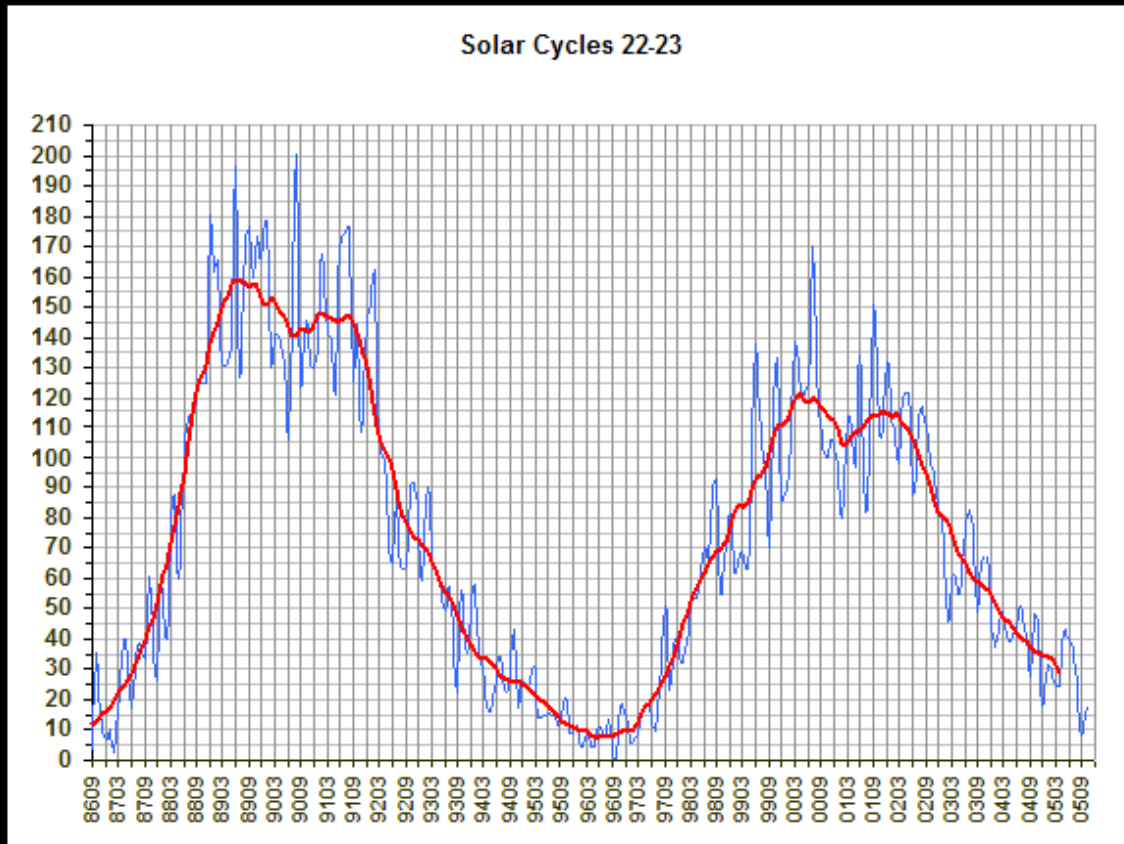
Capturing Sunspot Eruptions by Durney's Double Rings





Muñoz-Jaramillo, Nandy, Martens & Yeates (2010, ApJL)

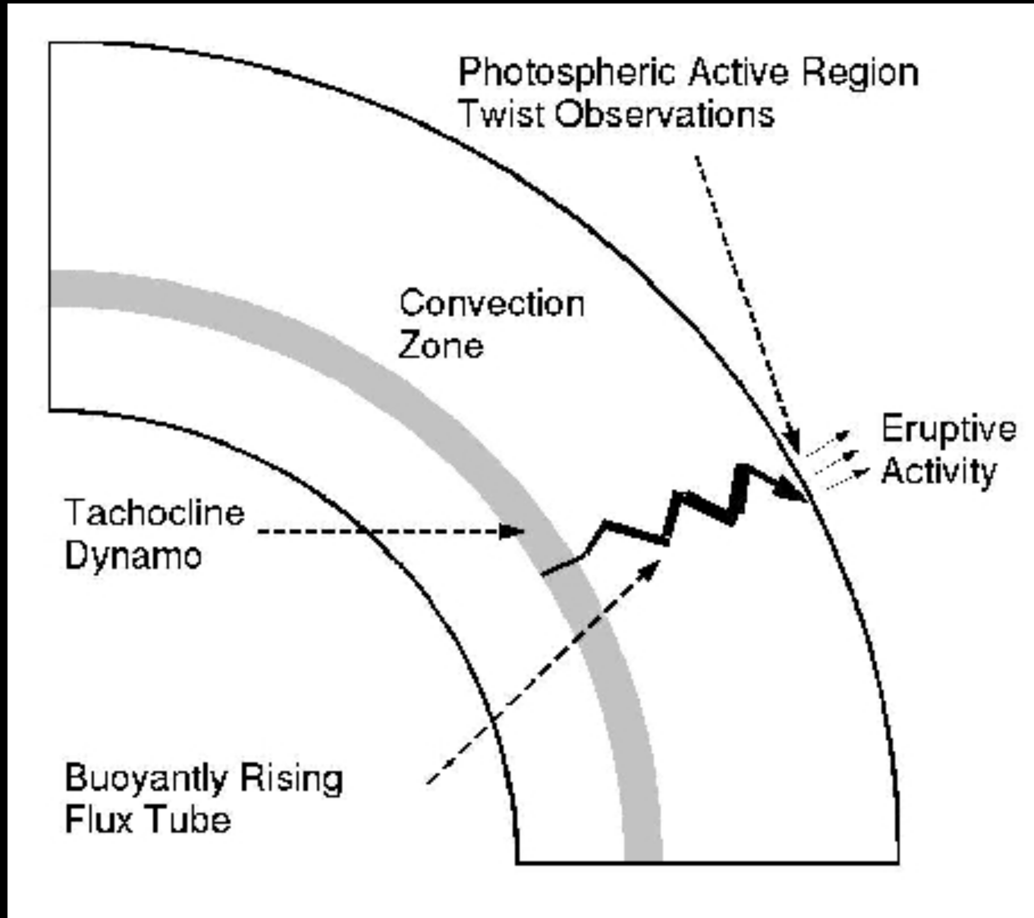
- Double-ring eruption algorithm reconciles dynamo simulations with surface flux transport simulations



Fluctuations and Predictions

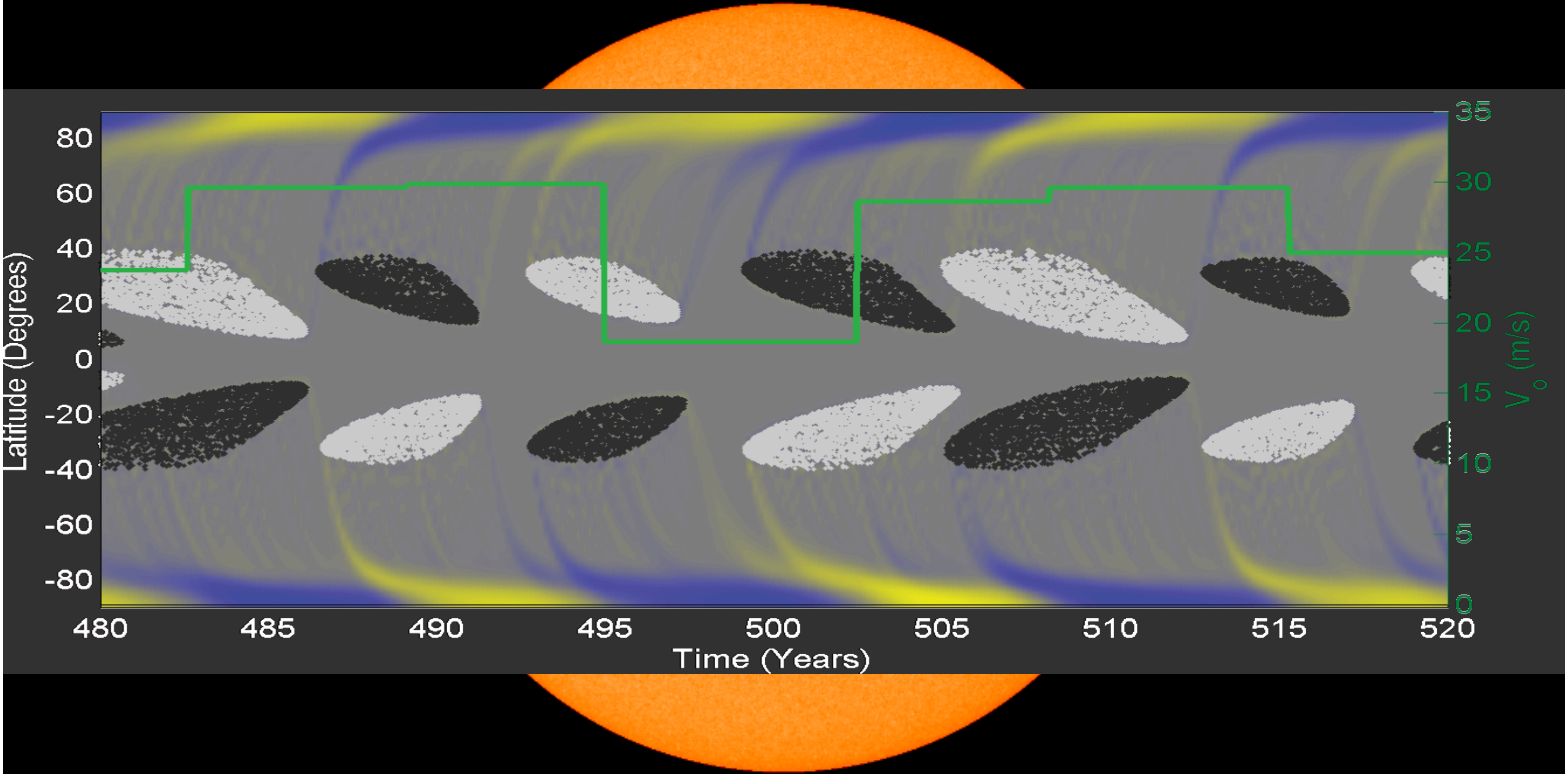
The first step towards predictions is to understand the origin of solar cycle fluctuations

Origin of Solar Cycle Irregularities?



- Poloidal field source (eruption of tilted bipolar sunspots) is stochastic
- Feedback of field on flows introduces non-linearity
- But in weakly non-linear, near-critical dynamo number regime, stochastic fluctuations, flow variations likely introduce variability

Cycle Irregularities: The Unusual Minimum of Solar Cycle 23



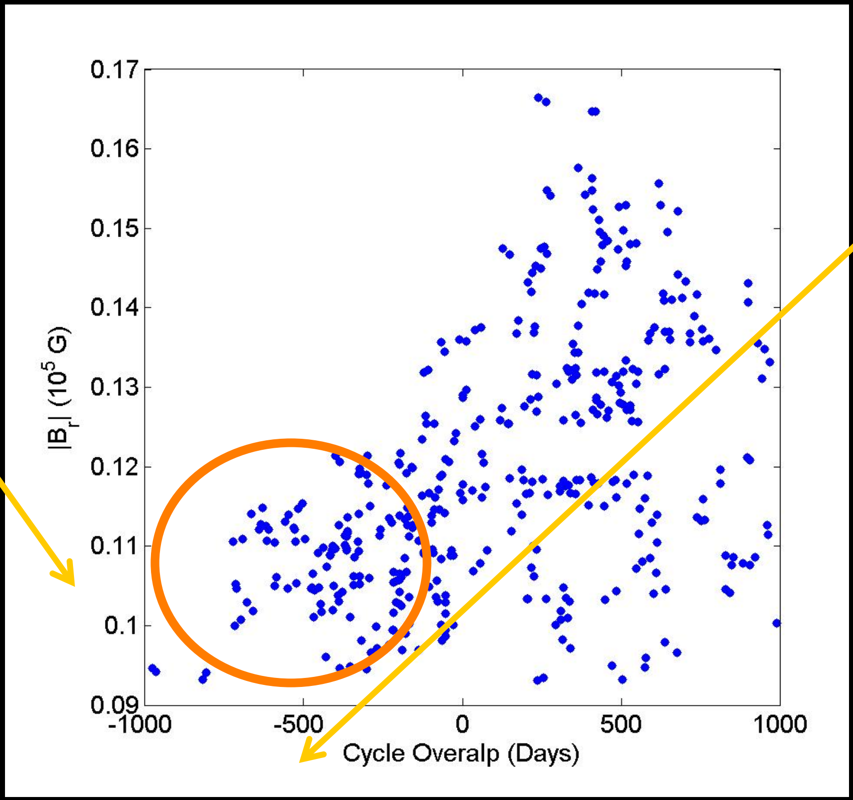
• Variability in "butterfly wing" overlap by meridional flow fluctuations (Nandy, Muñoz-Jaramillo Martens 2011, Nature)

The Minimum of Solar Cycle 23

- Defining characteristics of cycle 23 minimum:

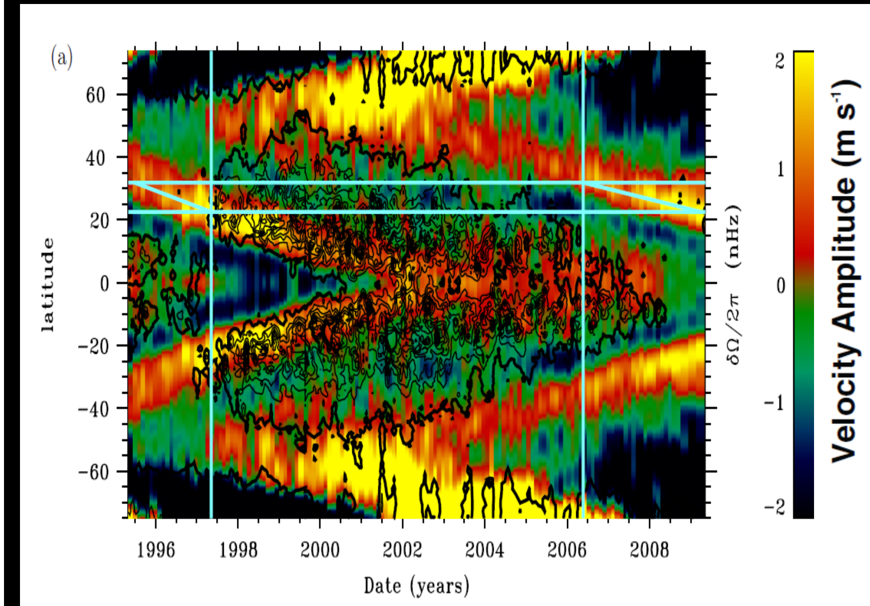
Weak polar field

Large number of sunspot-less days

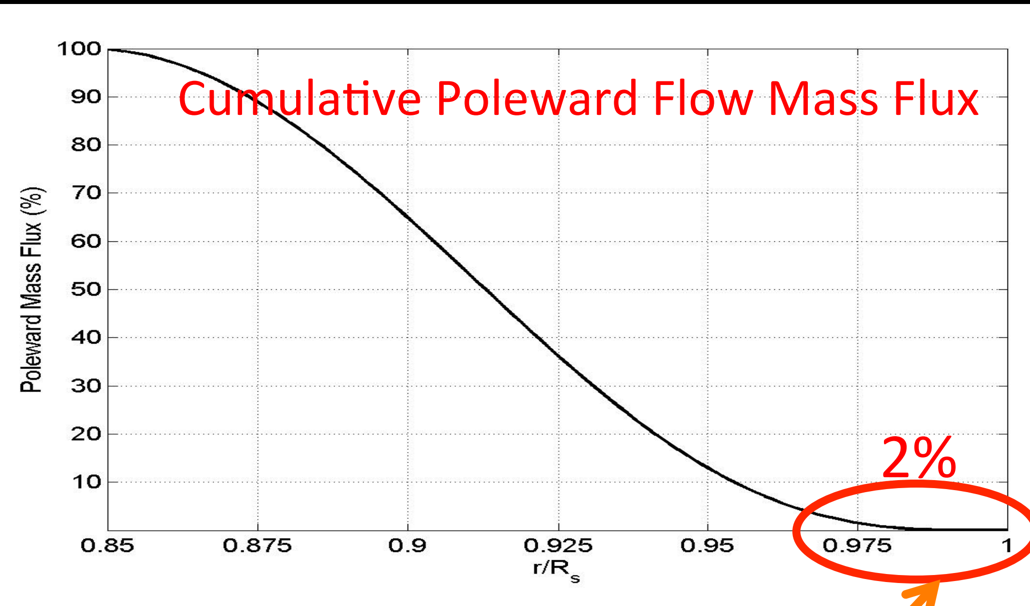


First model to match both weak polar fields and lack of sunspots

Comparisons with Observations



Howe et al. (2009, ApJL)

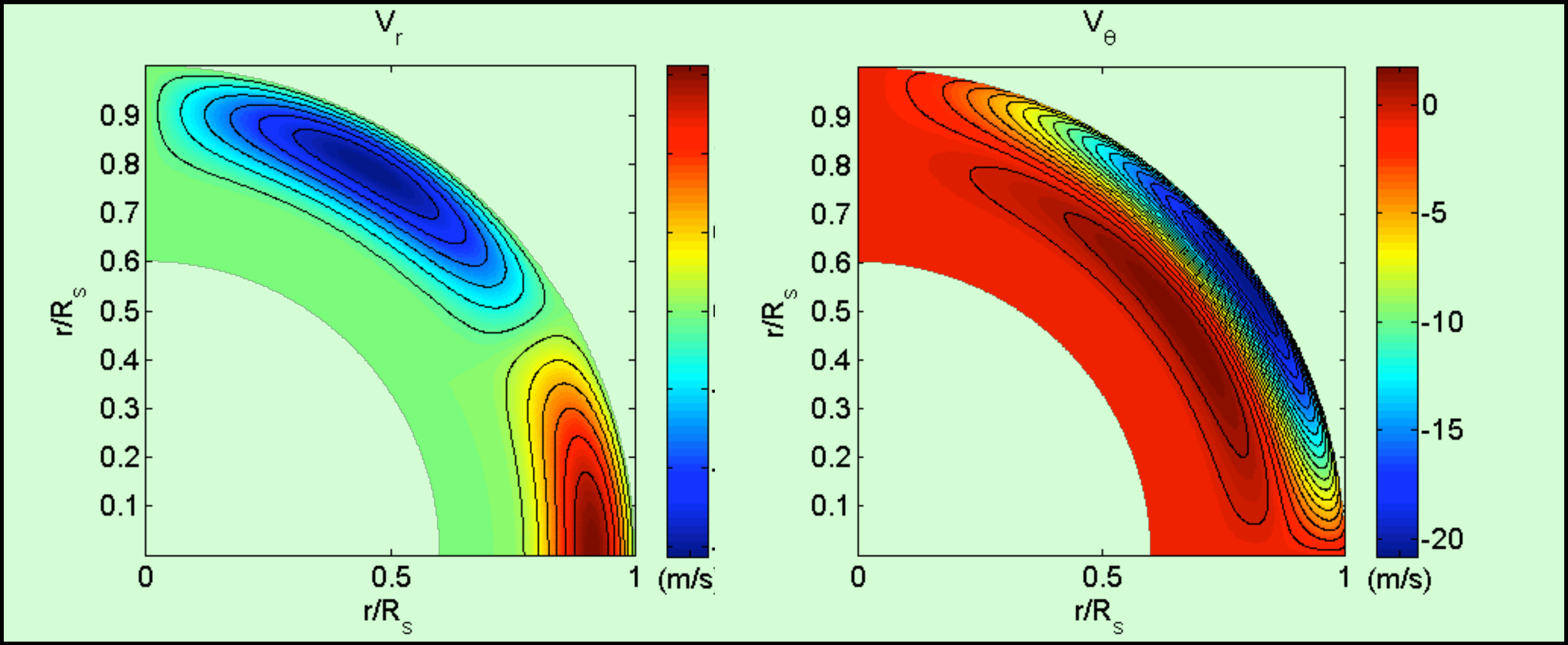


Hathaway & Rightmire (2010, Science)

- Torsional oscillation associated with cycle 24 relatively slow compared to cycle 23 – supports slower migration
- Surface doppler measurements indicate flow speed at surface higher at this minimum compared to earlier minimum – conflicting
- However surface flows alone:
  – cannot explain low polar fields of cycle 23 (*Jiang et al. 2010, ApJ*)

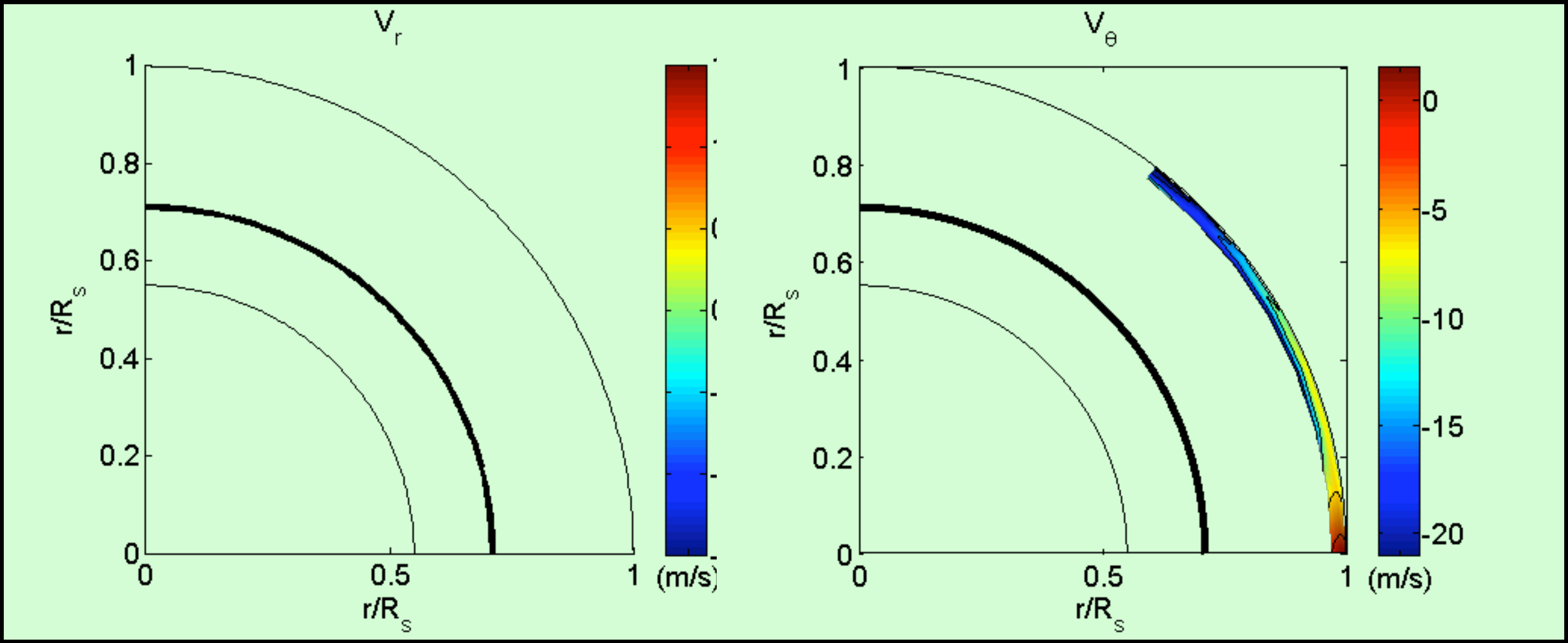
Constraining Meridional Plasma Flow in Solar Interior is a Problem

THIS IS WHAT WE WANT

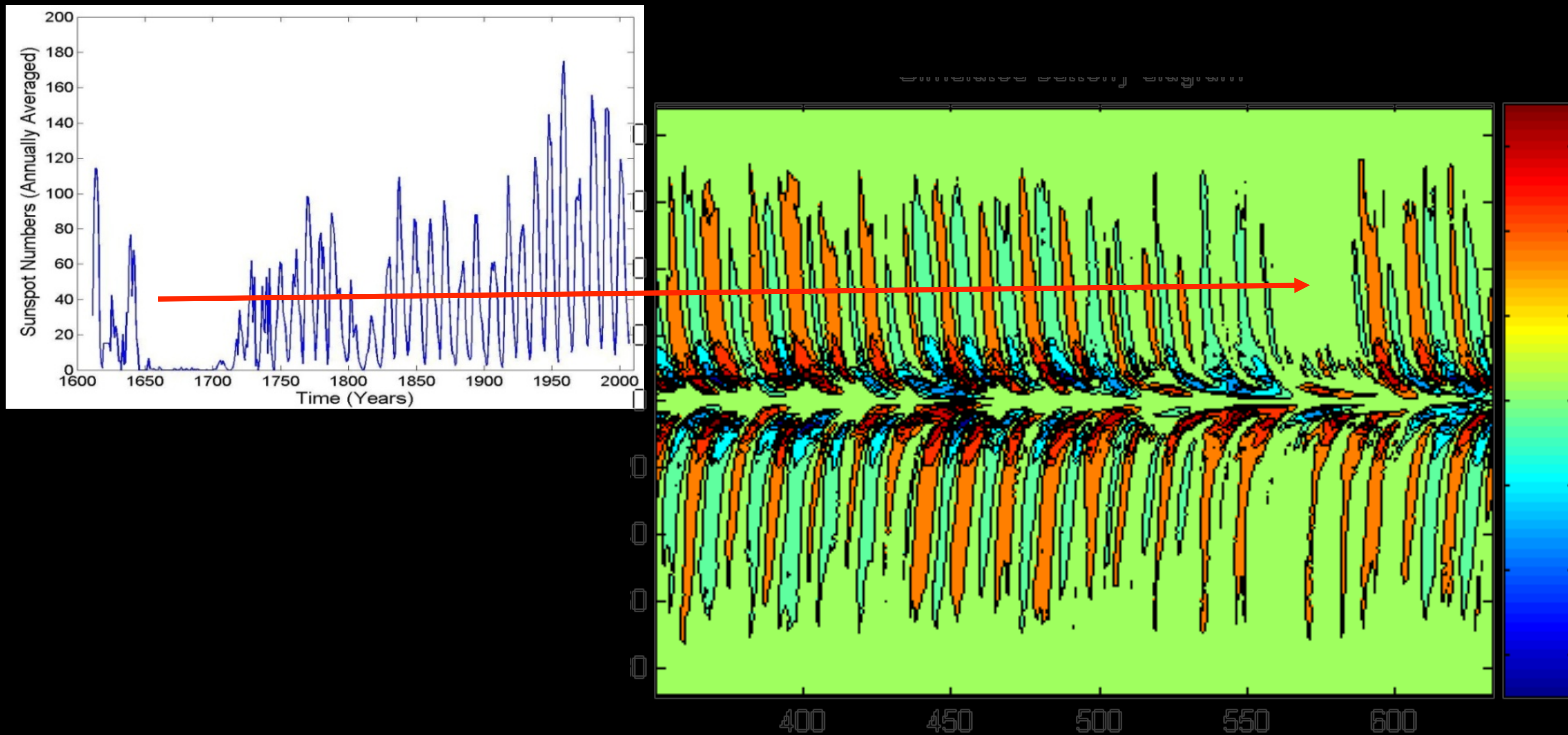


Constraining Meridional Plasma Flow in Solar Interior a Problem

THIS IS WHAT WE HAVE

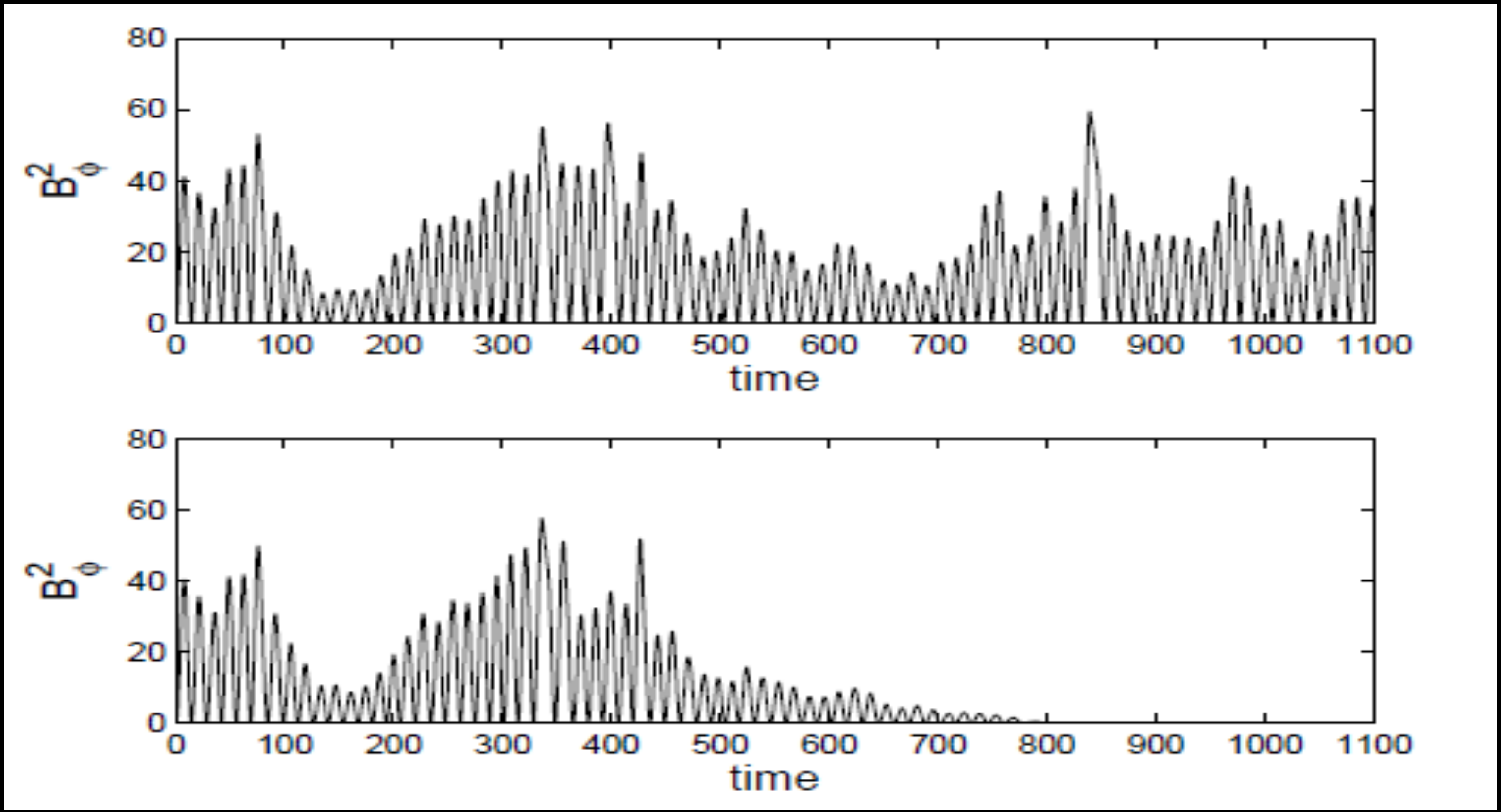


Cycle Irregularities: Origin of Maunder Minima



- Stochastic fluctuations (Charbonneau & Dikpari 2000,ApJ) or drastic changes in flow profiles (Karak 2010, ApJ) have been postulated
- As has been dynamical non-linearities (Tobias 1997, A&A)
- Understanding of grand minima episodes incomplete

How does the Solar Cycle Recover from a Maunder-like Minimum?



Hazra, Passos & Nandy (2012, in preparation)

- A properly set-up Babcock-Leighton model (with lower bound on quenching) cannot recover from a Maunder-like grand minimum!
- Think MF α-effect…

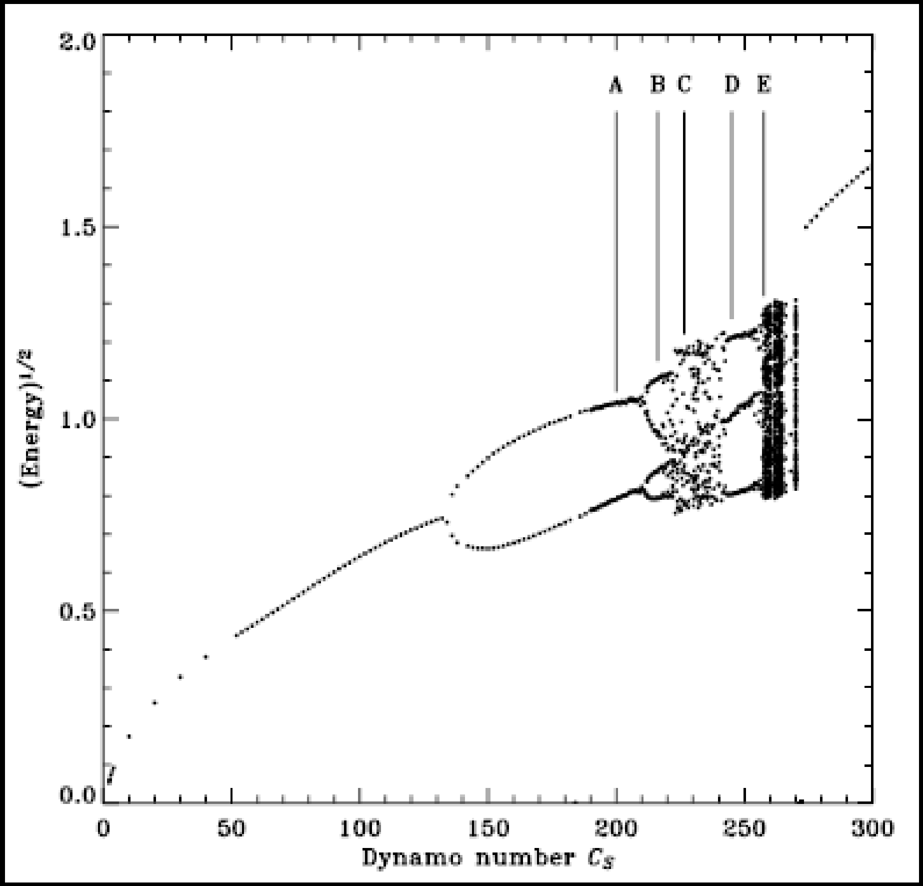
Origin of Fluctuations in the Solar Cycle: Path to Chaos

- Dynamical nonlinearities especially important in super-critical regimes
  —Tobias (1997, A&A)
  —Wilmot-Smith et al. (2005, 2006, ApJ)

- When source term dominates over sink term, random “kicks” in the forcing of the system become very important

- Can lead to chaotic behavior…

Dynamical Behavior of the Solar Dynamo



(Charbonneau, St-Jean & Zacharias 2005, ApJ)

- Is solar cycle weakly critical or in the highly critical, chaotic regime?

Chaotic Systems and Predictability

> When our results concerning the instability of nonperiodic flow are applied to the atmosphere, which is ostensibly nonperiodic, they indicate that prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long-range forecasting would seem to be non-existent.

(Lorentz 1963, J. Atmos. Sci.)

- Chaotic regime: small differences in initial conditions diverge
  - Is short-term prediction possible?

Towards Prediction: The Underlying Physics

Flux Transport Deterministic

Introduces time delay = memory

- Toroidal field evolution:

$$\frac{\partial B_\phi}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}\left(r v_r B_\phi\right) + \frac{\partial}{\partial \theta}\left(v_\theta B_\phi\right)\right]$$

$$= \eta\left(\nabla^2 - \frac{1}{r^2 \sin^2 \theta}\right)B_\phi + r\sin\theta\left(B_P.\nabla\right)\Omega - \nabla\eta \times \left(\nabla \times B_\phi\right)$$

$$\frac{dB_\phi(t)}{dt} = \frac{\omega}{L}A(t - T_0)$$

- Poloidal field

$$\frac{\partial A}{\partial t} + \frac{1}{r\sin\theta}\left(v_P \ldots\right. \qquad \ldots \left. r^2 \sin^2 \theta \right) \ldots$$

But Poloidal Field Observed

Poloidal Source Stochastic

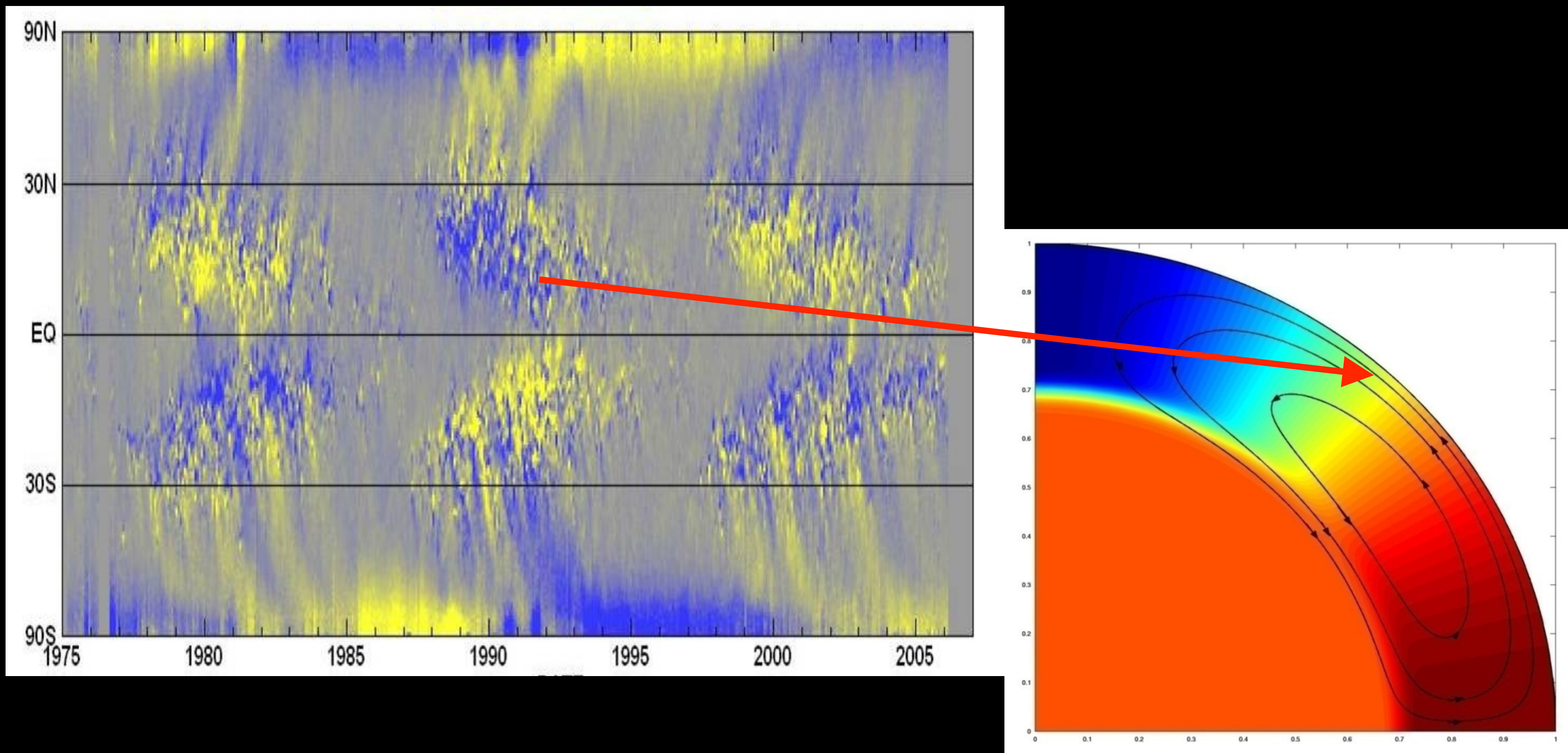
Random buffeting of

Rising flux tubes –

Tilt angle distribution

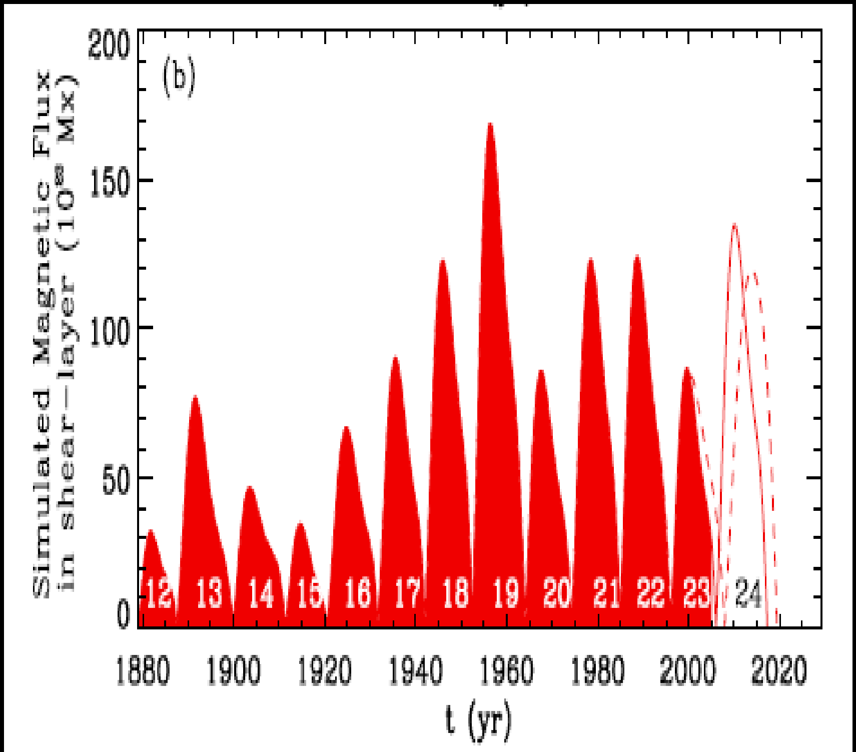
Non-linear

The Observed Poloidal Source at Surface

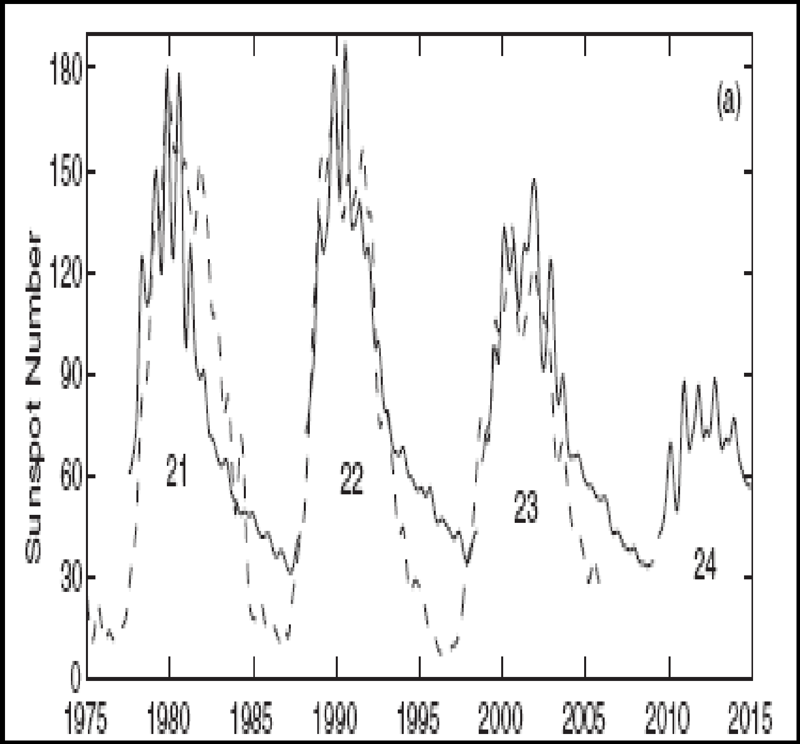


• Surface source for poloidal component of the field is observed
• This has been utilized for predicing the amplitude of cycle 24

Dynamo-based Solar Cycle Predictions



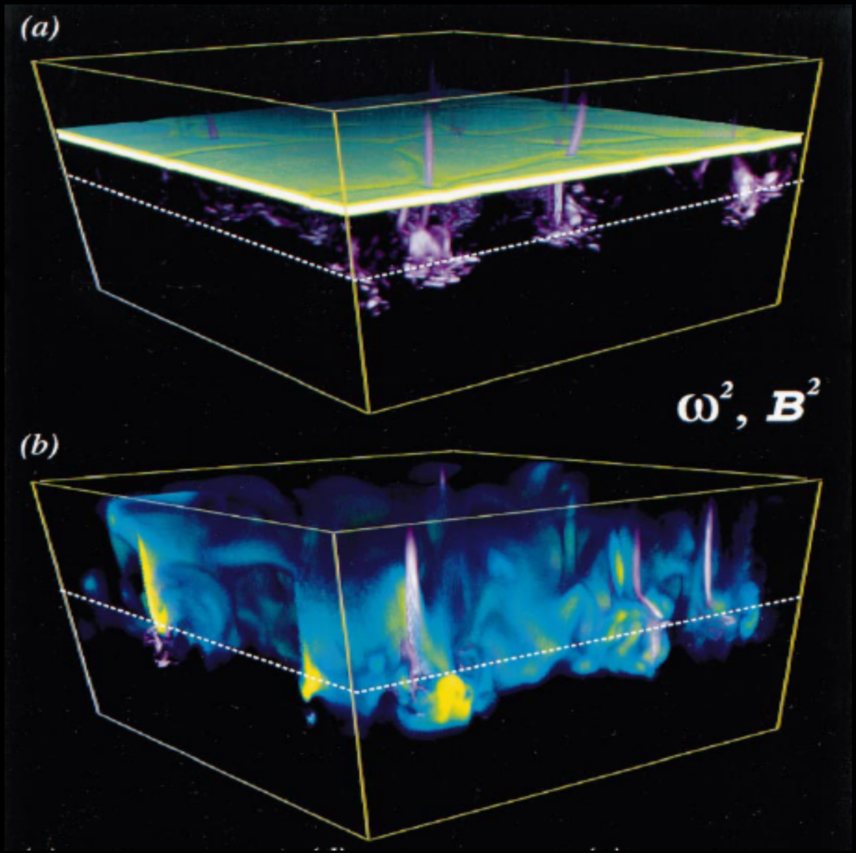
Dikpati et al. (2006, GRL)
Very Strong Cycle
Advection Dominated



Choudhuri et al. (2007, PRL)
Very Weak Cycle
Diffusion Dominated

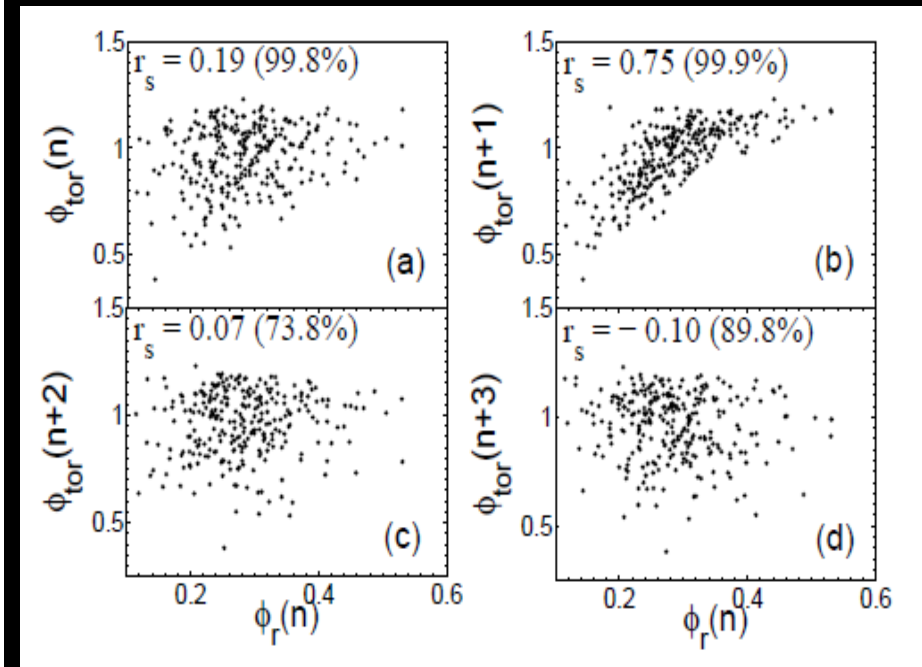
- Yeates, Nandy & Mackay (2008) have shown that this is due to the persistence of (long-term memory) in advection dominated models, as opposed to a one cycle memory in diffusion dominated models

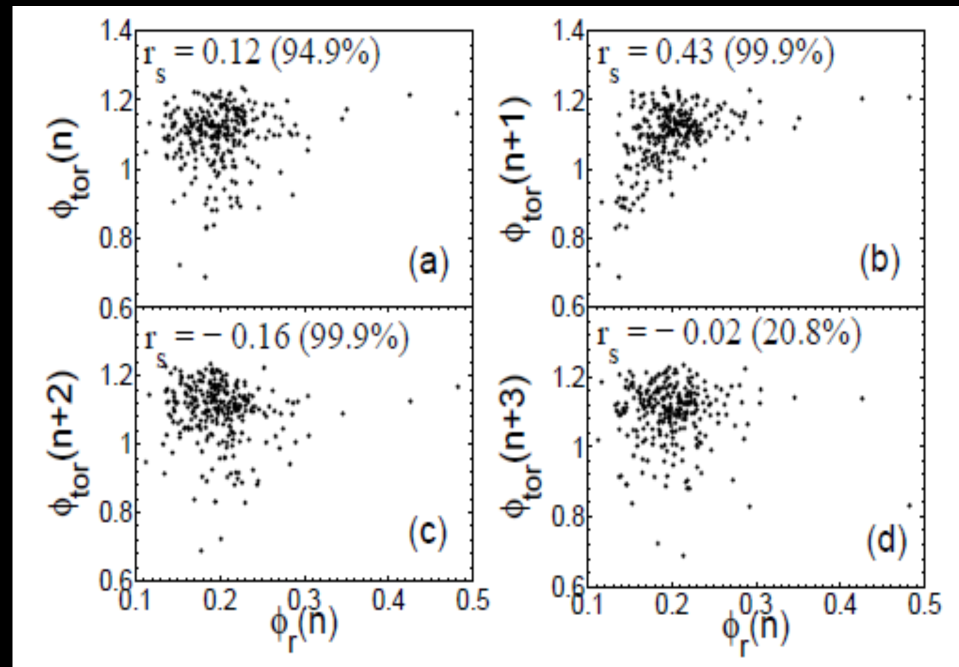
But Prediction Models Ignored Turbulent Pumping



- Preferential downward pumping of magnetic flux, in the presence of rotating, stratified convection – usually ignored in kinematic dynamos
- Suggests typical downward velocity ~ 10 m/s (Tobias et al. 2001, ApJ)
- Known to affect dynamics (Guerrero & Dal Pino 2008, A&A)
- Does it affect cycle memory?

Effect of Turbulent Flux Pumping on Cycle Memory





(Advection dominated – low η) (Diffusion dominated – high η)

Karak & Nandy (2012, PRL, submitted)

- Advection and diffusion dominated regime behave similarly!
- Memory reduces to one cycle for a pumping speed of 2 m/s

Stronger Turbulent Pumping Degrades Memory Further

TABLE I: Correlation coefficients (r_s) and percentage significance levels (p) for peak surface radial flux Φ_r of cycle n versus peak toroidal flux Φ_{tor} of different cycles for 275 solar cycles data. The first column denotes the amplitude of the turbulent pumping speed in various simulation studies. The top row corresponds to the case without turbulent pumping and subsequent rows corresponds to simulations with increasing pumping speeds.

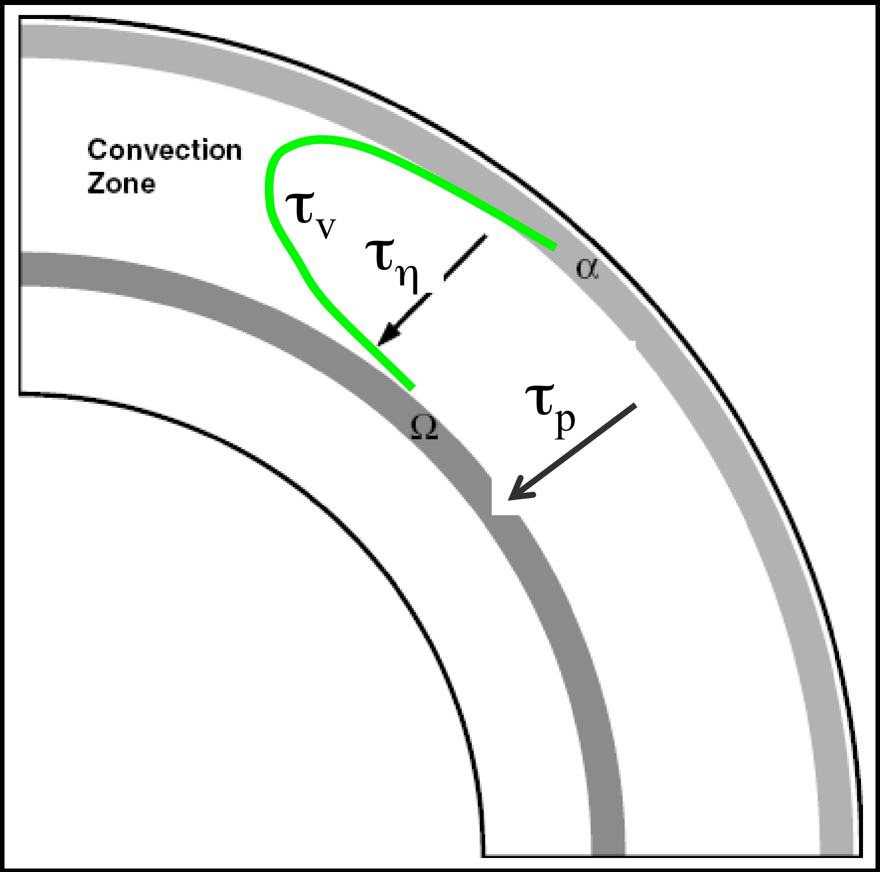
		Dif. Dom.	Adv. Dom.
Pumping	Parameters	r_s (p)	r_s (p)
0 m s^{-1}	$\Phi_r(n)$ & $\Phi_{tor}(n)$	0.19 (99.9)	0.57 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+1)$	0.64 (99.9)	0.77 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+2)$	0.04 (55.9)	0.46 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+3)$	0.22 (99.9)	0.27 (99.9)
1 m s^{-1}	$\Phi_r(n)$ & $\Phi_{tor}(n)$	−0.06 (67.0)	0.41 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+1)$	0.67 (99.9)	0.72 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+2)$	0.09 (83.9)	0.29 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+3)$	−0.02 (26.5)	−0.01 (18.9)
2 m s^{-1}	$\Phi_r(n)$ & $\Phi_{tor}(n)$	0.12 (94.9)	0.19 (99.8)
	$\Phi_r(n)$ & $\Phi_{tor}(n+1)$	0.43 (99.9)	0.75 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+2)$	−0.16 (99.9)	0.07 (73.8)
	$\Phi_r(n)$ & $\Phi_{tor}(n+3)$	−0.02 (20.8)	−0.10 (89.8)
3 m s^{-1}	$\Phi_r(n)$ & $\Phi_{tor}(n)$	0.11 (49.2)	0.29 (92.0)
	$\Phi_r(n)$ & $\Phi_{tor}(n+1)$	0.32 (99.9)	0.62 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+2)$	−0.18 (99.6)	0.07 (78.0)
	$\Phi_r(n)$ & $\Phi_{tor}(n+3)$	0.03 (36.6)	−0.10 (91.6)
4 m s^{-1}	$\Phi_r(n)$ & $\Phi_{tor}(n)$	0.19 (99.8)	0.30 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+1)$	0.26 (99.9)	0.46 (99.9)
	$\Phi_r(n)$ & $\Phi_{tor}(n+2)$	−0.16 (99.3)	0.07 (72.8)
	$\Phi_r(n)$ & $\Phi_{tor}(n+3)$	−0.10 (91.9)	−0.22 (99.9)

Stronger Turbulent Pumping

Shorter Solar Cycle Memory

- Cycle to cycle correlations decrease with increasing turbulent pumping
- Even one-cycle memory severely degrades for stronger pumping
- Implies early predictions will fail or be inaccurate

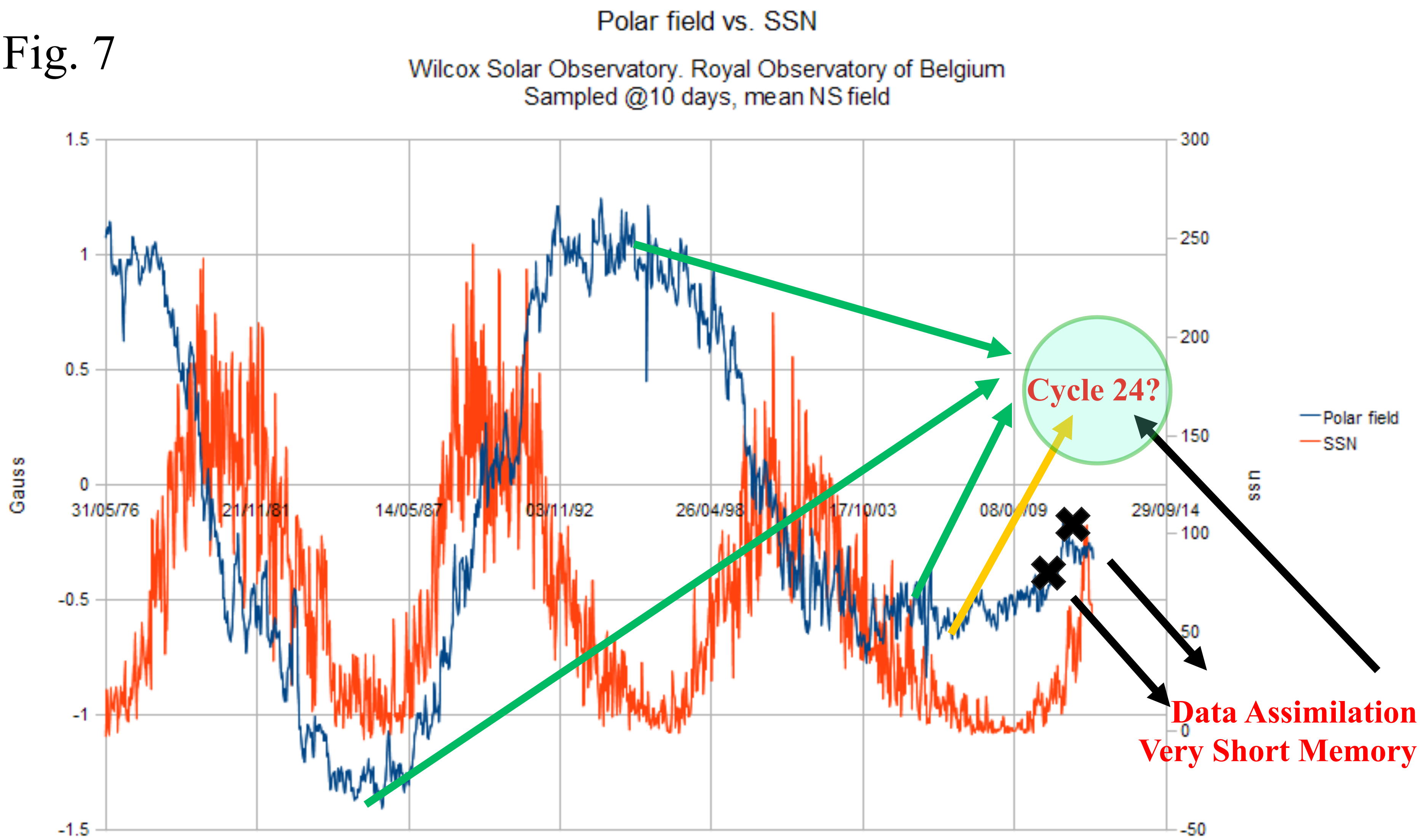
Timescale of Physical Processes Govern Memory



- Meridional Flow (20 m/s)
  τ_v = 20 yrs (Long memory)
- Turbulent Diffusion (1 x10^{12} cm^2/s)
  τ_η = 14 yrs (Moderate memory)
- Turbulent Pumping (v =2 m/s)
  $\tau_{pumping}$ = 3.4 yrs (Short memory)

Long Memory: Polar field of multiple cycles seeds next sunspot cycle

Fig. 7



Short Memory: Polar field at minimum seeds next cycle only

Summary

- Understanding of the solar cycle is still incomplete; however, we are making progress…..

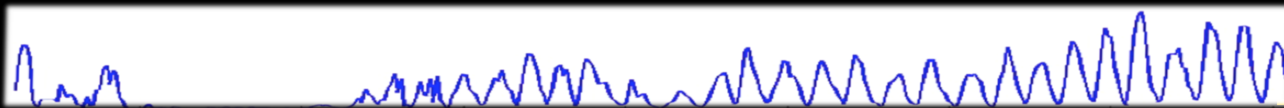
- Prediction is still possible in chaotic systems; but dependent on timescale of physical processes driving system

- Memory of the solar cycle is likely limited to one cycle or less

- Reliable predictions possible only at solar minimum; long-term multi-cycle prediction likely implausible (explains early diverging forecasts)

- Development of data assimilation techniques important for predictions (efforts underway – Jouve et al. 2011, ApJ)

- Major advances likely when understanding from kinematic dynamos, full MHD, flux tube dynamics models and helioseismology converge



…..The Future

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