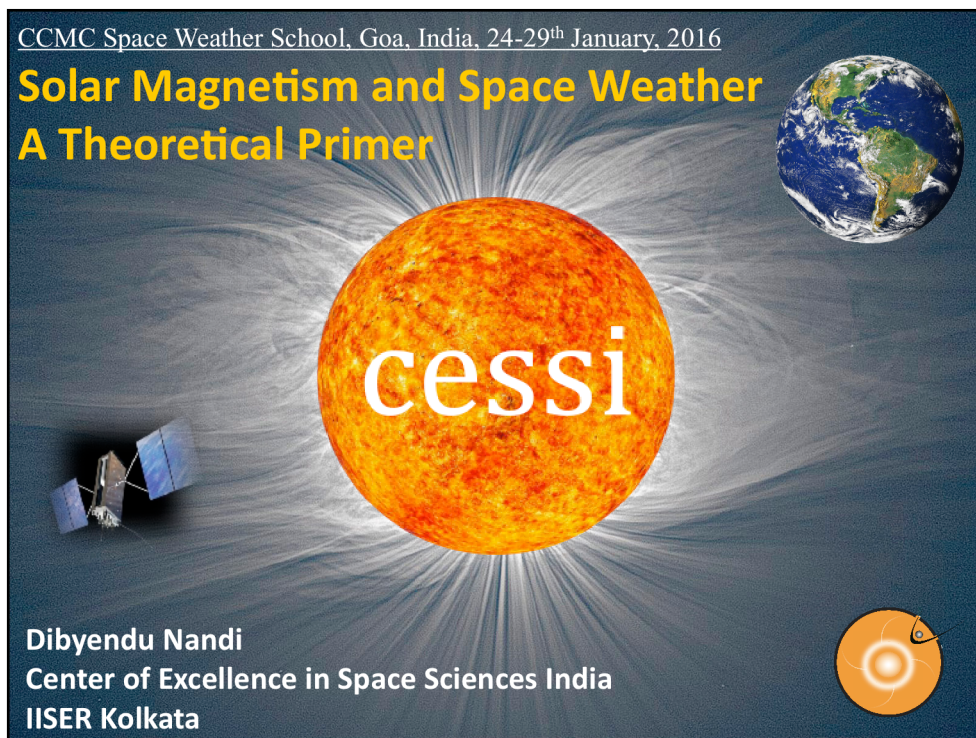
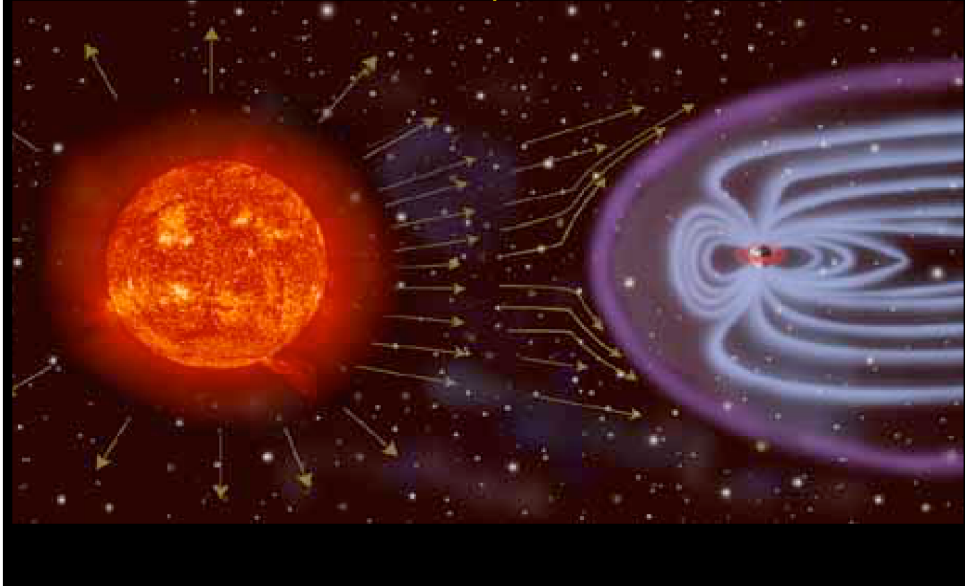




My name is Dibyendu. I lead the Center of Excellence in Space Sciences India (CESSI) at IISER Kolkata where one of our primary focus is to use theoretical, computational and observational tools to understand the origin of solar magnetism and based on this understanding, develop physics based predictive models of solar activity. More on CESSI can be found at:

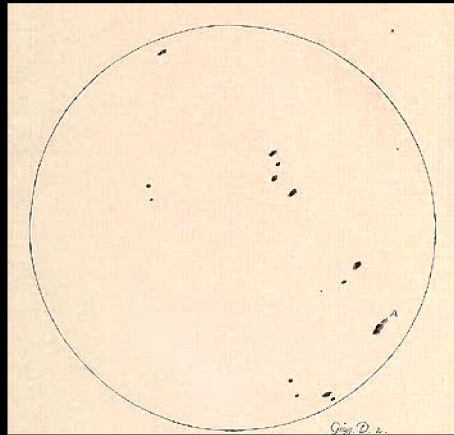
<http://www.cessi.in>.

The Sun varies and this variation modulates the electromagnetic and particulate environment of the heliosphere



The Sun is the most dynamically active astrophysical object in the solar system. Its activity varies, this variation being primarily modulated by its changing magnetic output on timescales of hours to decades to millennia. This variation is manifest in its changing radiative, electromagnetic and particle flux output which in turns governs the environment within the heliosphere. This changing environment or space weather as it has come to be known, forces planetary atmospheres and climate and technological systems that are deployed in space.

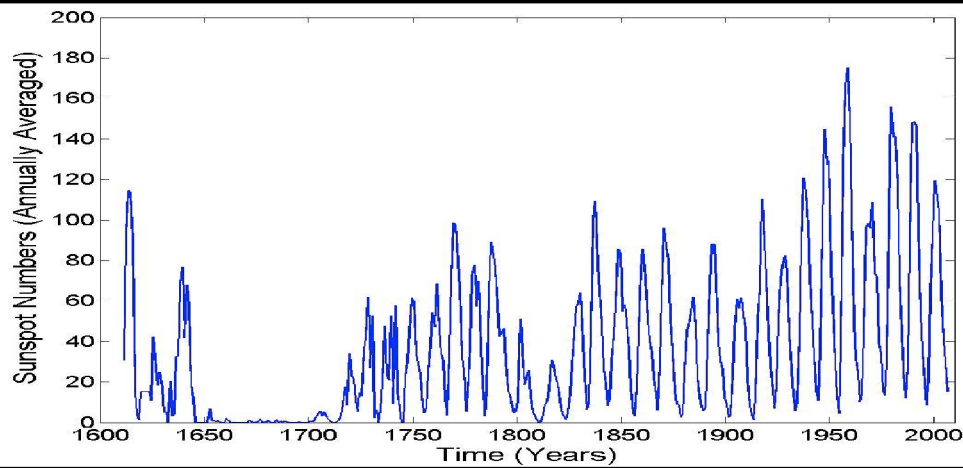
Sunspots and the Solar Cycle



- First systematically observed by Galileo, Fabricius, Scheiner
- Radius $\sim 10,000$ Km
- Strongly magnetized $\sim 1,000$ Gauss (Hale 1908)
- The number of sunspots varies cyclically with fluctuating amplitudes

Sunspots are concentrated regions of intense magnetic fields on the Sun which are often larger than the size of the Earth. They have been observed for over four centuries now. The sunspot time series show that the number of spots on the solar surface varies periodically with an average period of 11 years. This is known as the solar cycle or the sunspot cycle.

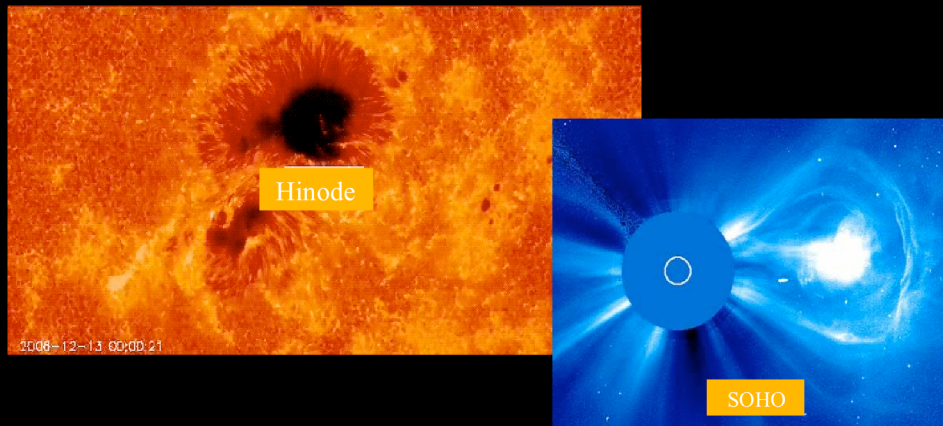
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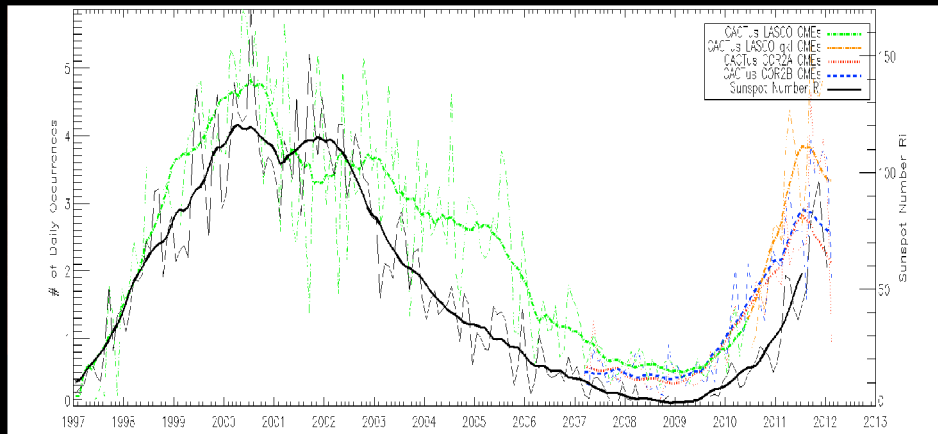
Sunspots are the Seats of Solar Storms



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

Sunspots are the seats of solar storms, highly energetic explosions which create extreme conditions in the solar system and adversely impact our space-based technologies. The number of solar storms and their frequency of occurrence is correlated with the sunspot cycle, with strong, high amplitude solar cycles generating more solar storms.

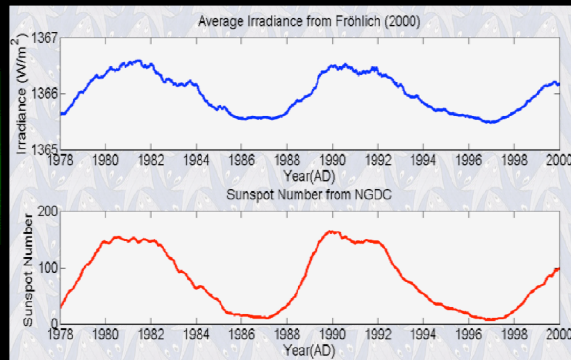
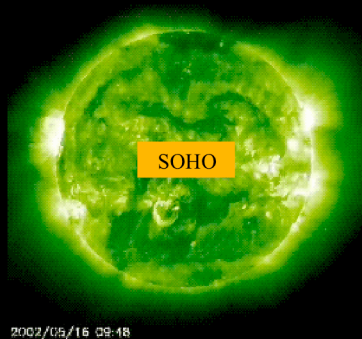
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Solar Energy Output Varies with the Sunspot Cycle



- The TSI (total solar irradiance) is modulated by Sun's magnetic output

**It is the primary natural energy input to the global climate system
— it is variable and not a constant!**

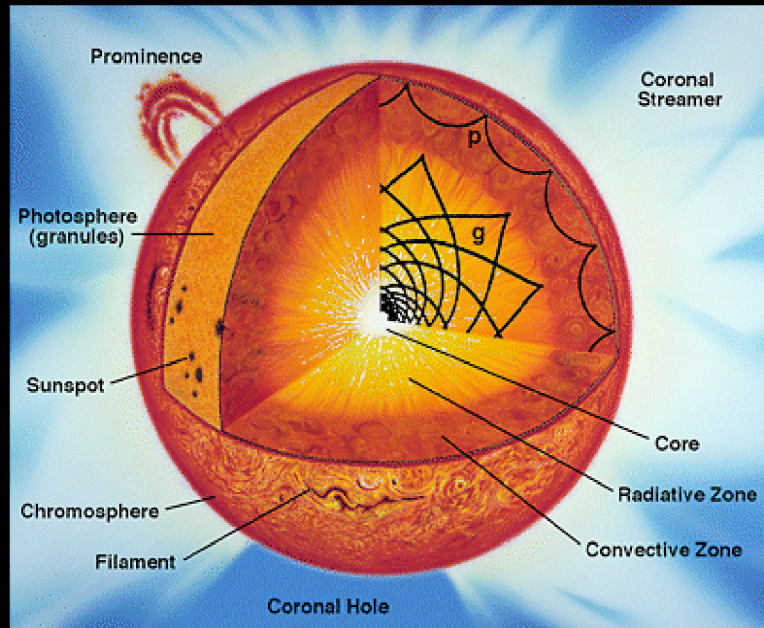
The Sun emits electromagnetic radiation as a black body with an effective temperature of about 5780 degrees Kelvin. A measurable, and useful indicator of this energy output is the total solar irradiance (TSI) – which is the total energy (integrated across all wavelengths) incident per unit time over one square meter just outside of the Earth's atmosphere. Observations show that this varies and the variation is modulated by the sunspot cycle. Stronger cycles imply higher energy output and weaker cycles imply lower energy output. In effect the Sun converts energy stored in its magnetic field to enhance its radiative output. This radiative energy output of the Sun is the primary natural source of energy for driving climate systems. Thus solar magnetic activity may also be relevant for planetary climates. However, note that climate models indicate that the solar contribution to global warming in modern times is small, with the dominant influence being anthropogenic.

Understanding Origin of Solar Magnetic Fields and Forecasting Space Weather Important

Solar Magnetic Fields
Solar Storms
Solar Wind Conditions
Solar Particle Fluxes
Solar Radiation Spectrum

Given that solar activity in the form of solar storms, solar wind, energetic particle and radiative fluxes control space weather, it is important to understand the physics of solar activity and push this understanding towards predictive models. Magnetism is at the heart of this activity and thus the first step in addressing space weather science is to understand the origin of solar magnetic fields and how they behave.

Physics of the Sun



Energy is generated in the Sun's core through nuclear fusion reactions and is transported by radiation in the inner 70% and by convection in the outer 30% of the Sun. The temperature inside the Sun is so high that matter is in the ionized or plasma state. Large and small-scale plasma motions sustained by convection in the outer convection zone of the Sun creates magnetic fields through a process known as the dynamo mechanism.

Origin of Solar Magnetic Fields

- Magnetic fields in astrophysical systems – which vary on timescales much shorter than the typical evolutionary timescale of the system – indicates the presence of magnetohydrodynamic dynamo action

- Dynamo in a nutshell:



- Source of Kinetic Energy:
 - Plasma motions within the solar convection zone
 - Large-scale motion (differential rotation, meridional circulation)
 - Small-scale turbulent convective motions

If magnetic fields are not created or sustained they can decay away based on the typical magnetic diffusion timescale of the system. When an astrophysical object shows magnetic variability at a time-scale shorter than its evolutionary timescales then there is more than a fair chance that that system hosts a magnetohydrodynamic (MHD) dynamo mechanism which feeds on plasma motions to generate magnetic fields. Most stars, galaxies and some planets like the Earth have MHD dynamos in their interior.

Magnetohydrodynamic Dynamo Theory

- Governing equation:
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$
- Magnetic Reynolds Number:
$$R_m = \frac{VBL}{\eta} \quad \text{---}$$
- In Astrophysical systems, R_m usually high, magnetic field creation possible and fields are frozen with the plasma
—Diffusion timescale $\tau_\eta >$ Flow timescale τ_v
- In solar interior, plasma $\beta \gg 1$ (gas pressure higher than magnetic pressure and therefore, plasma flows govern field dynamics)
—Regime of magnetohydrodynamic dynamo action in the Sun

The magnetic induction equation follows from Maxwell's equations and the generalized Ohm's law. The induction equation governs the behavior (evolution in time and space) of magnetic fields ($\mathbf{B}$) in a plasma with a given velocity field ($\mathbf{v}$) and magnetic diffusivity (η). The magnetic Reynolds number is the ratio of the source to the dissipative term in the induction equation. In astrophysical systems magnetic Reynolds number is high and thus magnetic fields can be sustained against dissipation. In the solar interior since the plasma pressure is higher than the magnetic pressure, plasma flows can twist, stretch and deform magnetic fields – processes that are important for inducing magnetic fields and dynamo action.

Complete Set of MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

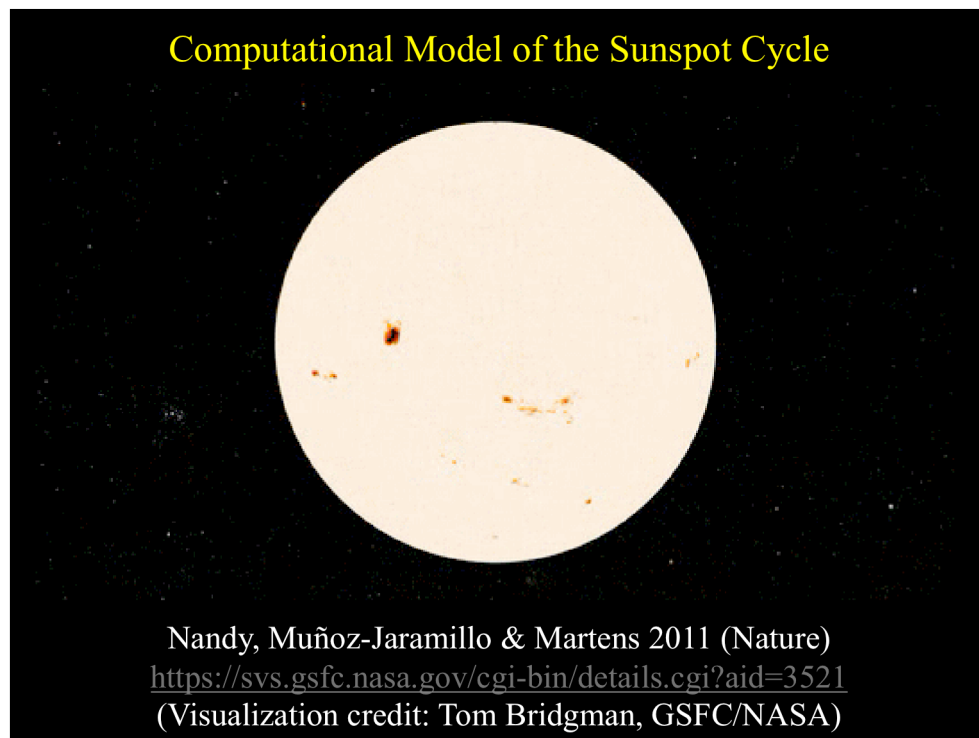
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{4\pi\rho} + \mathbf{g} + \nu \nabla^2 \mathbf{v}$$

$$\frac{\partial p}{\partial t} + (\mathbf{v} \cdot \nabla) p + \gamma p \nabla \cdot \mathbf{v} = Q$$

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

$$\nabla \cdot \mathbf{B} = 0$$

In addition to the induction equation, a self-consistent treatment of a MHD system requires the mass (continuity), momentum (Navier-Stokes) and energy conservation equations with the solenoidal (divergence-free) condition for the magnetic field. In practice, it is computationally very intensive to solve the full set of equations in a global domain, and often the results are not in agreement with observations (e.g., solar internal plasma flows cannot be reproduced exactly). Alternative physical models with certain assumptions and parameterizations (e.g., the kinematic regime wherein the magnetic feedback on flows is considered negligible) and driven by observations of solar plasma flows have proven very useful under these circumstances.



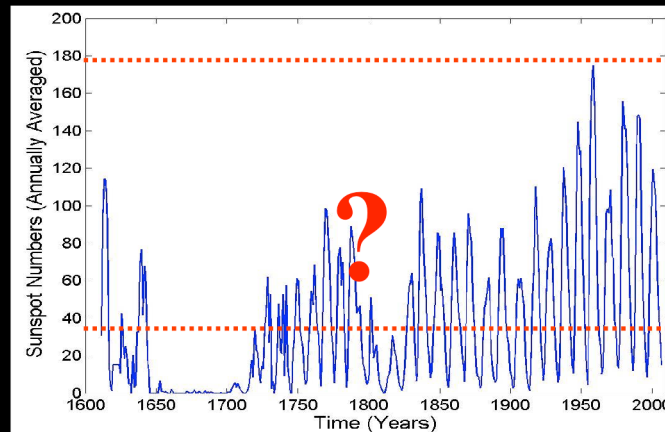
This visualization shows the evolution of the solar toroidal (right-hand meridional panel) and poloidal (left-hand meridional panel) of the Sun's internal magnetic fields based on data from a kinematic solar dynamo model (Nandy, D., Muñoz-Jaramillo, A. & Martens, P.C.H. 2011, *Nature*, Volume 471, Page 80). Periodic reversals in the Sun's internal magnetic field as well as the equatorward migration of the Sun's toroidal field (which generates sunspots) can be seen in this computer simulation. The Sun's poloidal field contributes to the large-scale open magnetic flux in the heliosphere which modulates cosmic ray flux at Earth.

Simulation movies and visualizations can be downloaded from:

<https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3521>

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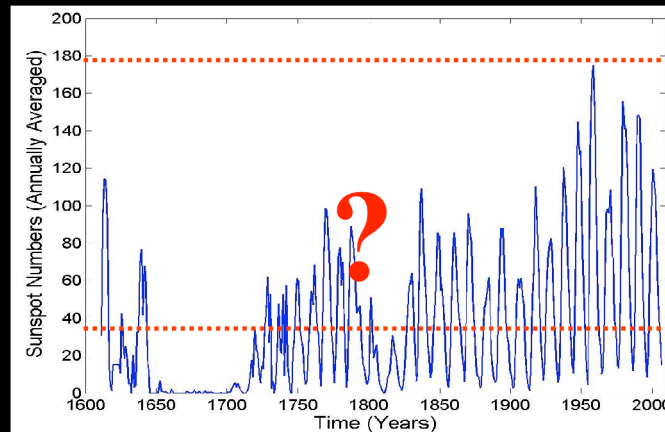
Predicting Sunspot Cycle Amplitude Challenging!



- Sunspot cycle mean period ~ 11 years, small variation in period
- However, large amplitude fluctuations
- Forecasting cycle amplitudes is the holy grail of solar physics

While general features of the sunspot cycle are understood to some extent, many outstanding challenges remain in understanding the complete physics. This state of affairs is clearly reflected in the non-convergence of predictions for the amplitude of solar cycle 24.

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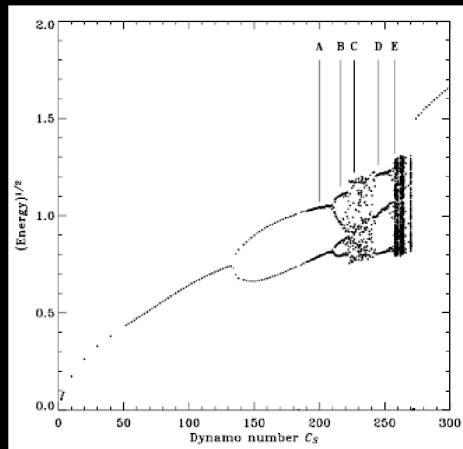
Bar chart showing the number of papers (F_{ref}) for various references. The y-axis ranges from 0 to 200. The bars are color-coded by year: red for 2004, blue for 2005, black for 2006, yellow for 2007, and orange for 2008. A large red question mark is placed above the bars. The references are listed on the right side of the chart, with their corresponding years in parentheses.

Reference	Year	F_{ref}
Melis et al. (2004)	2004	40
Chiriac et al. (2004)	2004	45
Shenoy et al. (2004)	2004	50
Sonoo (2006)	2006	70
Wargand et al. (2005)	2005	75
Stauden et al. (2007)	2007	80
Schatten (2006)	2006	85
Saravalli (2006)	2006	90
Janak (2006)	2006	95
Janak (2008)	2008	100
Alvarez (2007)	2007	105
Alvarez and Smith (2006)	2006	110
Thompson (2008)	2008	115
Al et al. (2008)	2008	120
Probst (2008)	2008	125
Taylor (2008)	2008	130
Taylor (2005)	2005	135
Basin (2007)	2007	140
Spence (2005)	2005	145
Schulz (2004)	2004	150
as for (2006)	2006	155
Kim et al. (2004)	2004	160
Basin et al. (2006)	2006	165
Nevill-Jones (2007)	2007	170
Taylor (2006)	2006	175
Prakas et al. (2006)	2006	180
modified Verma (2006)	2006	185
Chen et al. (2006)	2006	190
Sant (2007)	2007	195
Salway et al. (2004)	2004	200
Salway et al. (2005)	2005	205
Melis and Orsica (2006)	2006	210
as for (2006)	2006	215
Helway and Wilson (2008)	2008	220
Helway et al. (2006)	2006	225
Podolchikova et al. (2008)	2008	230
Thompson (2008)	2008	235
Thompson (1997)	1997	240
Horvath (2006)	2006	245

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

While general features of the sunspot cycle are understood to some extent, many outstanding challenges remain in understanding the complete physics. This state of affairs is clearly reflected in the non-convergence of predictions for the amplitude of solar cycle 24.

Dynamical Behavior of the Solar Dynamo

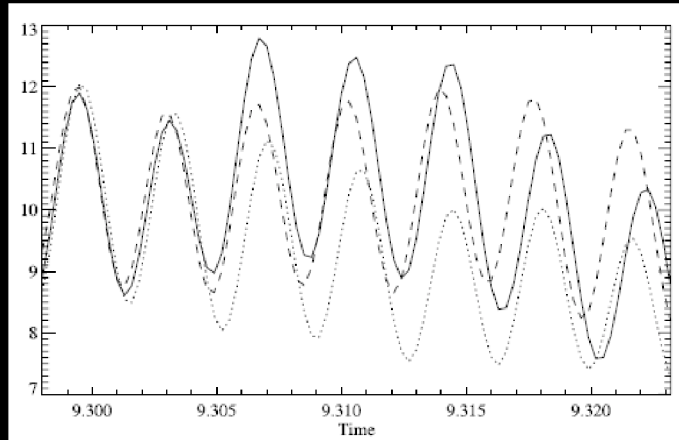


(Charbonneau, St-Jean & Zacharias 2005, ApJ)

- A non-linear, forced system exhibits a wide range of dynamic behavior
—Including irregular and chaotic output

The solar dynamo is a non-linear system which is driven by turbulent convective plasma motions. When the dynamo number (which measures the relative efficacy of source terms to dissipative terms) is very high, the system may exhibit irregular or chaotic behavior.

Chaotic Systems and Predictability



(Bushby & Tobias 2007, ApJ)

- Chaotic regime: small differences in initial conditions diverge
 - Long-term prediction not possible
 - Is short-term prediction possible?

Long-term prediction is thought to be impossible for a chaotic system, wherein, small differences in initial conditions diverge rapidly. Since no observation is perfect or in other words an exact measurement of all the possible parameters of a system is not possible (more so for a far away astrophysical object), long-range forecasts will not be precise.

Towards Prediction: The Underlying Physics

- Toroidal field evolution:

Flux transport terms deterministic

Introduces time delay = memory

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

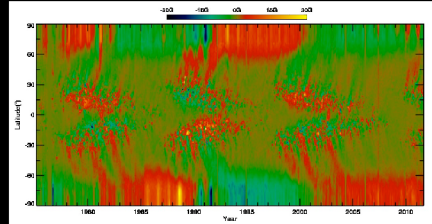
$$= \eta \left(\nabla^2 - \frac{1}{r^2 \sin^2 \theta} \right) B_\phi + r \sin \theta (B_P \cdot \nabla) \Omega - \nabla \eta \times (\nabla \times B_\phi)$$

Toroidal Source
Deterministic

- Poloidal field evolution:

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

But poloidal source observed!



The coupled dynamo system of equations for the Sun's toroidal and poloidal magnetic fields has an in-built dynamical “memory” due to the finite time taken by flux transport processes to move around fields from one source region to another. This dynamical memory can be utilized for predictions based on certain observables.

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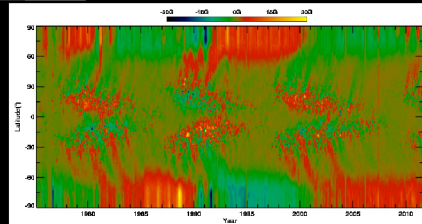
Flux transport terms deterministic

Introduces time delay = memory

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

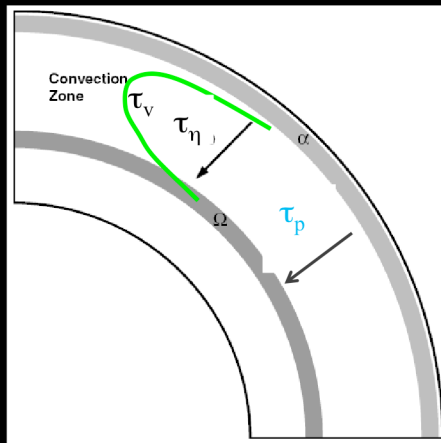
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Competing Flux Transport Mechanisms and Memory



- Meridional Flow (15—20 m/s)
 $\tau_v = 20$ yrs (slow process)
- Turbulent Diffusion ($1 \times 10^{12} \text{ cm}^2/\text{s}$)
 $\tau_\eta = 14$ yrs (intermediate)
- Turbulent Pumping ($v = 2 \text{ m/s}$)
 $\tau_{\text{pumping}} = 3.4$ yrs (fast process)

Dynamo models used for prediction
ignored turbulent pumping

Explored in other contexts recently
Guerrero & Dal Pino 2008, A&A
Do Cao & Brun, 2011, AN

Dijpati & Charbonneau 1999, ApJ
Nandy & Choudhuri, 2002, Science
Chatterjee et al. 2004, A&A
Yeates, Nandy & Mackay 2008, ApJ
Hotta & Yokoyama 2010, ApJ
Karak & Nandy 2012, ApJL

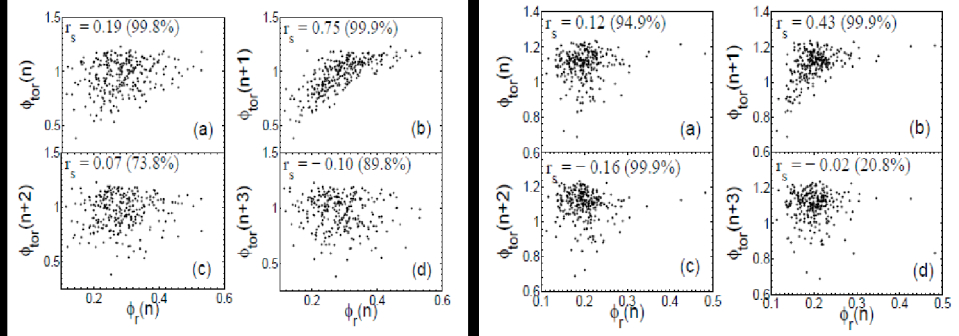
$T_v = 10\text{—}20$ years (Mid—low latitudes, L = length of circulation streamline, $v_{\text{max}} = 26 \text{ m/s}$)

$T_\eta = 14$ years ($L = 0.3R$, $\eta = 1 \times 10^{12} \text{ cm}^2/\text{s}$)

$T_{\text{pumping}} = 3.4$ years ($L = 0.3R$, $v_{\text{pumping}} = 2 \text{ m/s}$)

Magnetic Flux Transport, Memory and Predictability

(Yeates, Nandy & Mackay 2008, ApJ, Karak & Nandy 2012, ApJL)



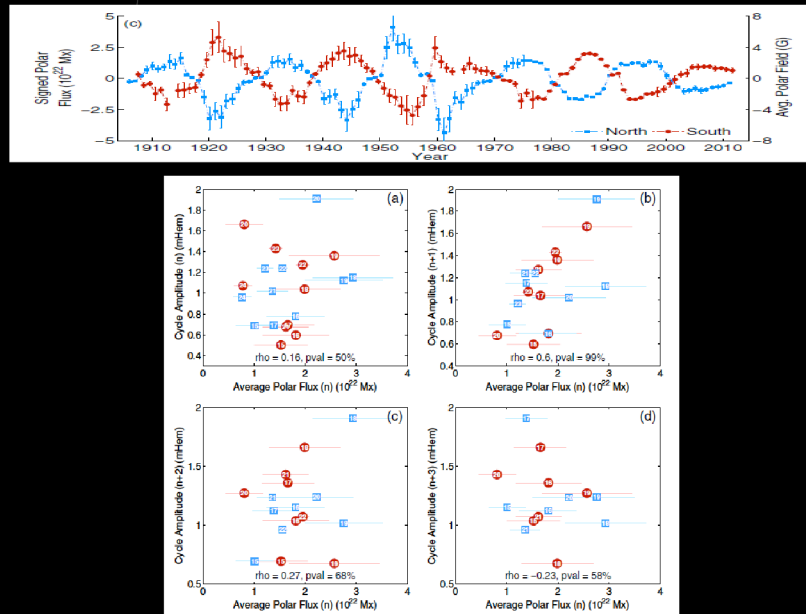
(Advection dominated – low η)

(Diffusion dominated – high η)

- Memory reduces to only one cycle when turbulent pumping is used
- Both advection and diffusion dominated dynamos behave similarly
- Our simulations indicate long-term prediction not possible

Advection by meridional circulation, dispersal by turbulent diffusion and transport by turbulent pumping are important flux transport processes in the Sun's interior. Their interplay governs the dynamical memory of the solar dynamo. Solar dynamo simulations were performed with stochastic forcing (i.e., random fluctuations included) in which correlations between the polar field strength and future cycle amplitudes under diverse flux transport regimes were recorded. Our simulations show that turbulent pumping is more efficient than either diffusion or meridional circulation and transports magnetic fields from the top of the Sun's convection zone to the bottom within a few years -- thus resulting in a short solar cycle memory.

Observational Verification of Short Solar Cycle Memory (Munoz et al. 2013, ApJL)



Correlations between future sunspot cycle amplitudes and polar faculae measurements (a proxy for the solar poloidal field) supports the theoretical simulations results and indicates that solar cycle memory is indeed short.

Summary

- Solar magnetic fields are generated by the interplay of plasma flows and magnetic fields in the Sun's interior
- While we are beginning to understand some of the intricacies of the processes which sustain the solar cycle, we are still far away from a complete understanding
- Predictions a challenging task, but we are making progress
- We know that magnetic flux transport processes govern the memory and predictability of the sunspot cycle
- Memory of the cycle is short and hence prediction window is just about a cycle; data assimilation necessary for accurate forecasting

References and Resources

Dynamo Models of the Solar Cycle (Paul Charbonneau)
<http://solarphysics.livingreviews.org/Articles/lrsp-2010-3/>

Solar Dynamo Visualizations (NASA Scientific Visualization Studio)
<https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3521>

Magnetohydrodynamics
<https://en.wikipedia.org/wiki/Magnetohydrodynamics>

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<http://www.iiserkol.ac.in/~dnandi/>