The Sun's Magnetic Cycle: Current State of our Understanding

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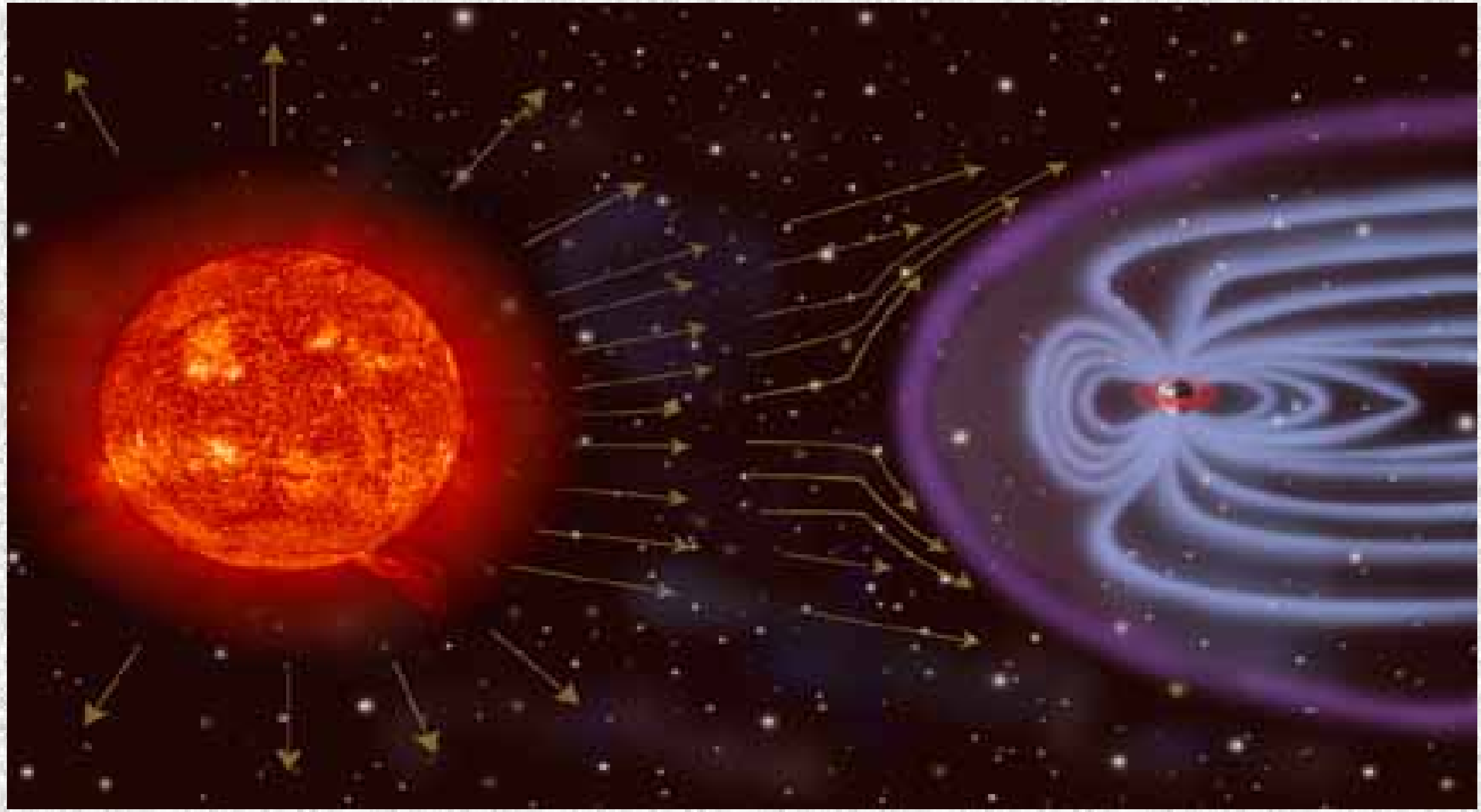
Outline:

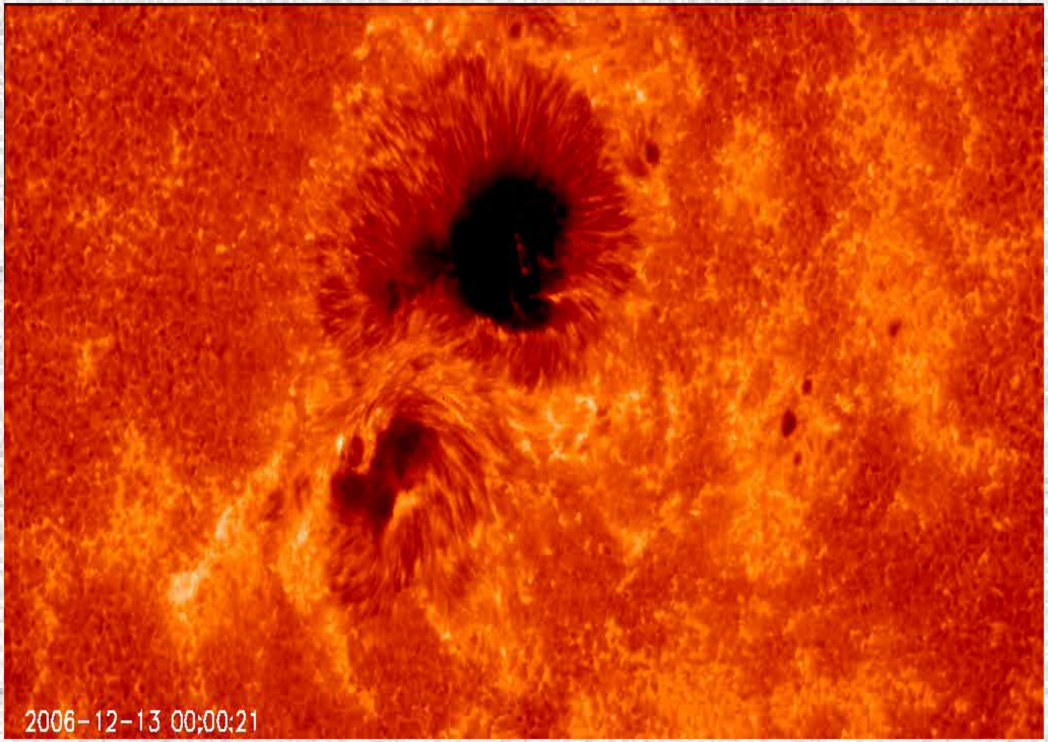
- The need to understand solar variability
- The solar cycle: Observational characteristics
- MHD: Basic theoretical perspectives; Historical development
- The modern era – kinematic dynamo models
- Summary

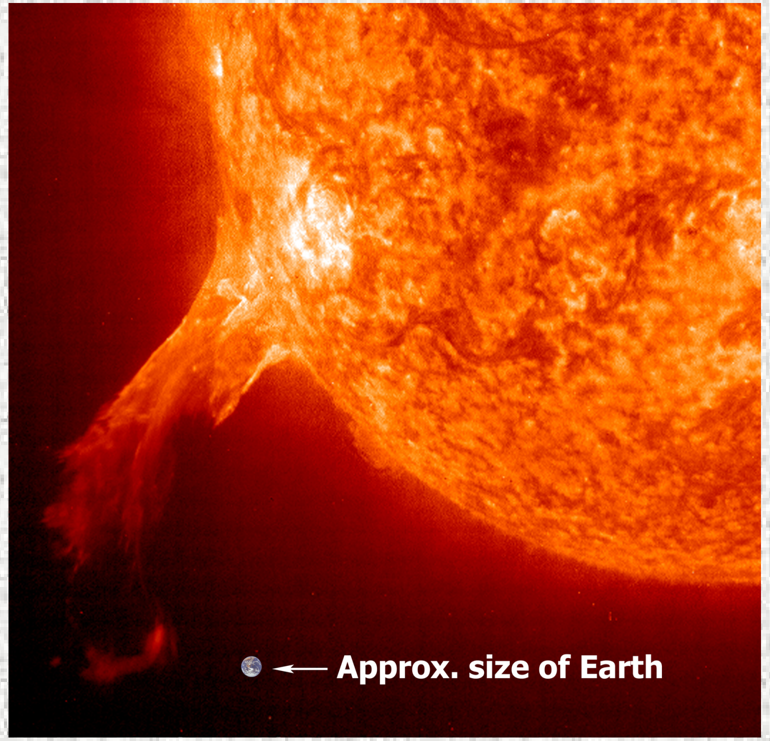
Why Study the Sun?



- Nearest astrophysical laboratory for verifying our theoretical ideas about magnetohydrodynamics and plasma physics
- The Earth and the solar system is immersed in an environment – the heliosphere – that is governed by the Sun's wind and magnetic output

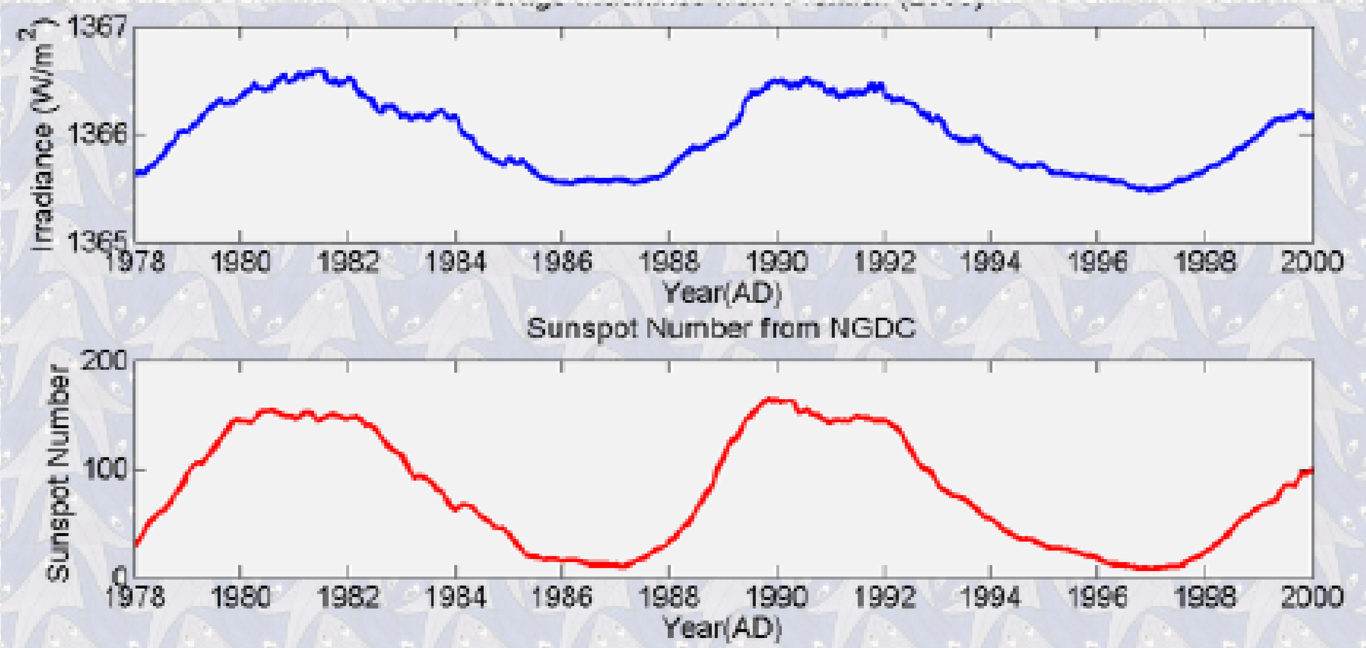
Why Study the Sun?





- Solar flares and coronal mass ejections (CMEs), the biggest explosions in the solar system – eject magnetized plasma and charged particles
- These disrupt: Satellite operations & Telecommunications facilities
  Electrical power grids, Northern oil pipelines
  Air-traffic on polar routes (used since 2000s)
- Warning system industry worth ~ $ 2B/year (source: SEC/NOAA-US)

Why Study the Sun?



- The total solar radiative output (TSI), unfortunately, known widely as the solar constant, is coupled to the Sun's magnetic output
- It's the primary energy input into the global climate system; it varies!
- This slow, long-term variation is known to affect global temperature
- Maunder minimum – a period of low solar activity (1645-1715 AD) – coincided with the "Little Ice Age" – a period of global cooling
- So what is the Sun's role in global climate change?
  – Will illuminate the role of anthropogenic causes of global warming

My Research

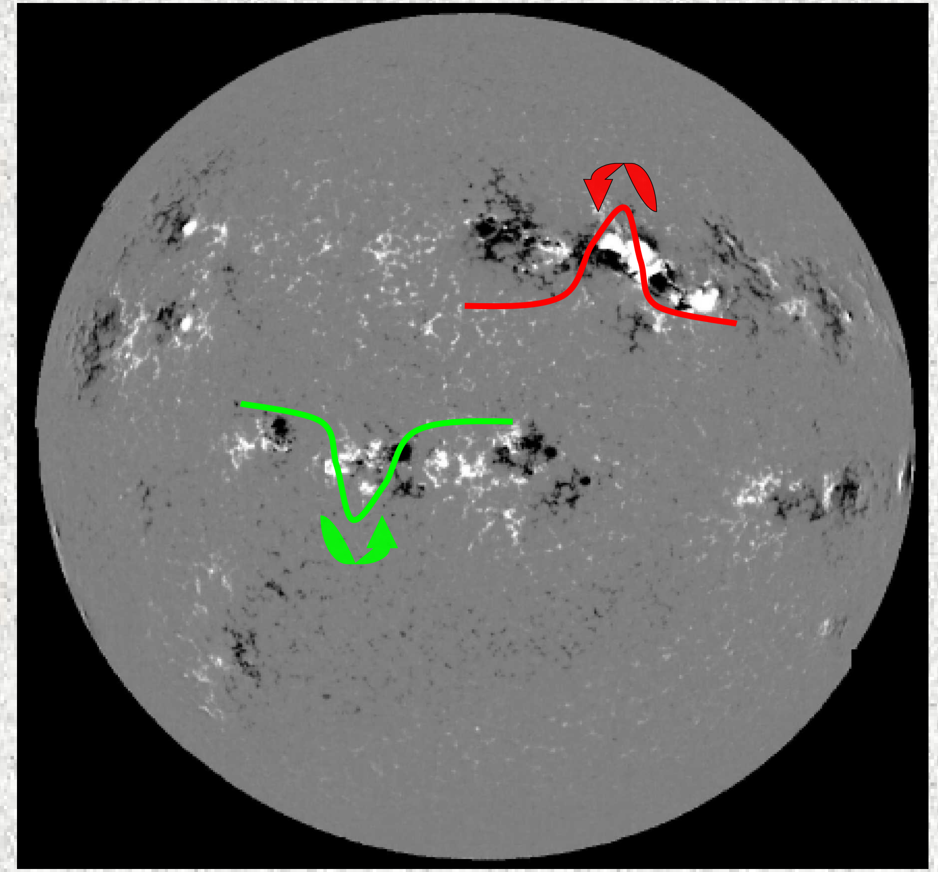
- The MHD of Solar and Stellar Plasma Systems
  - Dynamo origin of stellar magnetic fields
  - Interaction of flux tubes with turbulent convection
  - Coronal heating mechanisms

- Physics of Solar Flares and Coronal Mass Ejections
  - Instabilities and magnetic reconnection of flux tubes
  - Observational constraints on physical mechanisms
  - Predictions: Space weather forecasting techniques

- Solar Forcing of Space and Global Climate
  - Understanding long-term solar variability
  - Causes and consequences of solar irradiance variations

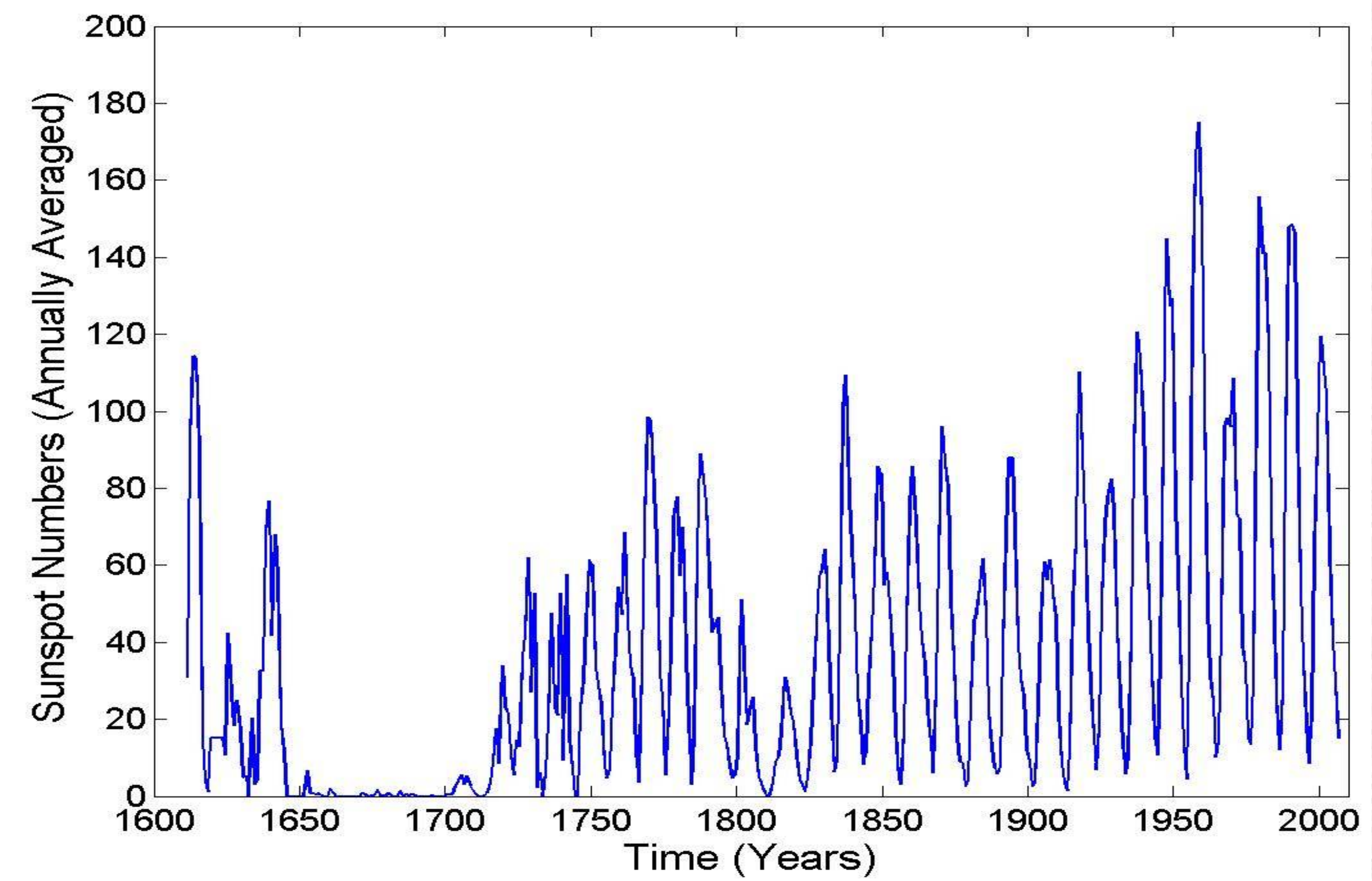
- Today: I will focus on just one of these: Origin of the Solar Cycle

Sunspots as Tracers of Solar Activity: Tilt & Orientation



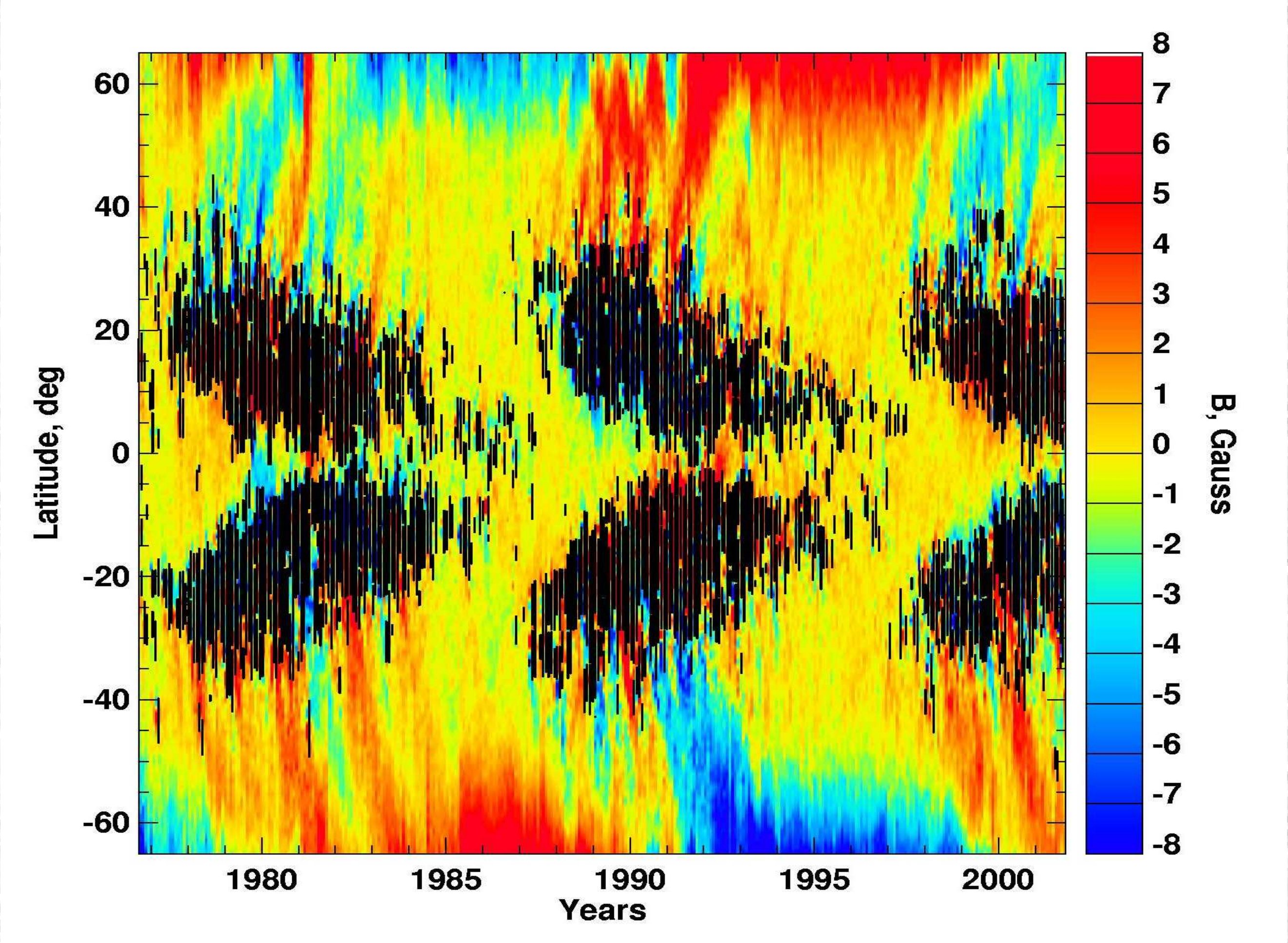
- First telescopic observations by Galileo and Scheiner (early 1600s)
- Hale (1908) discovered sunspots are strongly magnetized ~ 1000 G
- Sunspot pairs have systematic tilt, which increases with latitude
- The polarity orientation is opposite in the two hemispheres

Sunspots as Tracers of Solar Activity: The Solar Cycle



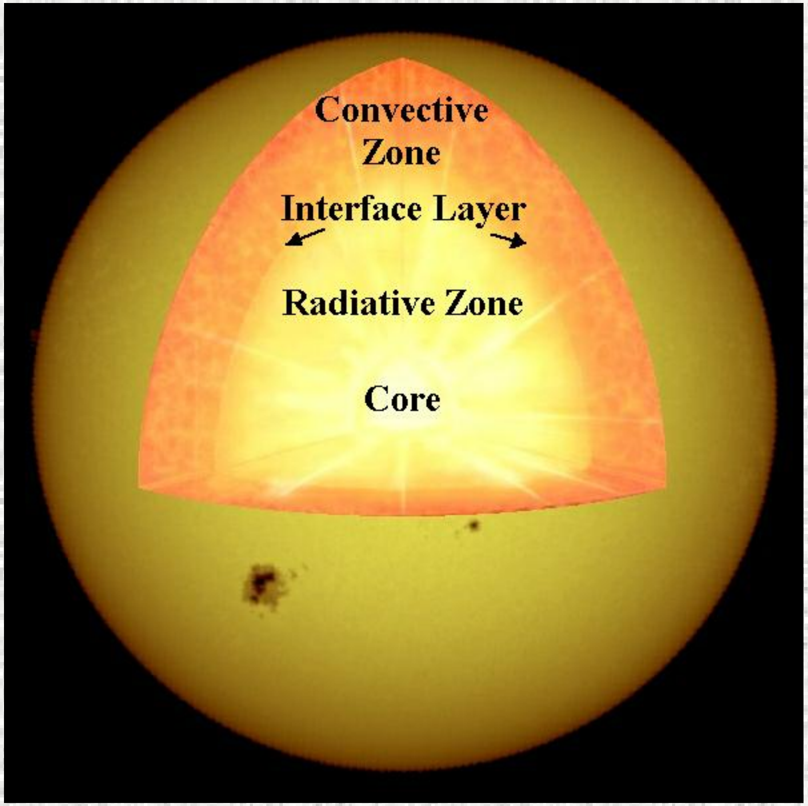
- Number of sunspots observed on the Sun vary with time
- Time variation is predominantly cyclic, mean period is 11 years
- However, there are large amplitude fluctuations

Sunspots as Tracers of Solar Activity: The Butterfly Diagram



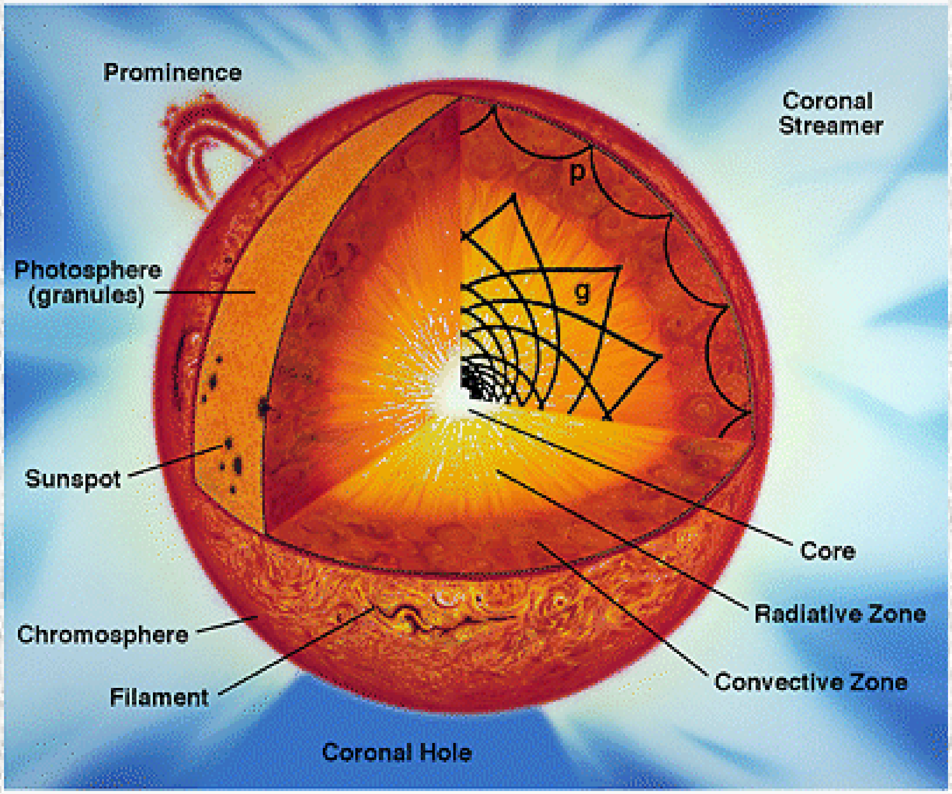
- Equatorward migration of sunspots
- Poleward migrations of weak surface radial field
- Polar field reversal at time of sunspot maximum
- Both have an average periodicity of 11 years

Window to the Solar Interior: The Flow of Energy



- Energy generated in the core (inner 25% of the Sun)
- Transported by radiation in the Radiative Zone (inner 70%) – through multiple absorption and re-radiation
- By convection in the Convection Zone (opaque, outer 30%); radiated away from Photosphere (surface) as a black body

Window to the Solar Interior: Plasma Motions



- Interior temperature exceeds a million degrees
- Matter exists in the plasma state (highly ionized)
- Convection zone has both small scale turbulent flows and large scale structured flows, in other words we are dealing with…
- The dynamics of magnetized plasmas – enter MHD!

Some Issues in MHD: The Governing Equation

- The Induction equation:

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

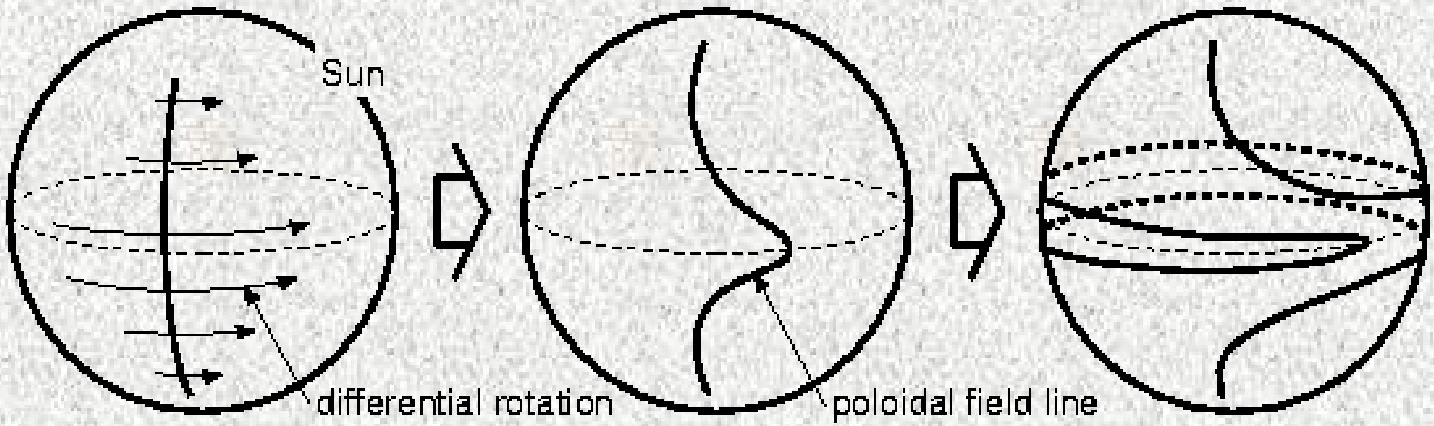
- Magnetic Reynolds Number:

$$R_m = \frac{VB / L}{\hbar B / L^2} = \frac{VL}{\hbar}$$

- In Astrophysical systems, R_M usually high, magnetic fields move with plasma – flux is frozen (Alfven, 1942)

- Magnetoconvection (Chandrasekhar 1952, Weiss 1981) – convective region gets separated into non-magnetic and magnetic space – the latter constitutes flux tubes

Historical Development – Toroidal Field & Sunspot Creation



Poloidal field

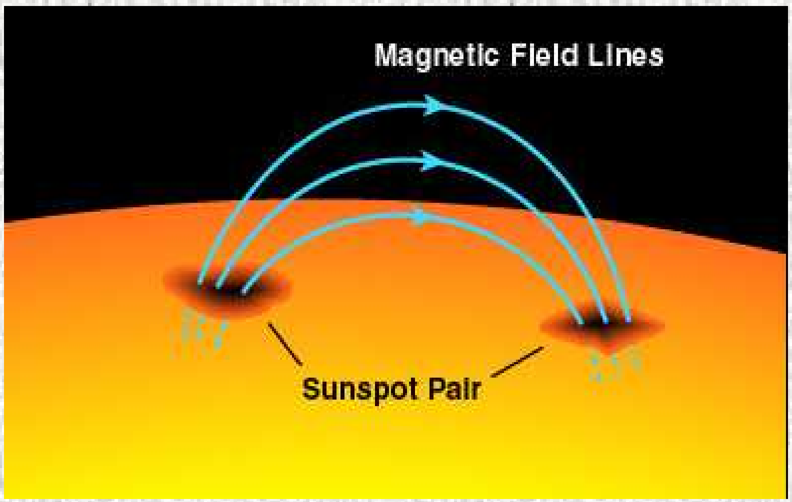
Toroidal Field

- Stability – Magnetic Buoyancy (Parker 1955)

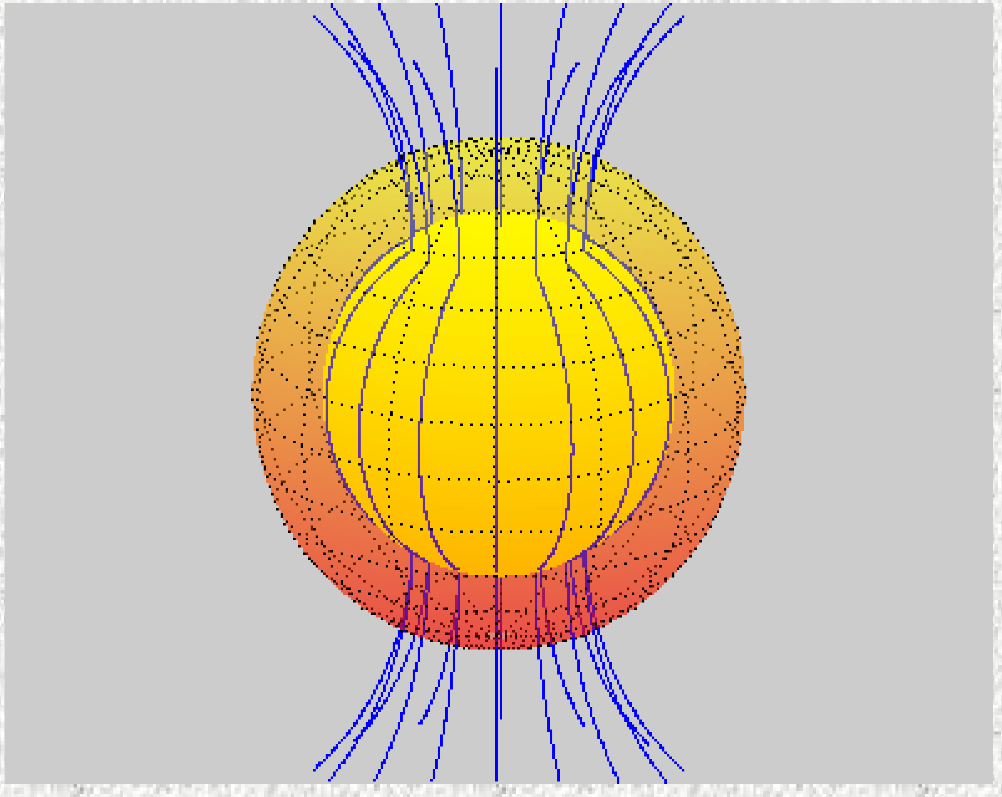
$$P_E \quad P_I \quad \frac{B^2}{8}$$

Internal < External

- Buoyant eruption, Coriolis force imparts tilts

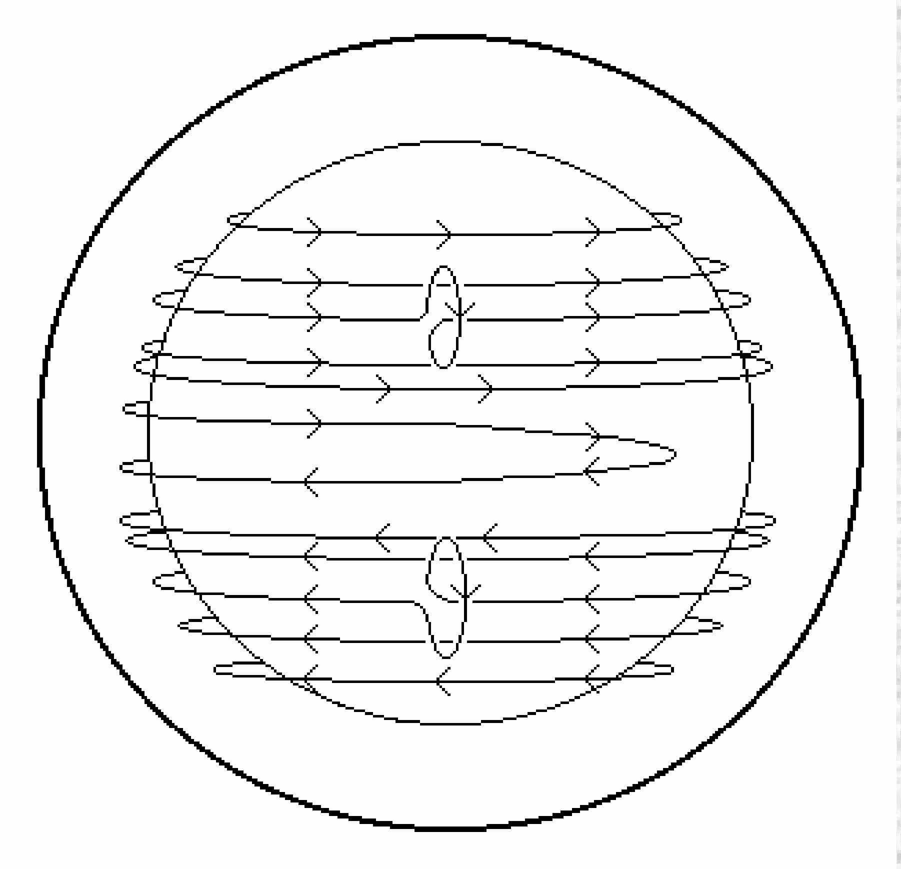


Historical Development – Toroidal Field Generation – Omega Effect



- -effect in action: Faster rotating equator stretches an poloidal field in the direction of rotation to create the toroidal fields
- Where is the toroidal field generated?
  - Convection zone susceptible to buoyancy, ruled out (Parker 1975)
  - In the overshoot layer, at base of convection zone (Spiegel & Weiss 1980; van Ballegooijen 1982)

Historical Development – Poloidal Field Generation – The MF _-effect



- Small scale helical convection – Mean-Field   -effect (Parker 1955)
- Buoyantly rising toroidal field is twisted by helical turbulent convection, creating loops in the poloidal plane
- The small-scale loops diffuse to generate a large-scale poloidal field

Last Two Decade – Flux Tube Dynamics and a Crisis in Dynamo Theory

- Interaction of Coriolis force with buoyantly rising magnetic flux tubes would force them poleward if **B** < 10^5 G (Choudhuri & Gilman 1987)

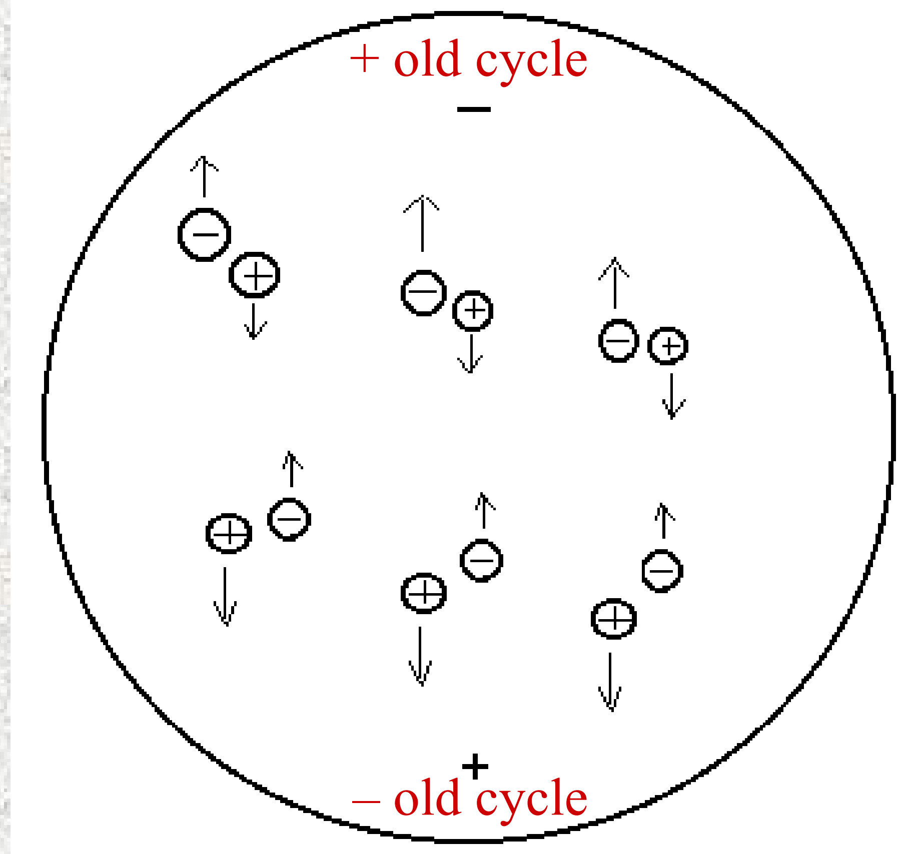
- To match Joy's law (tilt angles of sunspots) and other morphological properties of solar active regions **B** ~ 10^5 G (D'Silva & Choudhuri 1993, Fan, Fisher & DeLuca 1993)

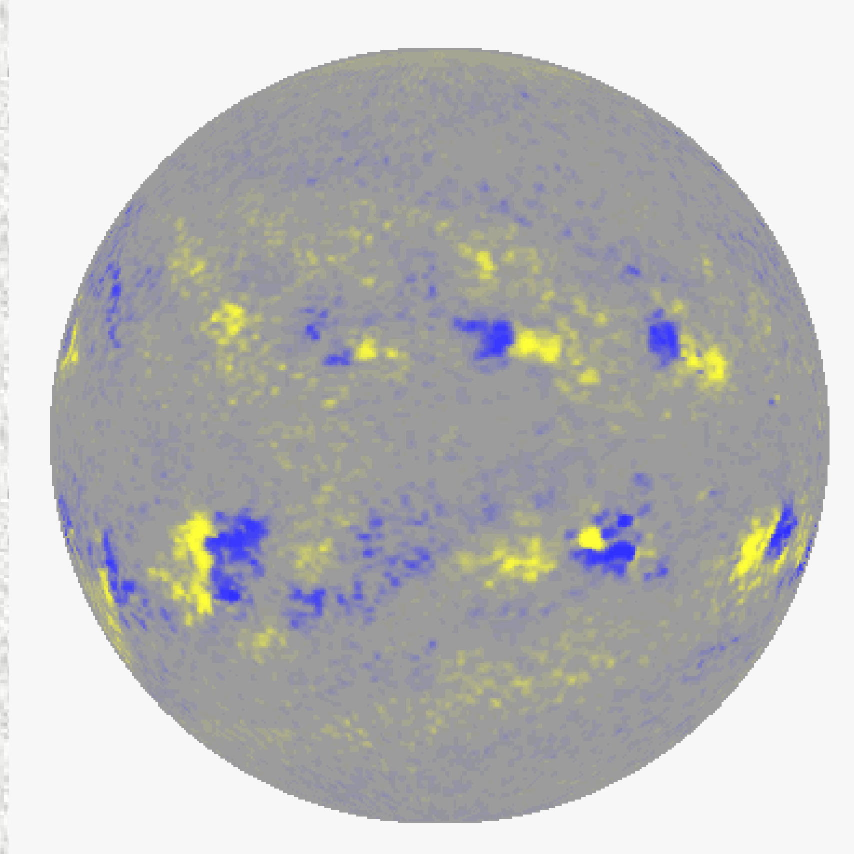
- Flux tubes with **B** < 10^5 G can be stored in the overshoot layer beneath the base of the convection zone, only stronger flux tubes escape out (Moreno-Insertis, Schüssler & Ferriz-Mas 1992)

- Strength of flux tubes at SCZ base **10^5 G**
  Equipartition field in convection zone **10^4 G**

- Small-scale helical convection will get quenched – alternative ideas for poloidal field generation necessary for the Sun

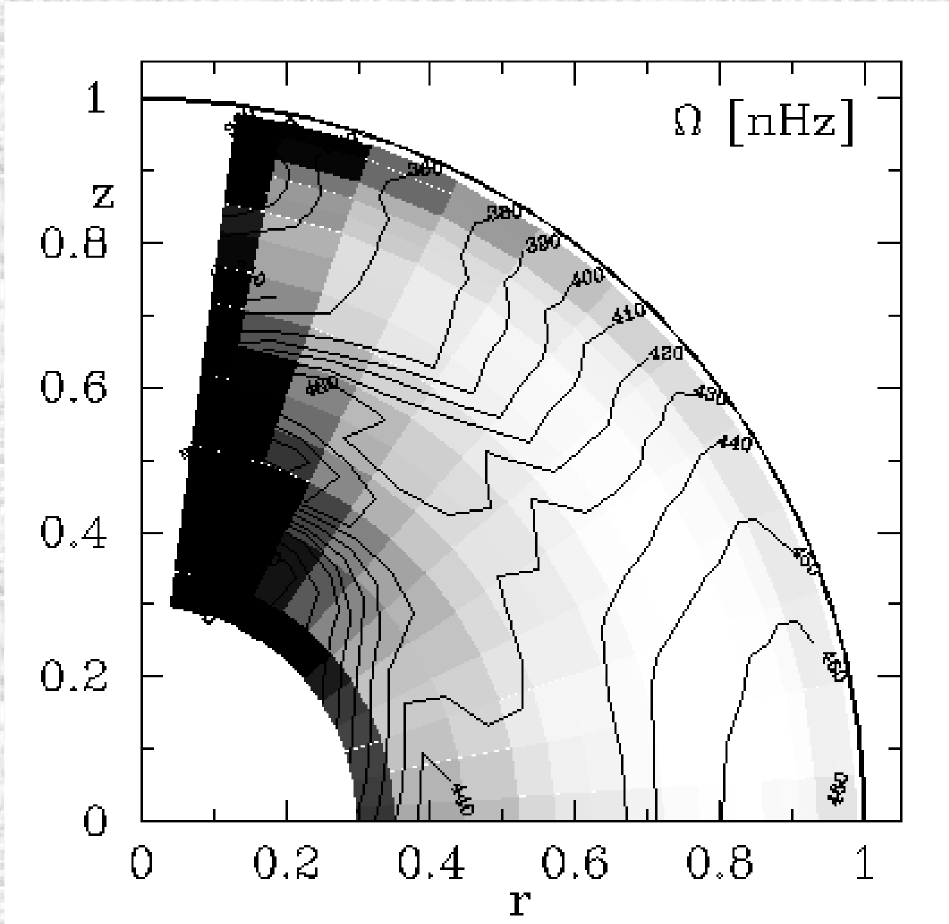
The Modern Era: Revival of the Babcock-Leighton Idea

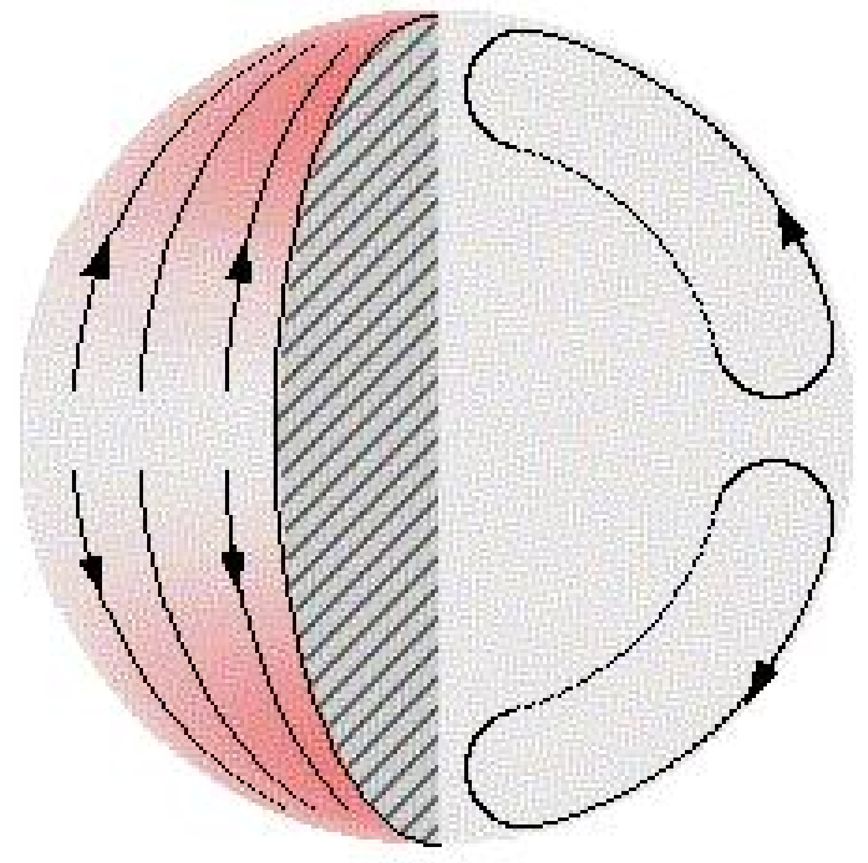




- Babcock (1961) & Leighton (1969) idea – decay of tilted bipolar sunspots – distinct from the MF   -effect – <u>and is observed</u>

The Modern Era: Large Scale Internal Flows from Helioseismology





- Differential rotation in the interior determined from helioseismology, strongest rotational shear at tachocline at the base of the SCZ
- Poleward meridional circulation observed in the outer 15%, mass conservation requires a counterflow – possibly near base of the SCZ

Formulating the Axisymmetric Kinematic ___ Dynamo Model

- Axisymmetric Magnetic Fields:

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

- Axisymmetric Velocity Fields:

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

- Plug these into the Induction Equation:

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

to obtain…..

The ___ Dynamo Equations

- Toroidal field evolution:

$$\frac{B}{t} \quad \frac{1}{r} \quad \frac{}{r} \quad r v_r B \qquad \frac{}{} \quad v \; B$$

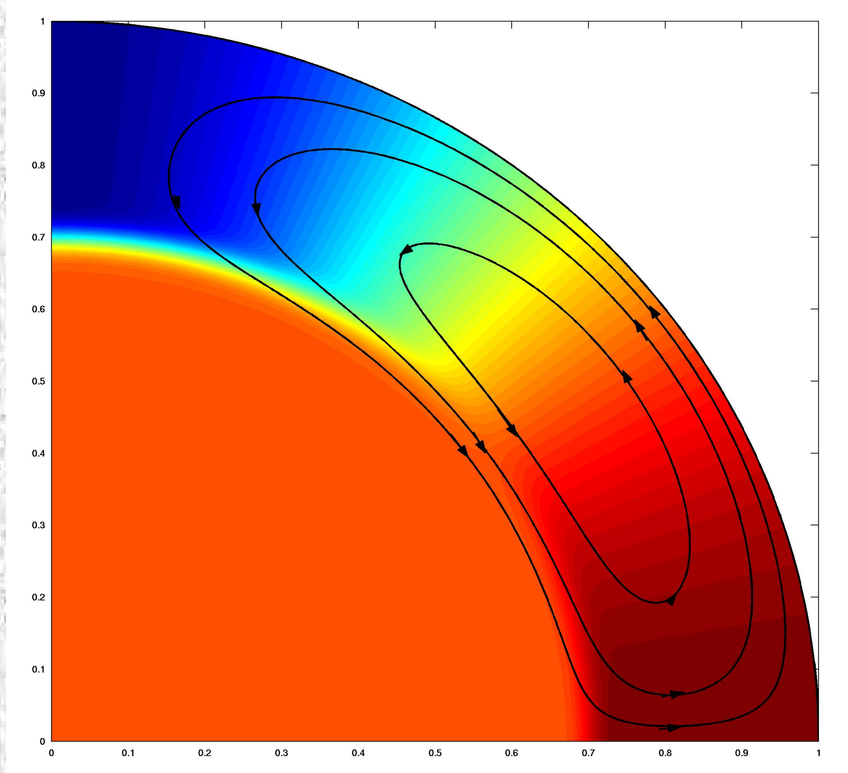
$$^{2} \quad \frac{1}{r^2 \sin^2} \quad B \qquad r \sin \qquad B_P . \qquad\qquad (\qquad B \;)$$

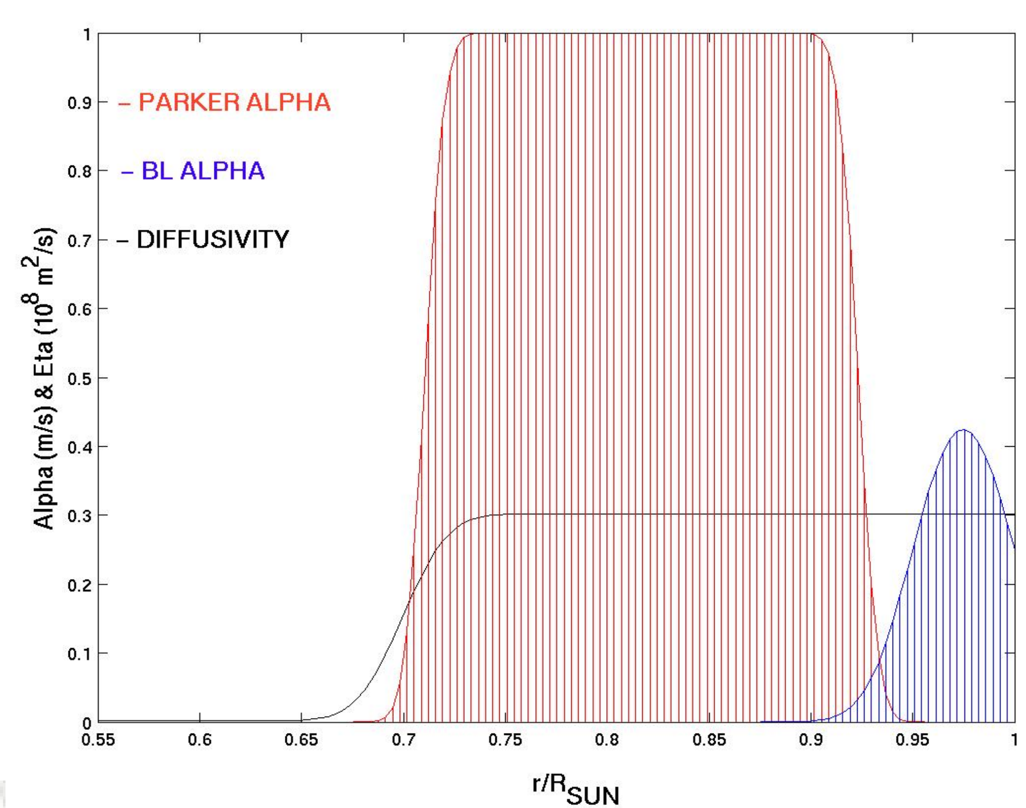
- Poloidal field evolution:

$$\frac{A}{t} \quad \frac{1}{r \sin} \quad v_P . \qquad r \sin \quad A \qquad\qquad 2 \quad \frac{1}{r^2 \sin^2} \quad A \quad S$$

- Where the BL alpha effect S B acts on buoyantly erupted toroidal fields

Model Inputs

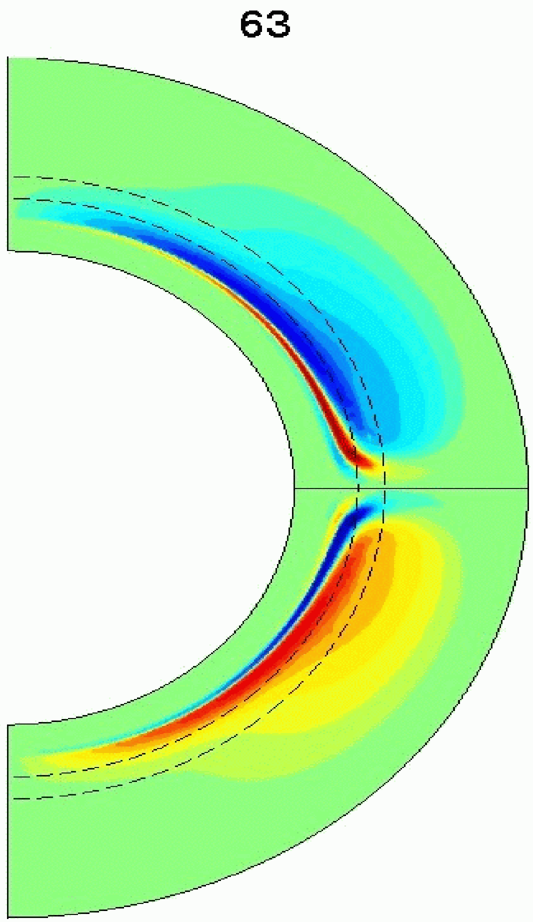


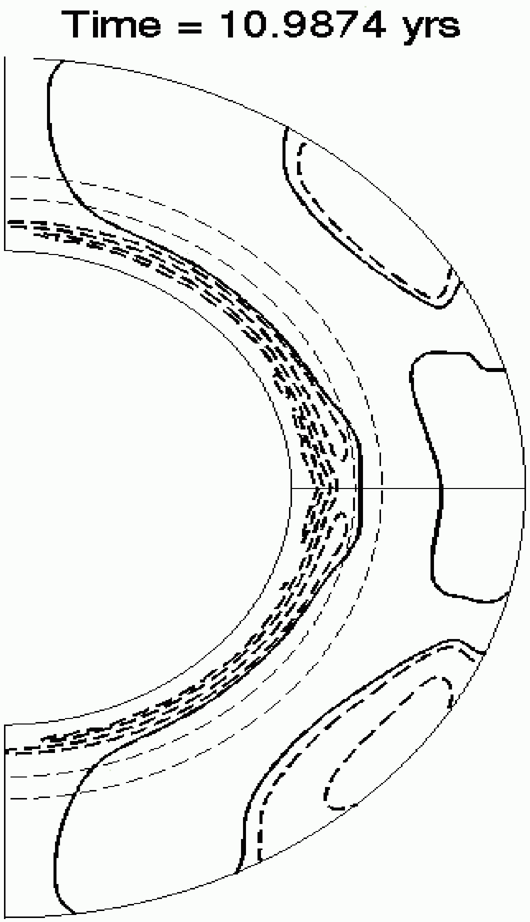


- Observed differential rotation (inferred from helioseismology)
- Meridional circulation profile that matches near surface observations
- A depth dependent diffusivity profile
- A functional form for the BL -effect (confined to near surface layers)
- Magnetic buoyancy algorithm (transports field exceeding threshold)

Solar Cycle Simulations

(Nandy & Choudhuri 2001, 2002; Nandy 2002, 2003; Nandy 2004; Chatterjee, Nandy & Choudhuri 2004; Yeates, Nandy & Mackay 2007)

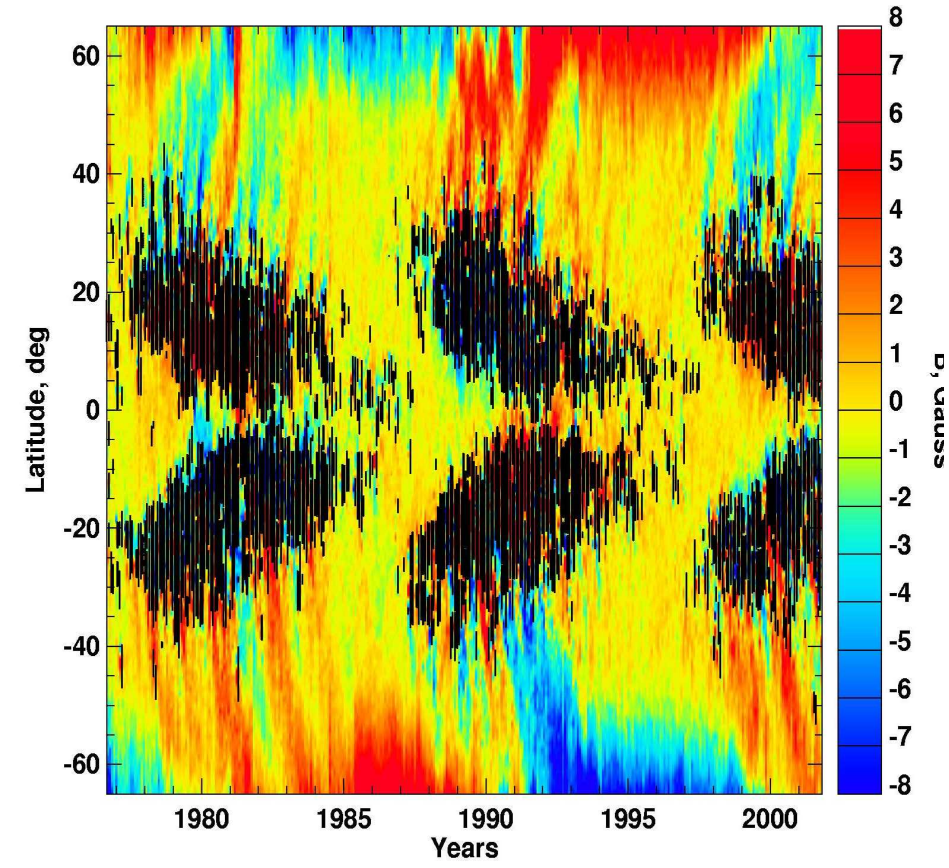


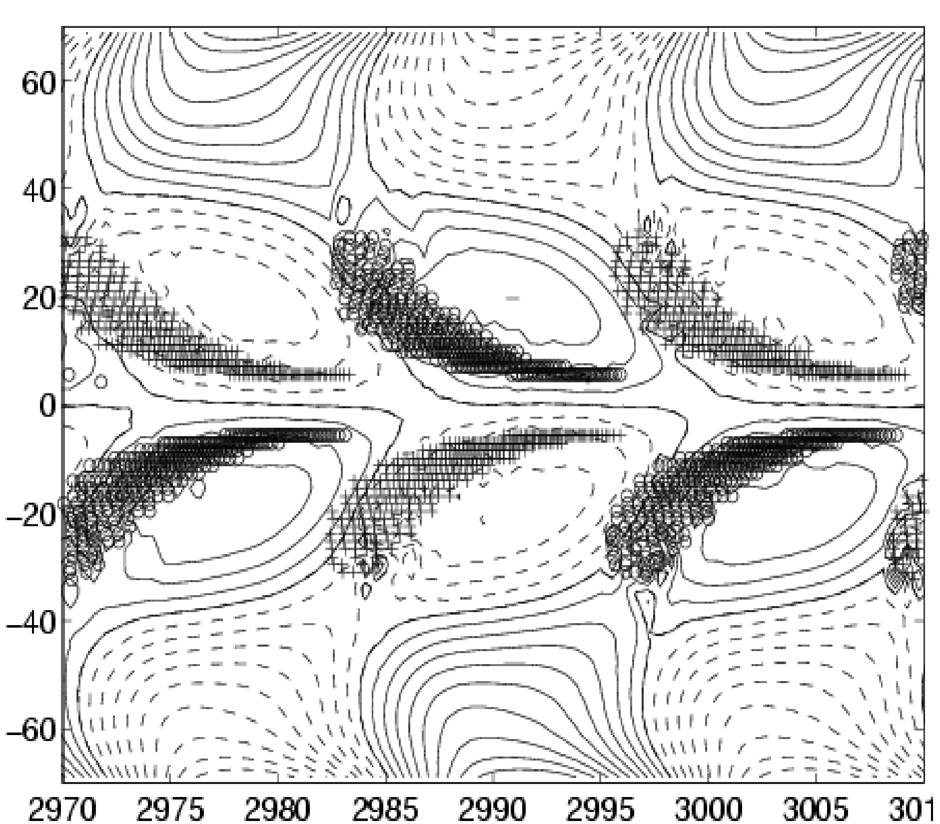


Toroidal Field Evolution

Poloidal Field Evolution

Solar Cycle Simulations



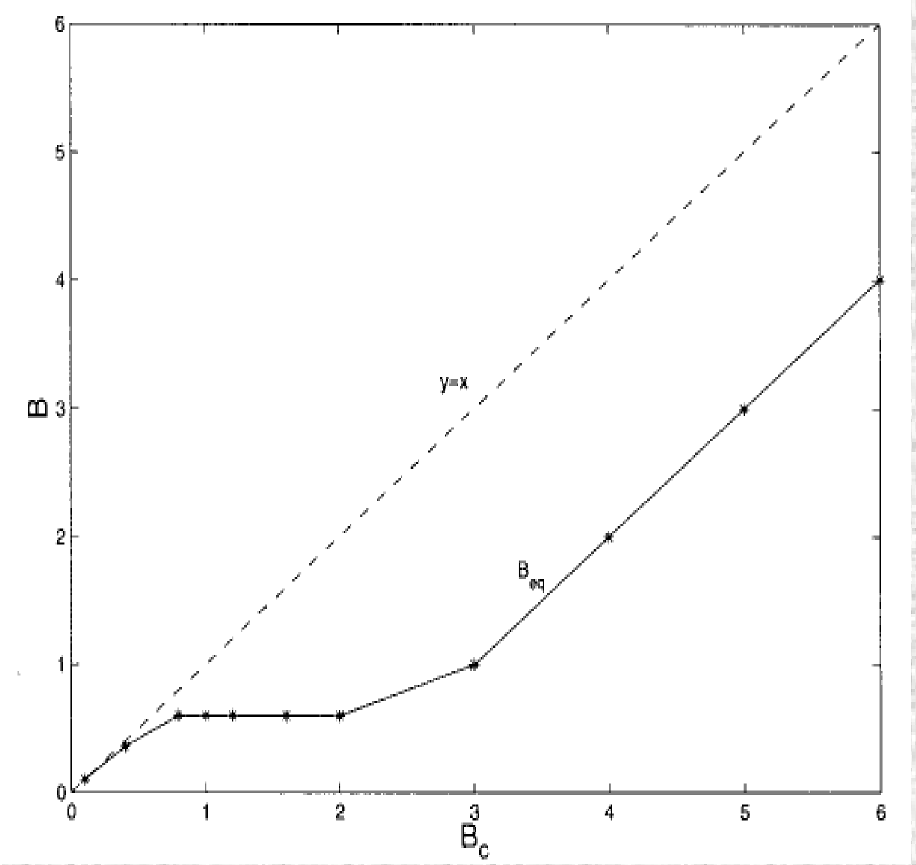


Observations

Simulations

- General characteristics agree well; <u>Even the relative phase of toroidal and poloidal field is reproduced (notoriously difficult in the past)</u>

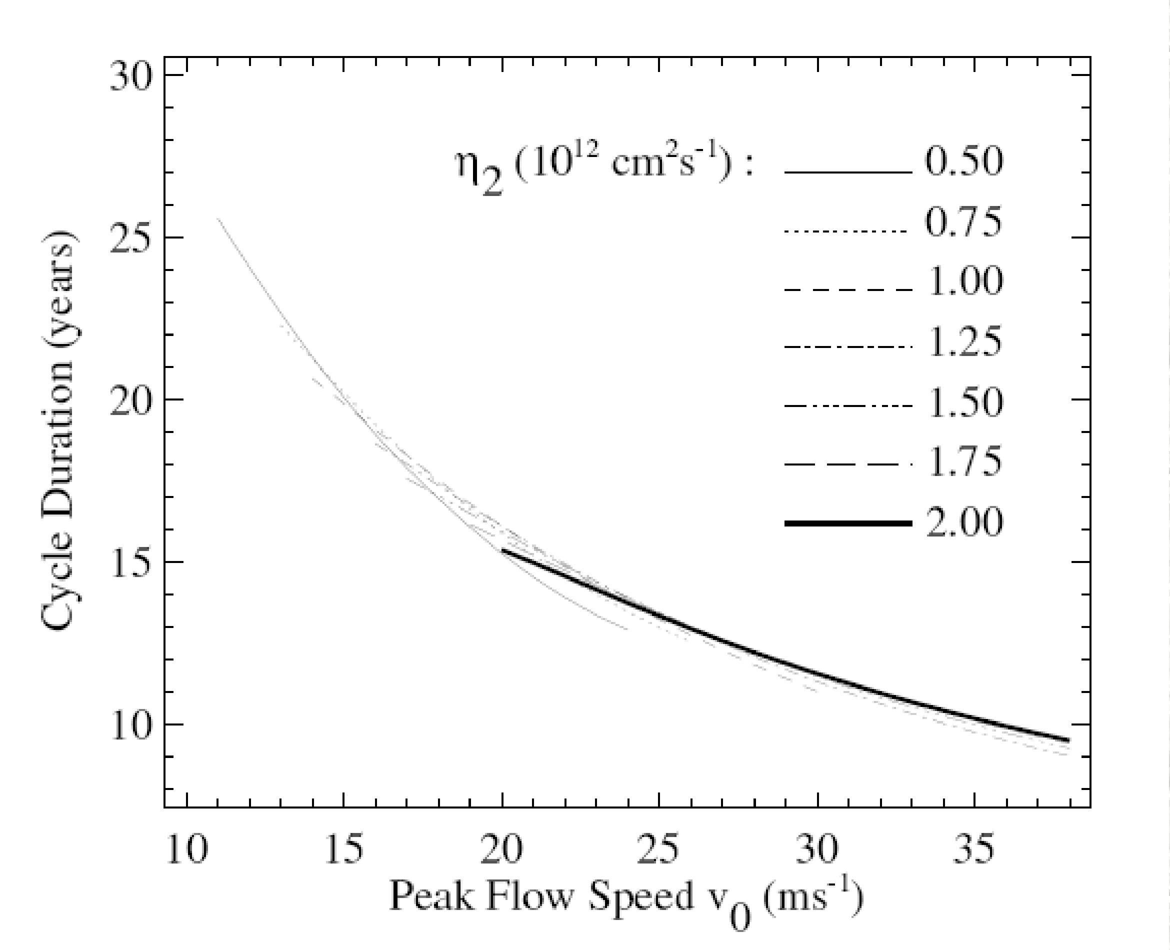
What Determines Solar Cycle Amplitude?



If the amplitude of the   -effect is fixed:

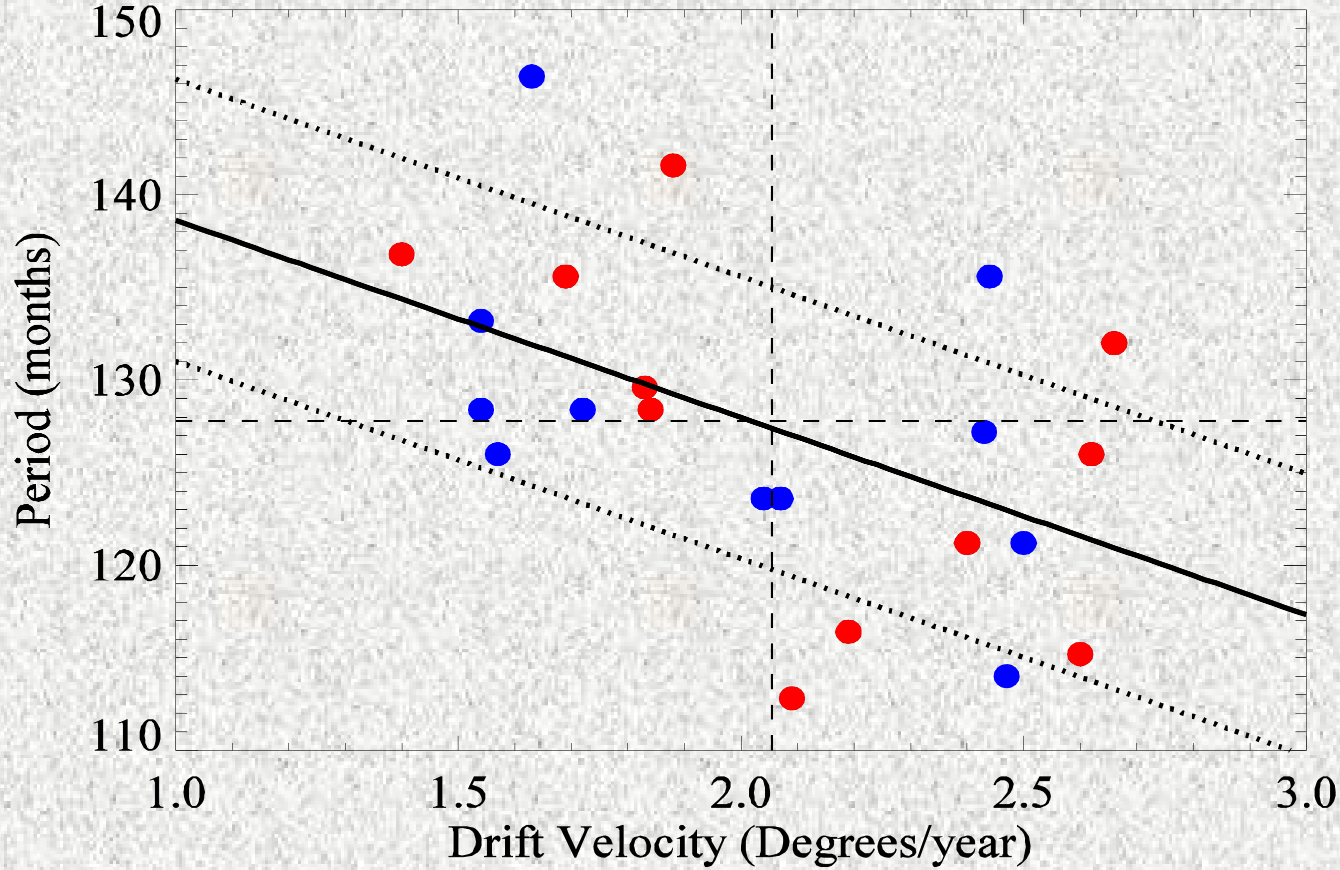
- Primary constraint: Critical threshold for buoyancy (B_c)
- Therefore peak toroidal field in the solar interior ~ B_c ~ 10^5 G
- Modulation around that by diffusivity and meridional flow

What Determines Solar Cycle Period? Theoretical Simulations



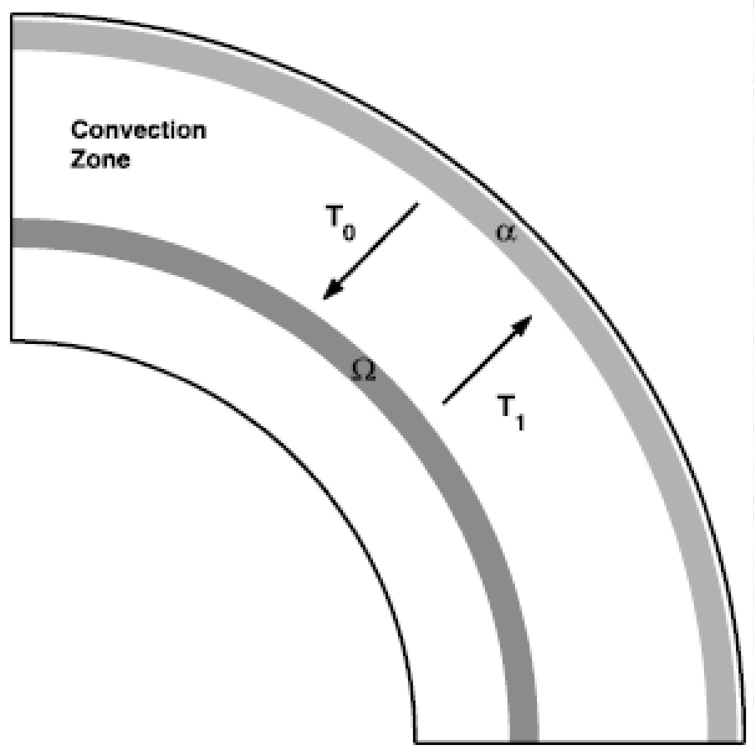
- The speed of the meridional circulation sets the sunspot cycle period
- Diffusivity has a small effect
- Note: Period is governed by slowest process in the dynamo chain

What Determines Solar Cycle Period? Observational Confirmation



- Based on observed solar cycle properties from 1874-2003 AD
- Cycle period is anti-correlated with sunspot drift velocity (cross-correlation coefficient -0.5, confidence level 95%)
- Confirms that the sunspot cycle is driven by meridional flow speed

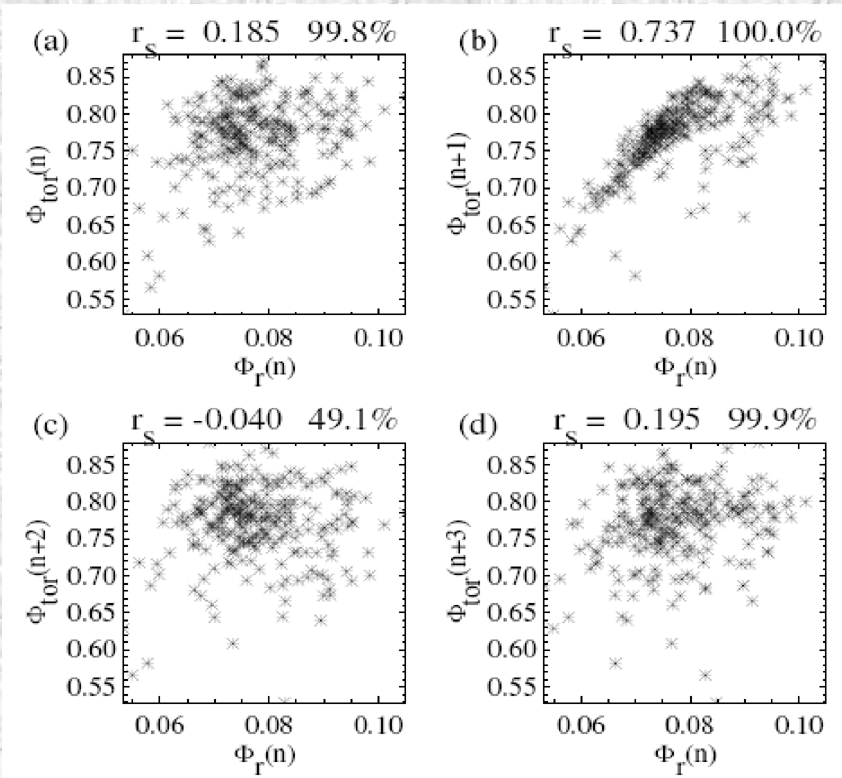
Fluctuation + Time Delay Dynamic + Memory = Solar Cycle Predictions



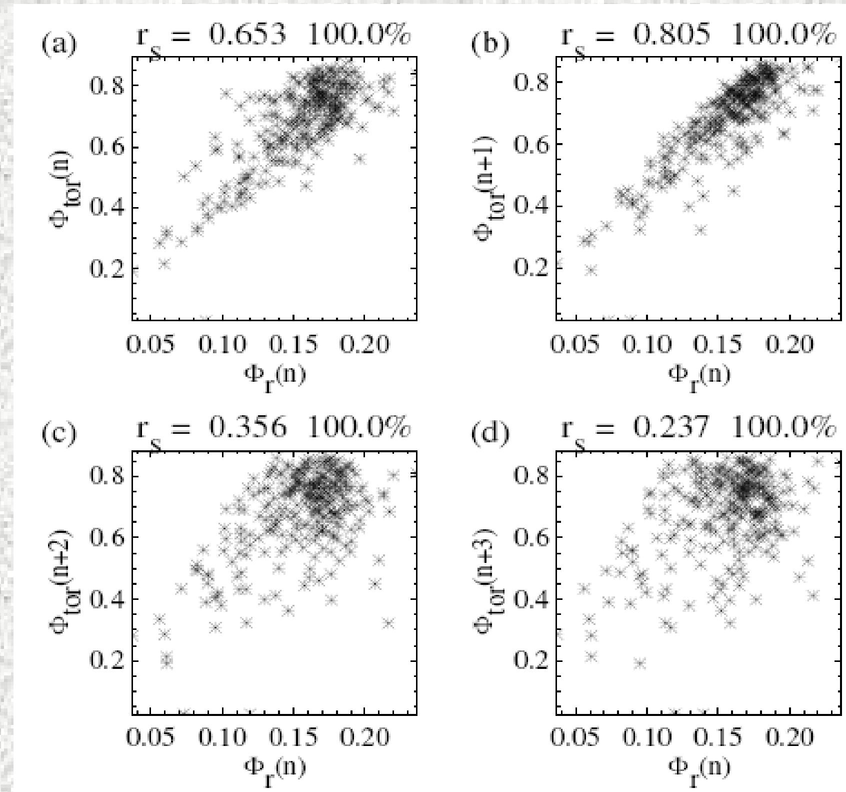
- Magnetic flux transport takes time, introducing solar cycle memory (Charbonneau et al. 2000, Wilmot-Smith, Nandy et al. 2006)
- Inherent stochastic fluctuations in the dynamo output are natural
- Memory of fluctuations survive based on time-delay; this property may lead to predictive capabilities (Nandy 2002)
- However, recent attempts lead to conflicting and controversial results (Dikpati et al. 2006, Choudhuri et al. 2007). Why?

The Physical Basis of Solar Cycle Predictions

(Yeates, Nandy & Mackay 2007)



(Diffusion Dominated Flux Transport)



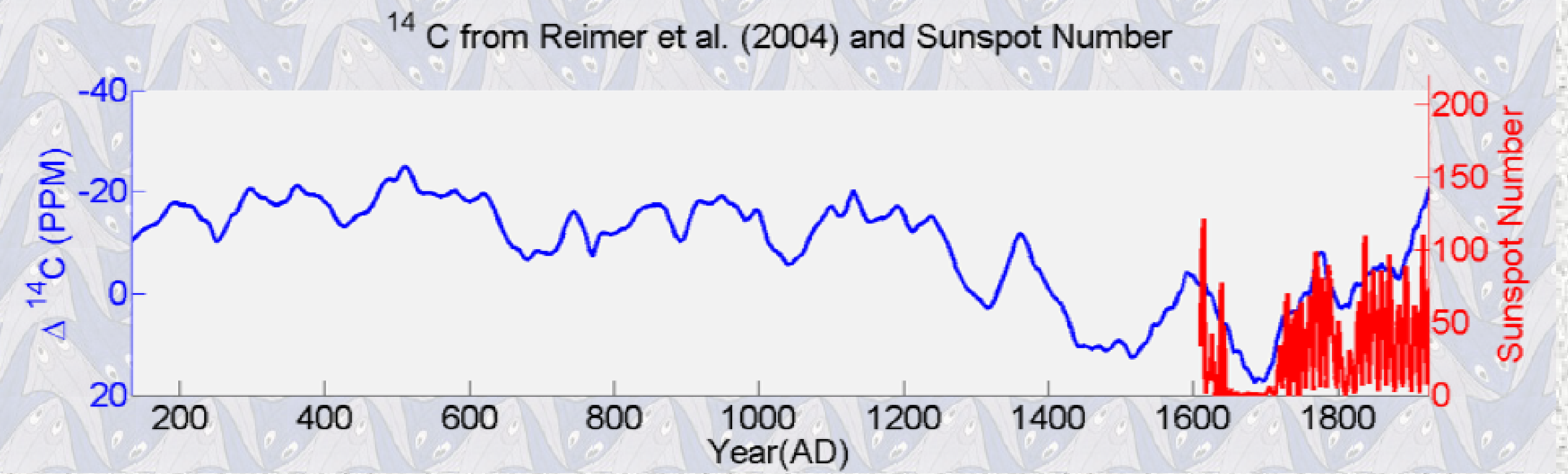
(Advection Dominated Flux Transport)

- Memory of fluctuations different in diffusive and advective regimes
- Diffusive flux transport short-circuits advective flux transport
- Understanding physics of flux transport key to predictions
- Detailed investigations of other related processes ongoing…

Conclusions: Insights from Solar Dynamo Modeling

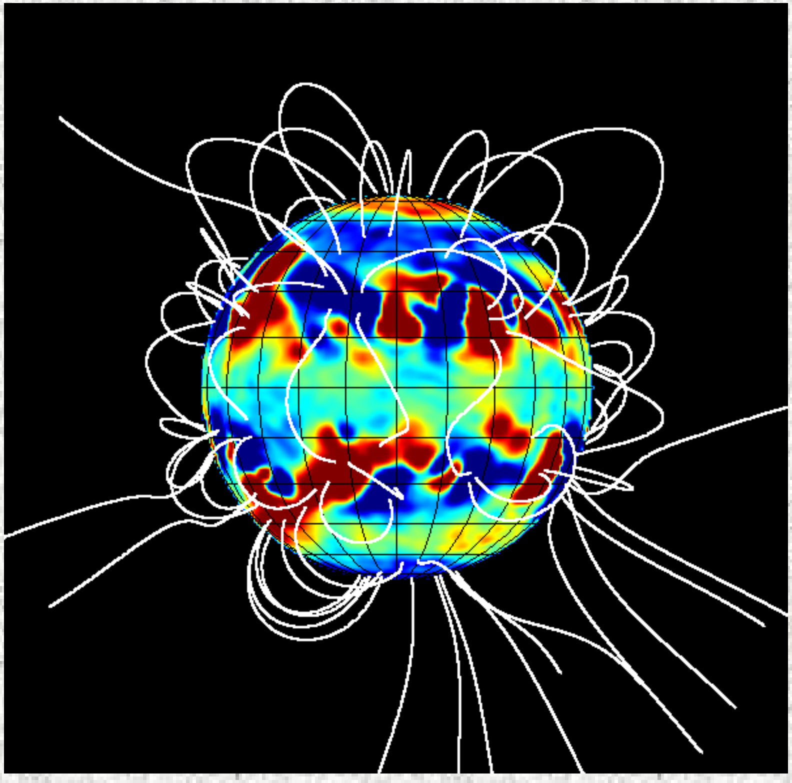
- Using observed large-scale flows (kinematic regime), we can reproduce the observed large-scale magnetic field evolution very well
- So, perhaps we are getting some aspects of the physics right
- Flux transport processes such as buoyancy, diffusion and meridional circulation extremely important for the solar magnetic cycle
- Magnetic buoyancy acts as a amplitude limiting factor for solar cycle
- Meridional circulation sets the sunspot cycle period
- Flux transport mediated time-delay dynamics introduces a memory mechanism in the Sun, that may be used for predicting the strength of future cycles
- Development of solar activity predictions is important for satellite operations, telecommunication facilities, planning of future space missions and understanding the future role of the Sun in the context of global climate change

Research Plans (or stuff that I didn't talk about) I: Physics of Dynamos



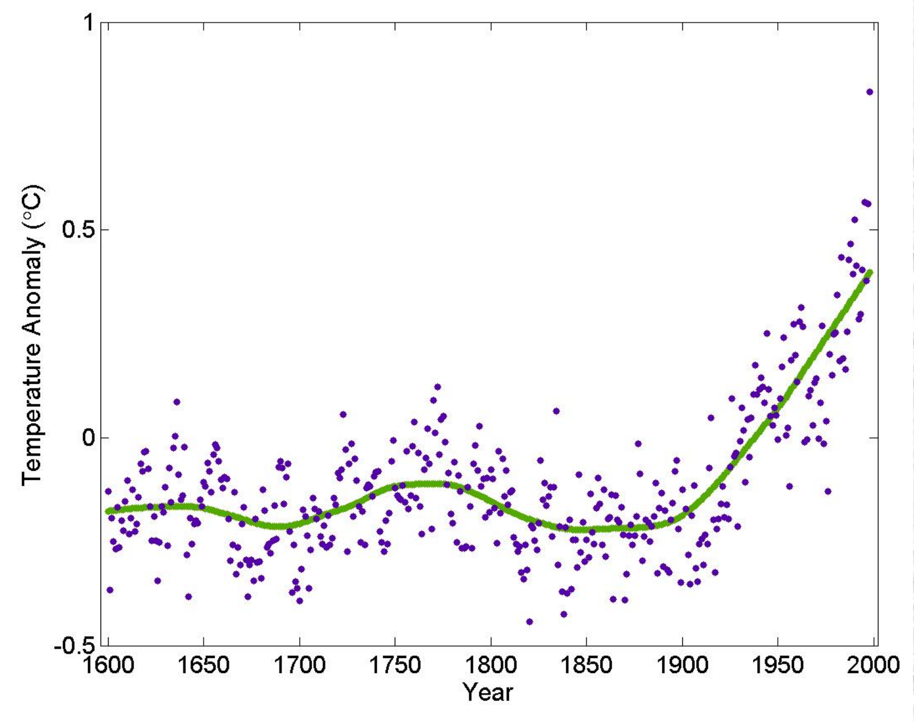
- Solar and Stellar Dynamos (Non-linear Dynamics)
  - Origin of grand maxima and minima in activity
    (How do they occur and how does the dynamo come out?)
  - The physics of solar cycle predictability
    (Is prediction possible at all; If yes, what determines it?)

Research Plans II: Space Weather – Models to Forecasts

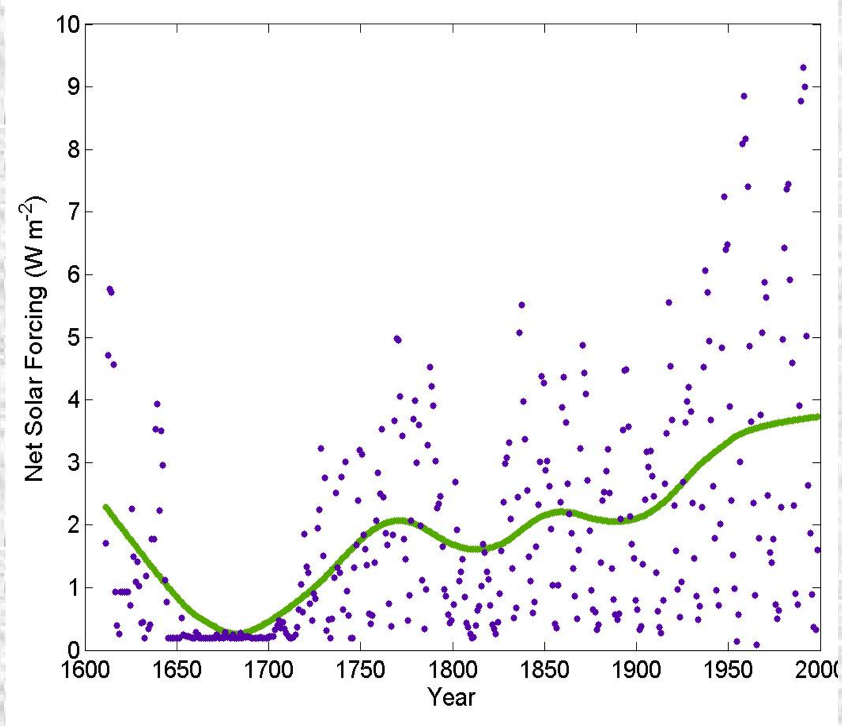


- Space Weather and the Heliosphere
  - Lower boundary driven model of the inner heliosphere
  - Observationally constraining processes of solar eruptions (Kink instability: Nandy et al. 2007, ApJL submitted)
  - Transition from basic research to operational forecasts (the ultimate test of any theory or model!)

Research Plans III: The Sun and Climate



(Mann et al. 2004)



(Nandy & Joy, work in progress)

- Space and the Global Climate
  - Reconstructing long-term solar variability: Stars as Suns Project (Solar-Stellar connection, Young-Earth radiation environment)
  - Quantifying TSI and Cosmic Ray fluctuations
  - The Sun's role in global climate change

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