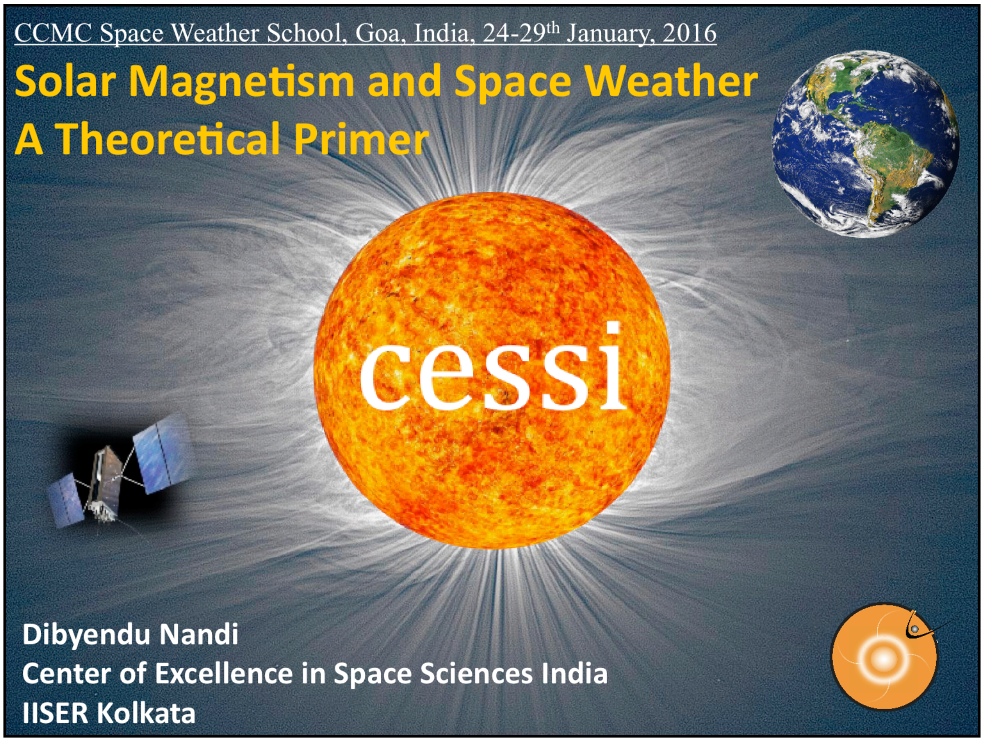
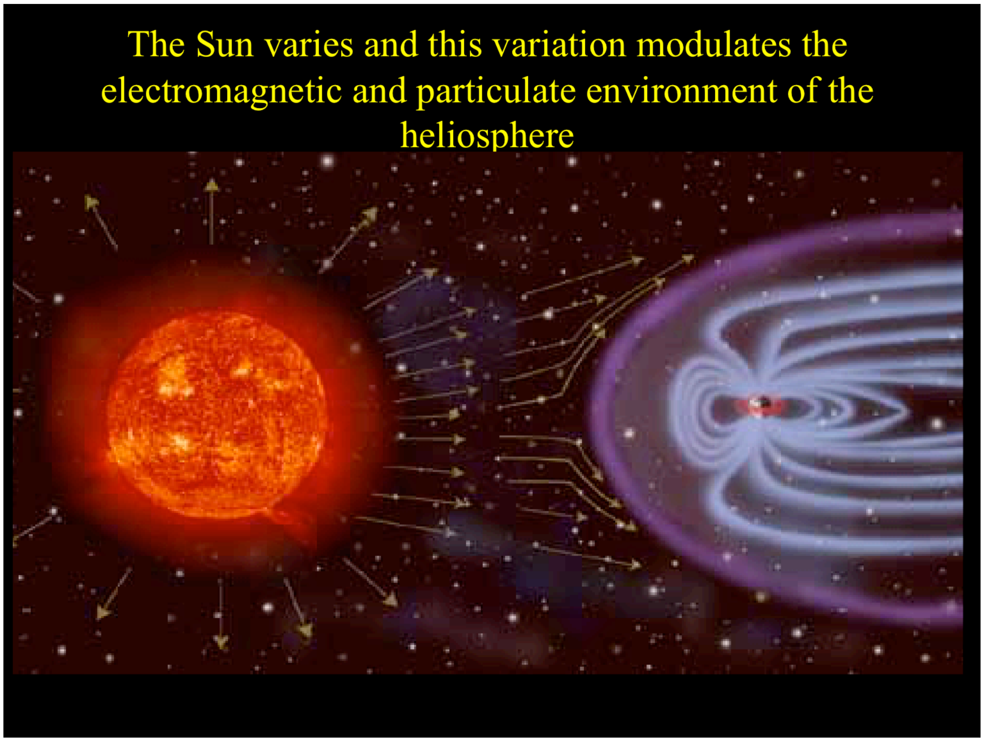


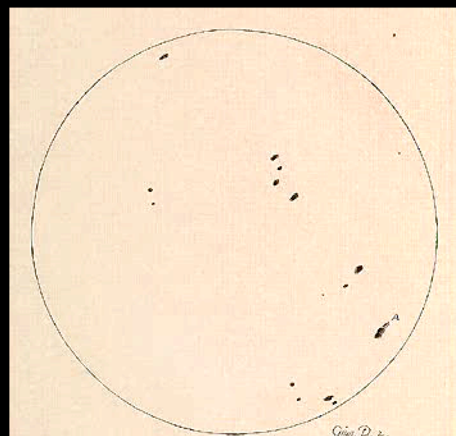
My name is Dibyendu. I lead the Center of Excellence in Space Sciences India (CESSI) at IISER Kolkata where one of our primary focus is to use theoretical, computational and observational tools to understand the origin of solar magnetism and based on this understanding, develop physics based predictive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

http://www.cessi.in.



The Sun 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.

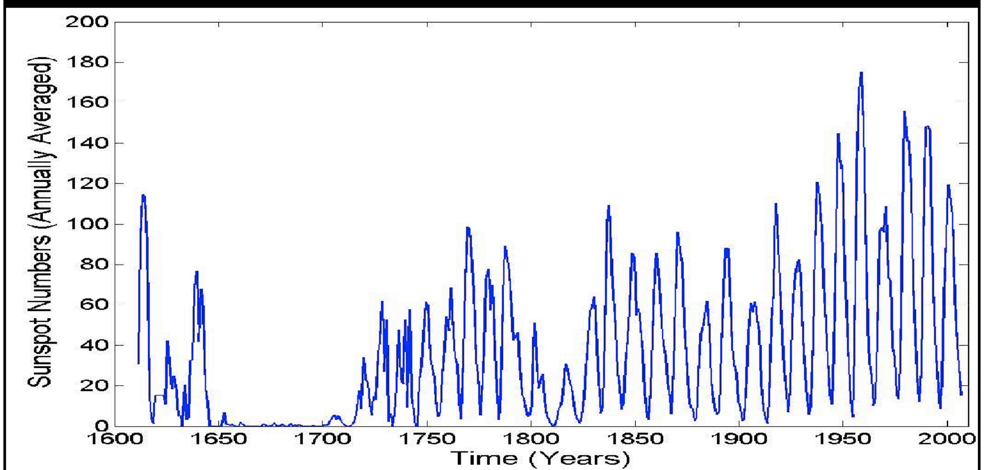
Sunspots and the Solar Cycle



- First systematically observed by Galileo, Fabricius, Scheiner
- Radius ~ 10,000 Km
- Strongly magnetized ~ 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.

Sunspots and the Solar Cycle



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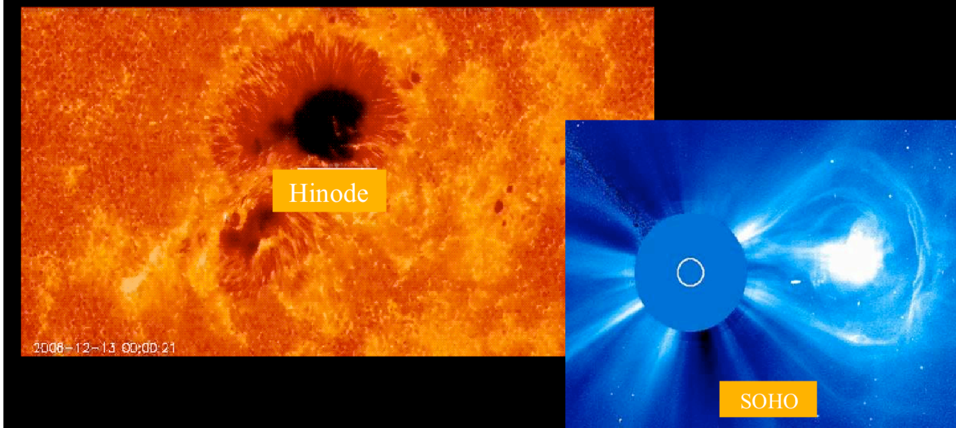
Sunspots are the Seats of Solar Storms



- Solar flares and coronal mass ejections (CMEs) – biggest explosions in the solar system – eject magnetized plasma and charged particles ($m \sim 10^{12}$ Kg, $v \sim 500$-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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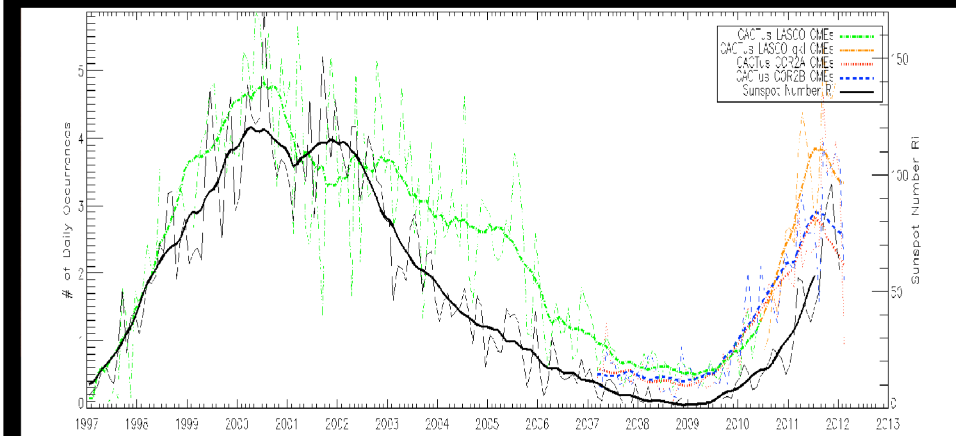

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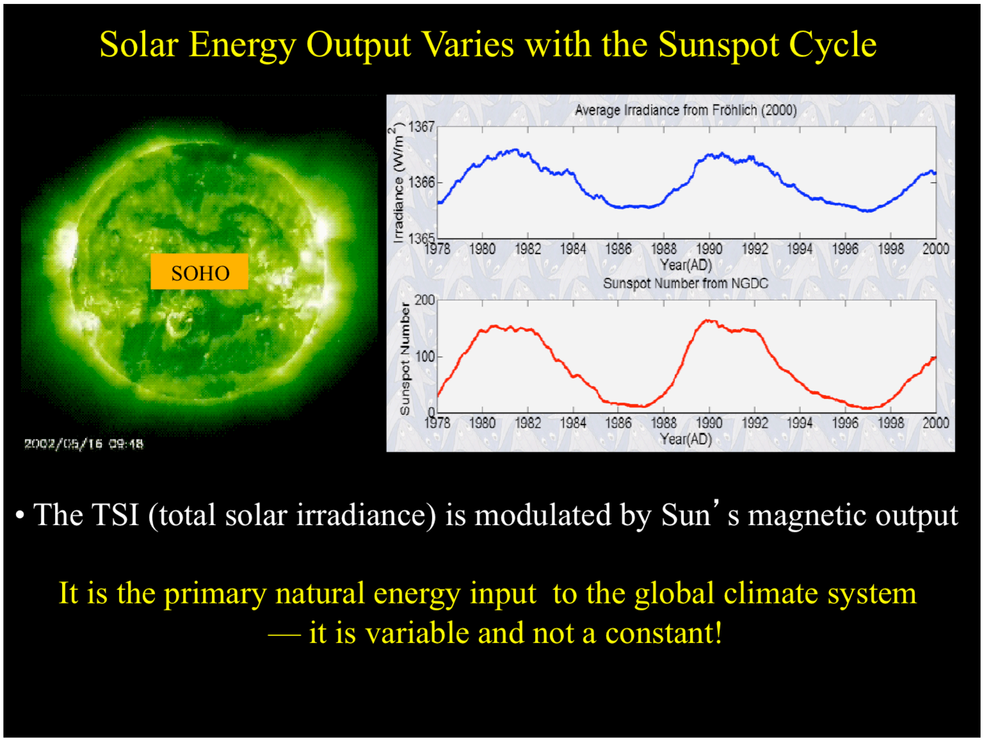
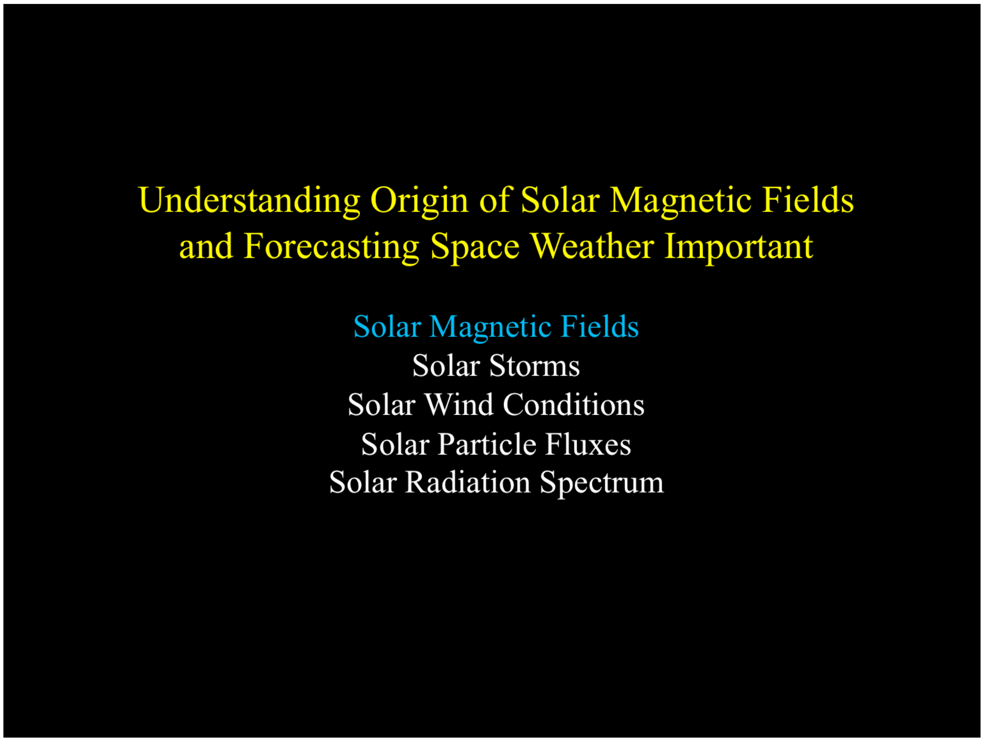
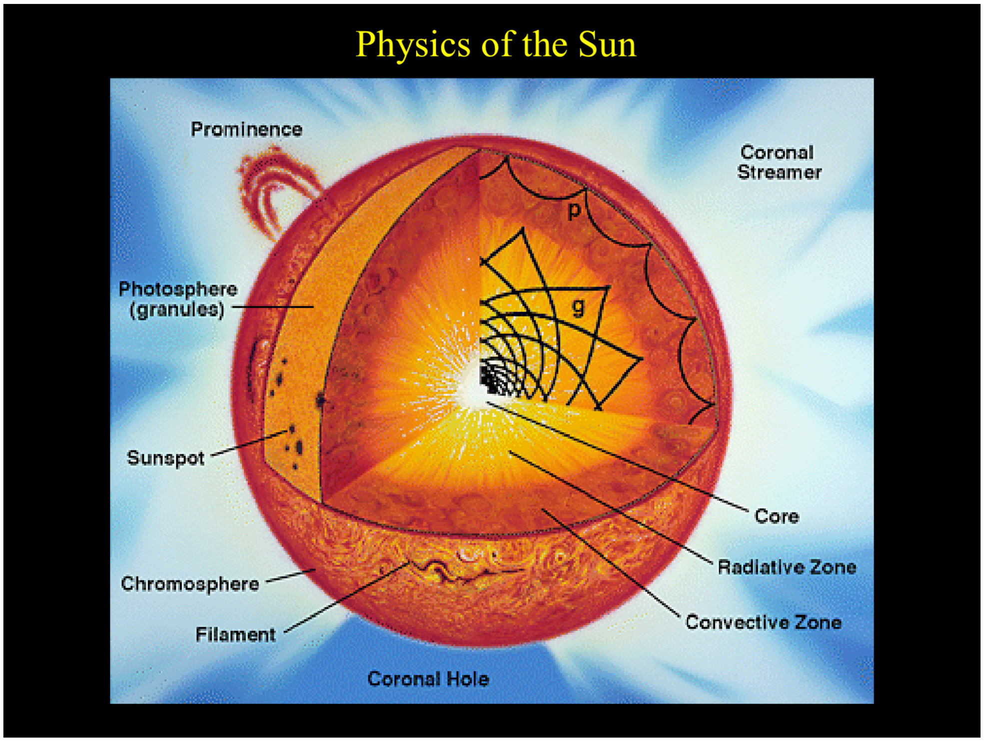


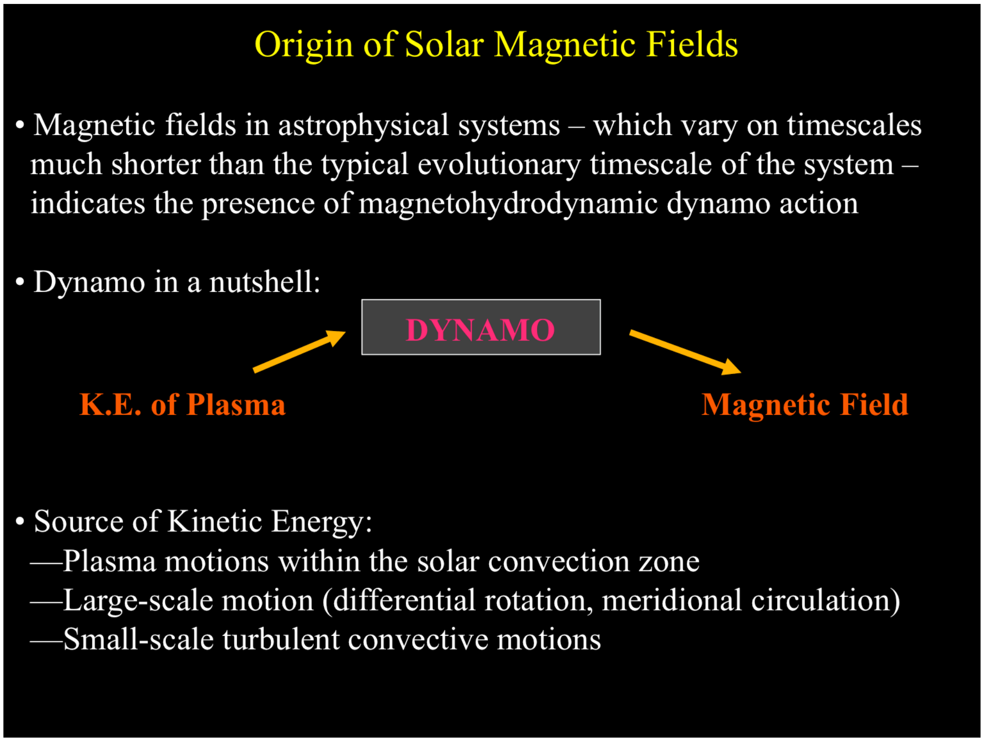
The Sun emits electromagnetic radiation as a black body with an effective temperature of about 5780 degrees Kelvin. A measurable, and useful indicator of this energy output is the total solar irradiance (TSI) – which is the total energy (integrated across all wavelengths) incident per unit time over 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.



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.



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.



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

- Magnetic Reynolds Number: $$R_m == \frac{VB\mathbb{L}VL}{\Gamma B\mathbb{L}^{\;2}} \quad —$$

- 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 $\beta >> 1$ (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 (B) in a plasma with a given velocity field (v) and magnetic diffusivity (eta). 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 inducting magnetic fields and dynamo action.

Complete Set of MHD Equations

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

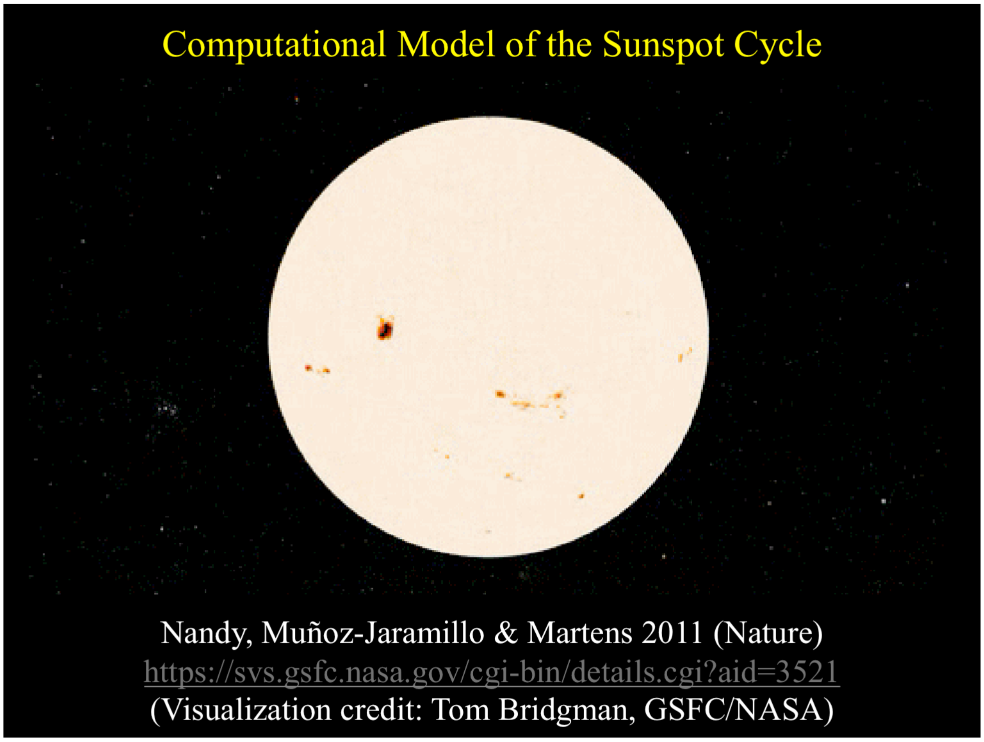
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{4\pi\rho} + \mathbf{g} + \nu \nabla^2 \mathbf{v}$$

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

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

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

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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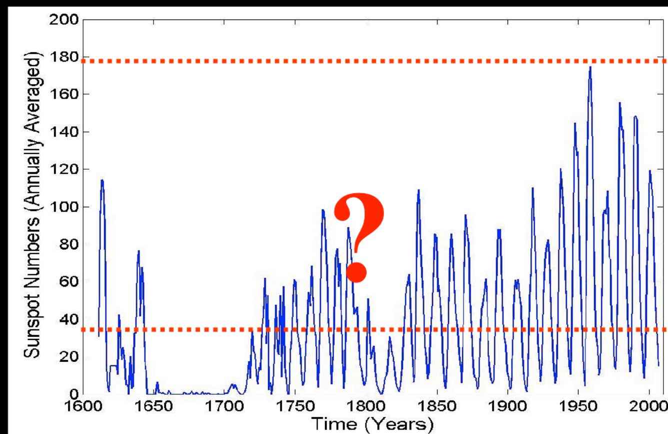
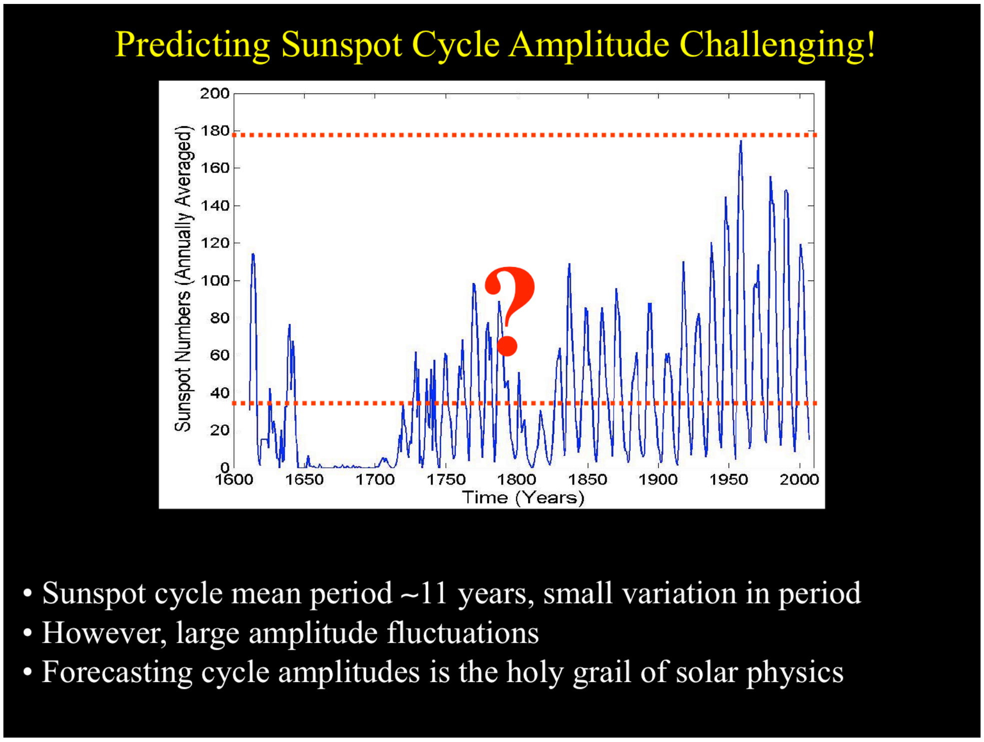
Predicting Sunspot Cycle Amplitude Challenging!



- 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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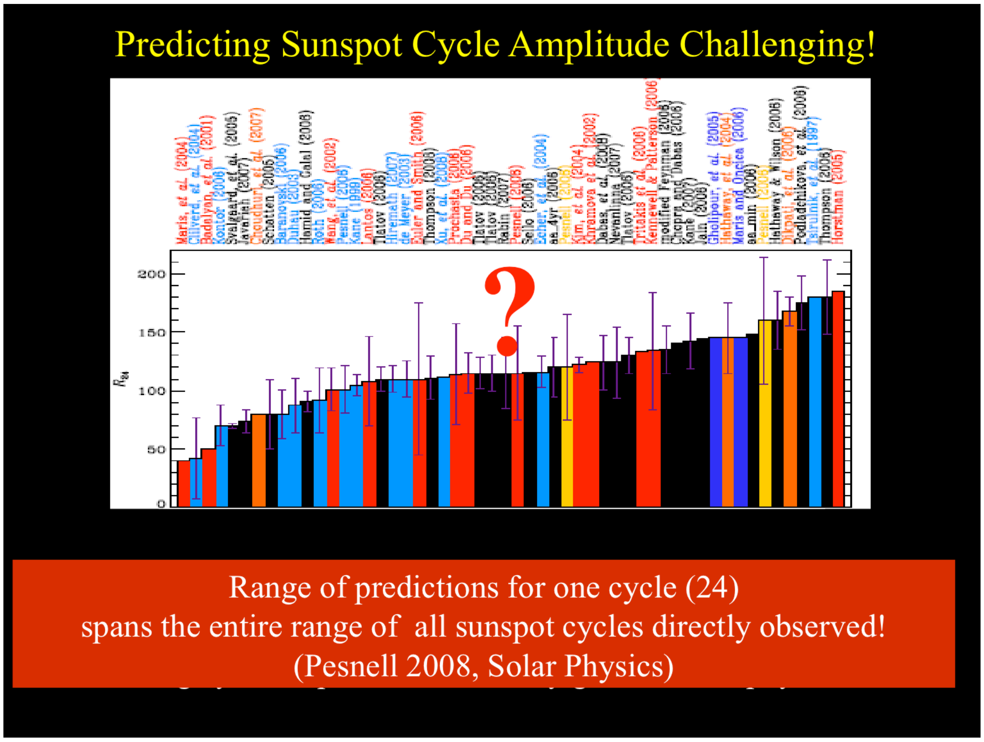

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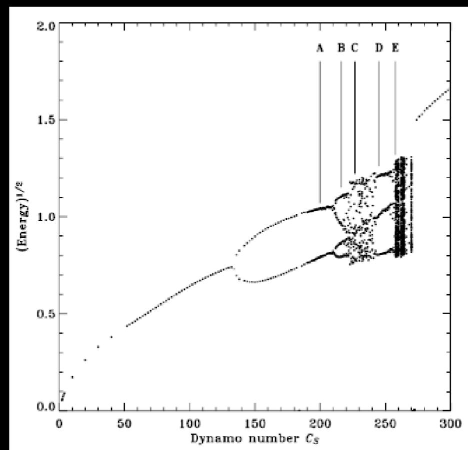
Dynamical Behavior of the Solar Dynamo

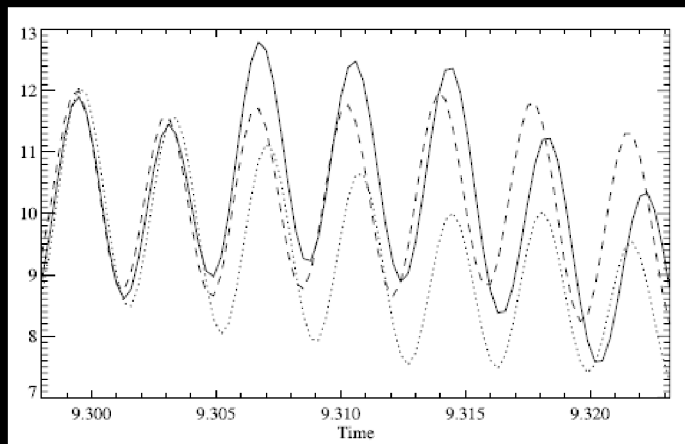


(Charbonneau, St-Jean & Zacharias 2005, ApJ)

- 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.

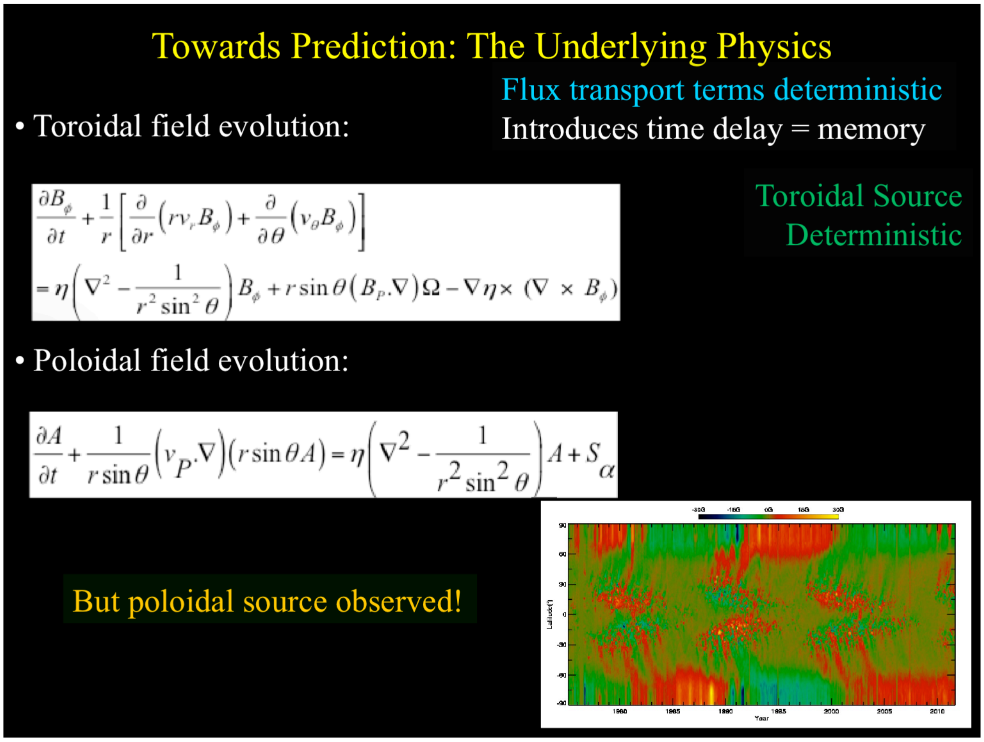
Chaotic Systems and Predictability



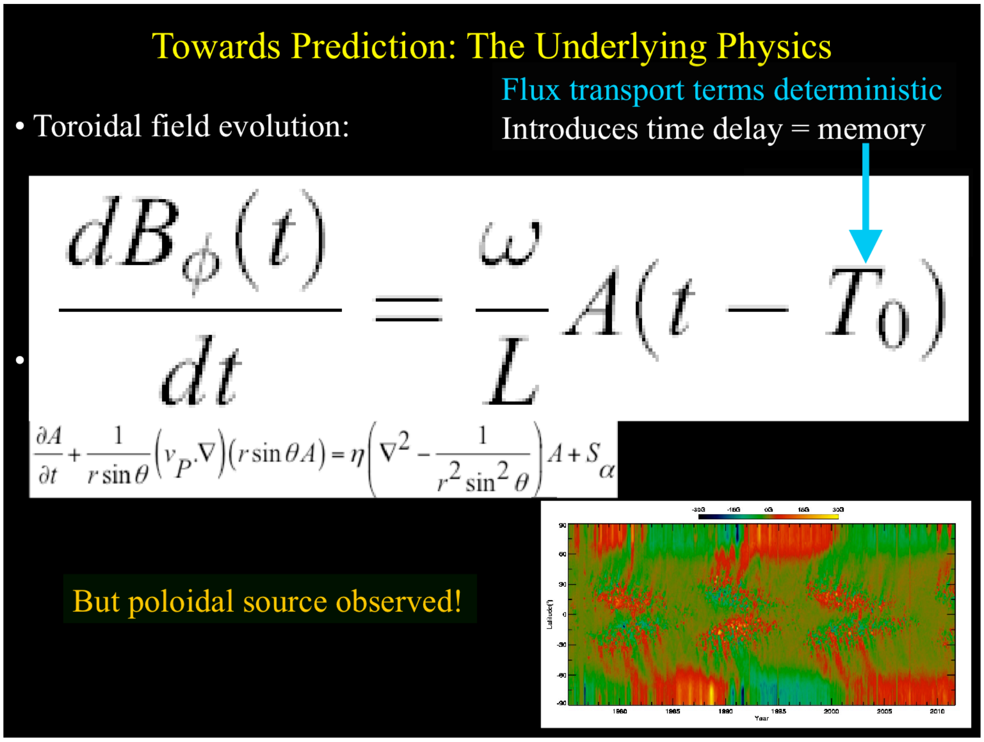
(Bushby & Tobias 2007, ApJ)

• 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.



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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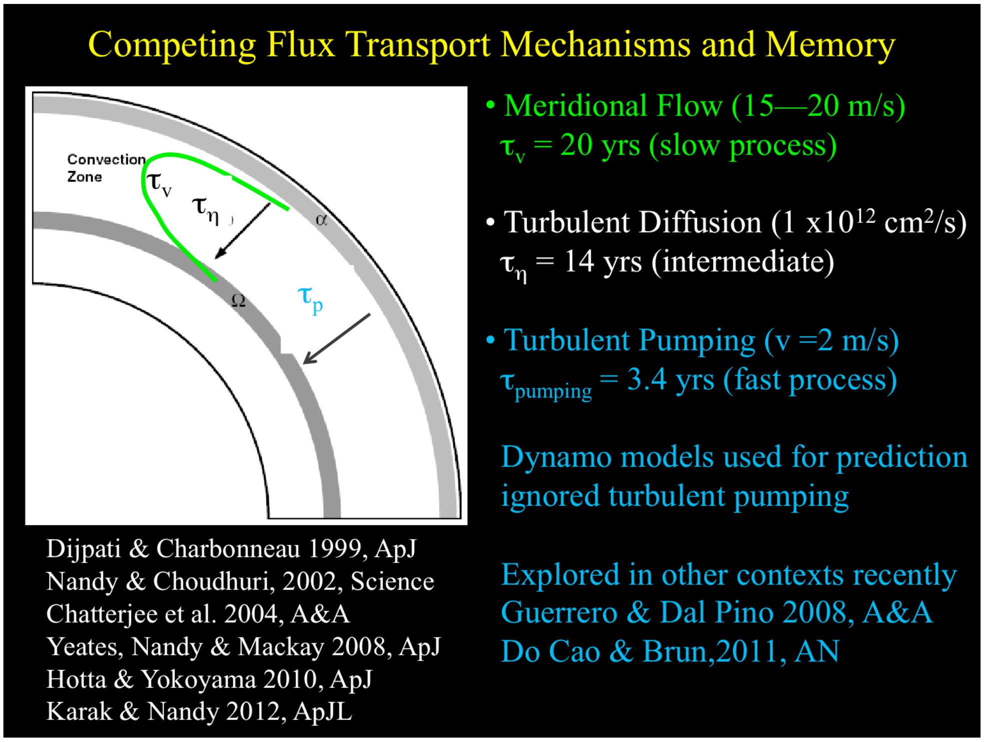
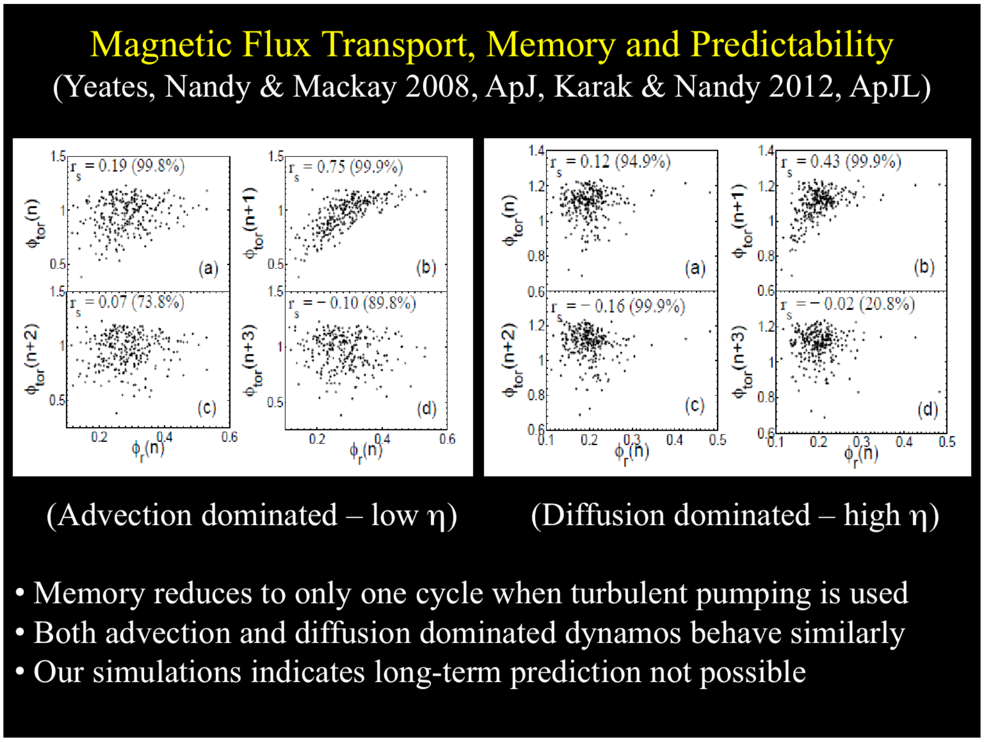


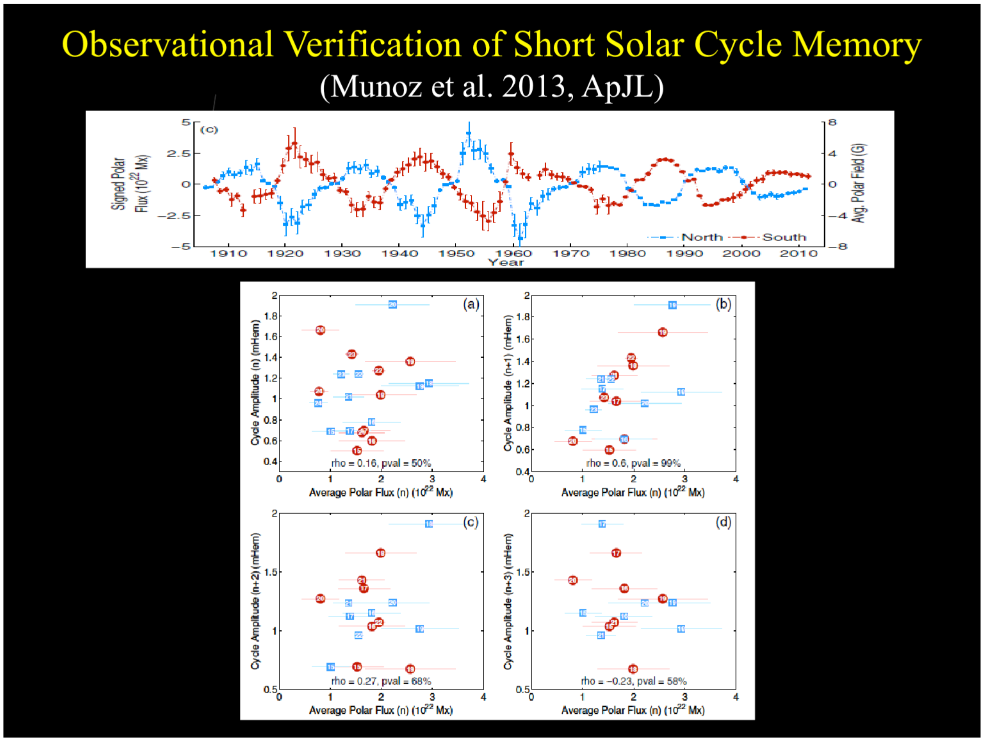
T_v = 10—20 years (Mid—low latitudes, L = length of circulation streamline, v_max = 26 m/s)

T_eta = 14 years (L = 0.3R, eta = 1 x 10^12 cm^2/s)

T_pumping = 3.4 years (L = 0.3R, v_pumping = 2 m/s)



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.



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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