The Solar Cycle: From Understanding to Forecasting

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Solar Magnetic Fields: Sunspots

- First telescopic observations by Galileo and Scheiner (1611 AD)
- Size about 10,000 Km
- Sunspots are strongly magnetized $\sim 1000$ 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 ($m \sim 10^{12} \text{ Kg, } v \sim 500-2000 \text{ km/s, } E \sim 10^{24} \text{ Joules}$)
- 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

Usoskin et al. 2003, PRL
Understanding & Forecasting Solar Activity Important

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:
  \[ \frac{\partial B}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \]

- 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 \( \tau_\eta > \) Flow timescale \( \tau_v \)

- In solar interior, plasma \( \beta >> 1 \) (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: $4.39 \times 10^9$ 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 $v \sim 100$ 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)

- 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


\[ \rho_{\text{Internal}} < \rho_{\text{External}} \]

• Buoyant eruption, Coriolis force imparts tilts (sunspots are tilted)
Poloidal Field Generation – The MF $\alpha$-effect

- Small scale helical convection – Mean-Field $\alpha$-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…
• 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:

\[ B = B e_\phi + \nabla \times (A e_\phi) \]

• Axisymmetric Velocity Fields:

\[ \mathbf{v} = \mathbf{v}_p + r \sin \theta \Omega e_\phi \]

• Plug these into the MHD induction equation:

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

And separate the two components to obtain…..
Building a Dynamo Model: The $\alpha \Omega$ Dynamo Equations

- Toroidal field evolution:

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

- Poloidal field evolution:

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

- Poloidal field source is parameterized by $S_\alpha$
- 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

Chatterjee, Nandy and Choudhuri (2004, A&A)
Capturing Sunspot Eruptions by Durney’s Double Rings


- 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

- 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:

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

- 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 $\alpha$-effect…
Origin of Fluctuations in the Solar Cycle: Path to Chaos

• Dynamical nonlinearities especially important in super-critical regimes — Tobias (1997, A&A)

• 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


• Is solar cycle weakly critical or in the highly critical, chaotic regime?
Chaotic Systems and Predictability

When our results concerning the instability of non-periodic 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

- Toroidal field evolution:
  \[
  \frac{\partial B_\phi}{\partial t} + \frac{1}{r} \left[ \frac{\partial}{\partial r} (rv_r B_\phi) + \frac{\partial}{\partial \theta} (v_\theta B_\phi) \right] = \eta \left( \nabla^2 \frac{1}{r^2 \sin^2 \theta} \right) B_\phi + r \sin \theta (B_p \nabla) \Omega - \nabla \times (\nabla \times B_\phi)
  \]

- Poloidal field evolution:
  \[
  \frac{dB_\phi(t)}{dt} = \frac{\omega}{L} A(t - T_0)
  \]

But Poloidal Field Observed

Flux Transport Deterministic
Introduces time delay = memory

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 predicting 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
- Known to affect dynamics (Guerrero & Dal Pino 2008, A&A)
- Does it affect cycle memory?
Effect of Turbulent Flux Pumping on Cycle Memory

(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

- 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)**
  \[ \tau_v = 20 \text{ yrs (Long memory)} \]

- **Turbulent Diffusion (1 x 10^{12} \text{ cm}^2/\text{s})**
  \[ \tau_\eta = 14 \text{ yrs (Moderate memory)} \]

- **Turbulent Pumping (v = 2 m/s)**
  \[ \tau_{pumping} = 3.4 \text{ yrs (Short memory)} \]
Long Memory: Polar field of multiple cycles seeds next sunspot cycle

Short Memory: Polar field at minimum seeds next cycle only

Fig. 7
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)


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

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