Improvements and Applications of Kinematic Models of the Solar Magnetic Cycle

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What are we modeling?

A historical perspective
Sunspots were first studied with the advent of the telescope (1610)

Hand drawing by Galileo

SOHO/MDI
The number of Sunspots observed on the Sun varies with time

(Schwabe 1843)

- Time variation is predominantly cyclic, mean period is 11 years.
Sunspots are associated with regions of strong magnetic field (Hale 1908)

Image from Hinode
Sunspots are associated with regions of strong magnetic field

(Hale 1908)

- A sunspot pair is commonly known as an **Active region**.
- Active regions have systematic tilt, which increases with latitude.
- The polarity orientation is opposite in the two hemispheres.
The most visible features of the cycle are associated with active regions.
The Magnetic Butterfly Diagram

- Equatorward migration of Active Regions.
- Poleward migrations of weak, diffuse field
- Polar field reversal at the maximum of the cycle.

Image by David Hathaway
Why are we Modeling it?

• The solar cycle modulates solar activity and space weather.

• Long term changes in the solar cycle can affect global climate.

• Understanding the solar magnetic cycle paves the way for understanding origin and evolution of magnetic fields in other stars.
Our understanding of the cycle

A brief introduction
The relative importance between these terms defines the physical properties of the system.

In Astrophysical systems, flows are usually more important than diffusivity – flux is frozen (Alfven 1942).
Plasma Flows in the Sun

Differential Rotation

Meridional Flow

Turbulent Convection
(Magnetic diffusivity)
The Solar Cycle in a Nutshell

Poloidal \( r - \theta \) \quad \Rightarrow \quad \text{Toroidal} \quad \phi

\[
\begin{align*}
\text{Diagram 1} & : & \text{Poloidal} & \text{Diagram 2} & : & \text{Toroidal}
\end{align*}
\]
The Solar Cycle in a Nutshell

Poloidal $r - \theta$ \quad \xrightarrow{\text{Differential Rotation}} \quad \text{Toroidal} \phi
The Solar Cycle in a Nutshell

Poloidal $r - \theta$ \hspace{2cm} Toroidal $\phi$

Differential Rotation

Active Region Emergence and Decay
Emergence of Active Regions due to Bouyancy

The balance between internal and external pressure leads to lower density inside the flux-tube.
Emergence of Active Regions due to Bouyancy

As the flux-tube rise, they are tilted by the coriolis force.
Active Region Decay

The decay of tilted bipolar active regions leads to flux accumulation at the poles. (Babcock 1961 & Leighton 1969)
The Solar Cycle in a Nutshell

Poloidal $r - \theta$ \quad \overset{\text{Differential Rotation}}{\rightarrow} \quad \text{Toroidal } \phi

\text{Active Region Emergence and Decay}

Meridional Flow \quad \overset{\text{Turbulent Diffusivity}}{\rightarrow}
How do we model it?
The 2.5D Kinematic Dynamo Model

- Based on the Mean-Field induction equation:
  \[
  \frac{\partial \vec{B}}{\partial t} = \nabla \times \left( \vec{v} \times \vec{B} + \alpha \vec{B} - \eta \nabla \times \vec{B} \right)
  \]

- Expressing the fields in axisymmetric form:
  \[
  \vec{B} = B\hat{e}_\phi + \nabla \times \left( \hat{A} \hat{e}_\phi \right)
  \]
  \[
  \vec{v} = r \sin(\theta) \Omega \hat{e}_\phi + \vec{v}_p
  \]

- Turbulent Diffusivity
- Poloidal Source
- Poloidal Field
- Toroidal Field
- Meridional Flow
- Differential Rotation
The 2.5D Kinematic Dynamo Model

- Based on the Mean-Field induction equation:

\[
\frac{\partial \overline{B}}{\partial t} = \nabla \times \left( \overline{\nabla} \overline{B} + \alpha \overline{B} - \eta \nabla \times \overline{B} \right)
\]

- Expressing the fields in axisymmetric form:

\[
\overline{B} = B \hat{e}_\phi + \nabla \times \left( A \hat{e}_\phi \right)
\]

\[
\overline{v} = r \sin(\theta) \Omega \hat{e}_\phi + v_p
\]
Dynamo Parameters

- Differential Rotation:
  - 6 well constrained

- Meridional Flow:
  - 2 well constrained
  - 1 reasonably constrained
  - 4 poorly constrained

- Magnetic Diffusivity:
  - 2 reasonably constrained
  - 5 poorly constrained

- Poloidal Source:
  - Incorrect Surface Dynamics

- 6 Parameters
- 7 Parameters
- 7 Parameters
Solar Cycle Predictions

- Yeates, Nandy & Mackay (2007) found that the relative values of the diffusive and advective timescales affects the dynamo memory resulting in different predictions.

- The dynamo ingredients with the greatest amount of poorly constrained parameters!
Constraining Velocity Fields

• Data taken by the Global Oscillation Network Group (GONG):
  • Differential rotation courtesy of Dr. Rachel Howe.
  • Meridional Circulation courtesy of Dr. Irene González-Hernández.

• Solar Model S courtesy of Dr. Jørgen Christensen-Dalsgaard.
Using the Helioseismic Differential Rotation

Analytical Profile of Charbonneau et al. 1999

Splines Interpolation of RLS Inversion

Composite Differential Rotation
Constraining the Meridional Flow using Helioseismic Data

This is what we want…
Constraining the Meridional Flow using Helioseismic Data

This is what we have.
Constraining the Meridional Flow

Latitudinal Dependence

Radial Dependence

Latitude

Radius

Normalized data and Fit

$V_\phi (\text{m/s})$

Set 1: $R_p = 0.6R_s$

Set 2: $R_p = 0.64R_s$

Set 3: $R_p = 0.7R_s$

Set 4: $R_p = 0.71R_s$
Conclusions

• We can now use the helioseismically determined differential rotation directly.

Before
• Meridional Flow:
  • 2 well constrained
  • 1 reasonably constrained
  • 4 poorly constrained

After
• Meridional Flow:
  • 3 well constrained
  • 4 poorly constrained

• Current helioseismic data cannot constrain the radial dependence of Meridional Flow, but we have laid out the methodology to assimilate meridional flow data as it becomes available.
Turbulent Diffusivity Quenching


- The most poorly constrained dynamo ingredient.
- For our analysis use the Solar Model S courtesy of Dr. Jørgen Christensen-Dalsgaard.
What we use vs. What theory suggests

\[ \eta \left( \text{cm}^2/\text{s} \right) \]

- **MLT and ModelS of Christensen-Dalsgaard 1996**
- **Dikpati & Gilman 2007**
- **Nandy & Choudhuri 2002**
- **Guerrero & de Gouveia Dal Pino 2007**
- **Rempel 2006**
- **Jouve & Brun 2007**
- **Munoz-Jaramillo, Nandy & Martens 2009**
There is a big problem…

- By increasing diffusivity to such high values the dynamo stops working.

Possible Solution

- Take account off the back-reaction that strong magnetic fields have on the turbulent velocity field.
There is a big problem…

- By increasing diffusivity to such high values the dynamo stops working.

Possible Solution

- We use the MLT estimated diffusivity profile and dynamically quench the diffusivity wherever there are strong magnetic fields.
Outcome of the Simulation

- The introduction of magnetic quenching allows for viable magnetic cycles 😊
How does diffusivity quenching relates to typical kinematic diffusivity profiles?
Typical diffusivity profiles capture the average effect of diffusivity quenching!
Typical diffusivity profiles capture the average effect of diffusivity quenching!

- We run a kinematic simulation using the geometric average and leaving all other parameters the same.

- When we compare to the dynamically quenched simulation we find that the most important properties of the cycle are roughly the same 😊

Dynamically Quenched

Kinematic Average
Conclusions

Before
- Magnetic Diffusivity:
  - 2 reasonably constrained
  - 6 poorly constrained

After
- Magnetic Diffusivity:
  - 8 reasonably constrained

• Through this work we started bridging the gap between kinematic diffusivity profiles and MLT estimates.

• Our results show that properly parameterized diffusivity profiles can capture (as a first approximation), the effects turbulent diffusivity quenching.
The double-ring: A better method of modeling the Babcock-Leighton mechanism


- An ingredient that has not received as much attention as it warrants.

- Our approach is based on an idea first proposed by Durney (1997).
Modeling the Solar Cycle

- Kinematic Dynamo Models
- Surface Flux Transport Simulations

Both based on the induction equation

Differences:
- 2.5D in the $r - \theta$ plane
- Self-excited.
- 2D in the $\theta - \phi$ plane.
- Forced.
Poloidal Field Regeneration

- In order to have accumulation of flux at the poles there has to be cross-equatorial cancellation.

- This process is driven by diffusion and hindered by meridional flow.

- The **slower** the meridional flow the **stronger** the polar field.
Modeling the Solar Cycle

- **Kinematic Dynamo Models**
  - The Discrepancy:
    - A *slow* meridional flow produces a *weak* polar field.

- **Surface Flux Transport Simulations**
  - A *slow* meridional flow produces a *strong* polar field.
Modeling Active Region Emergence and Decay

- **Kinematid Dynamo Models**
  - Traditionally modeled using a mean-field continuous source.

- **Surface Flux Transport Simulations**
  - Deposited as magnetic dipoles throughout the simulation.
Double Ring Algorithm

$\theta_{ar}$ = Co-latitude of emergence
$\Lambda$ = Latitudinal extent of the Active Region
$X$ = Latitudinal distance between the center of each polarity

Durney 1997, Muñoz-Jaramillo et al. 2010
Double Ring Algorithm

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Surface Magnetic Field Using the Double-Ring Algorithm

Continuous Source

Double Ring

Image by David Hathaway
Changing the Meridional Flow

- We make simulations changing the meridional flow from cycle to cycle and look at the polar field at the end of each cycle.
With the continuous source, kinematic dynamos fail to reproduce surface dynamics.

A slow flow leads to a weak polar field.
The Double-ring produces the correct surface dynamics

A slow flow leads to a strong polar field

With the double ring algorithm for active region eruption and poloidal field generation we successfully obtain surface dynamics in agreement with surface flux-transport simulations.
Understanding the Extended Solar Minimum of Cycle 23


• An opportunity that presented itself to test whether our dynamo model can explain observed magnetic field dynamics.
'Quiet Sun' baffling astronomers

By Pallab Ghosh
Science correspondent, BBC News
What makes minimum 23-24 unusual?

- Unusually large number of sunspot-less days (No cycle overlap)
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- Weak polar field strength
What makes minimum 23-24 unusual?

- Unusually large number of sunspot-less days (No cycle overlap)
  - Low values of solar irradiance

- Weak polar field strength
  - Solar wind speed, density and temperature at record low
  - Highest values of cosmic ray flux directly recorded
What makes minimum 23-24 unusual?

- Unusually large number of sunspot-less days (No cycle overlap)
  - Our model includes a realistic algorithm for sunspot eruption.
- Weak polar field strength
  - Our model captures successfully the dynamics of polar field generation
Which Cycle Ingredient is likely to be responsible for the characteristics of the minimum?

- Differential Rotation
- Meridional Flow
- Turbulent Diffusivity
- Poloidal Source
Solar Cycle Simulations

Run a simulation changing the meridional flow randomly at solar max between 15 m/s and 30 m/s

Sunspot maximum actually coincides with the start of the toroidal field cycle at the bottom of the convection zone.
Solar Cycle Simulations

- Self-consistent variation in length of minimum and polar field strength.
- 210 solar cycles simulated to establish a robust relationship between flow speed variations and nature of minimum.
What determines the nature of solar Minima?

1. Dependence on flow speed during declining phase of cycle

No significant correlation: Flow speed at minimum does not define the minimum!
What determines the nature of solar Minima?

2. Dependence on flow speed during rising-phase of cycle

Significant correlation:
Faster flow speed at an earlier (rising) phase of the cycle results in a deep minimum
What determines the nature of solar Minima?

3. Dependence on change in flow speed

**Polar Field**

**Cycle Overlap**

Significant correlation: Change from a fast to a slower meridional flow generates a deeper minimum.
The Minimum of Solar Cycle 23

Defining characteristics of cycle 23 minimum:

- Weak polar field
- Large number of sunspot-less days

Cycles without overlap consistently have weaker polar fields as observed during this minimum.
Summary

A recipe for a deep solar minimum
- Dispersal of the high latitude active region flux during the rising phase of the cycle, is the primary determinant of the resulting polar field strength.

- A fast flow carries both (positive and negative) polarities of active regions to the poles – no net flux – less polar field.

Wang, Robbrecht, & Sheeley (2009)
• Dispersal of the high latitude active region flux during the rising phase of the cycle, is the primary determinant of the resulting polar field strength.

• A fast flow carries both (positive and negative) polarities of active regions to the poles – no net flux – less polar field.

• Fast flow also inducts less internal toroidal field – ongoing cycle ends early.
Dispersal of the high latitude active region flux during the rising phase of the cycle, is the primary determinant of the resulting polar field strength.

A fast flow carries both (positive and negative) polarities of active regions to the poles – no net flux – less polar field.

Fast flow also inducts less internal toroidal field – ongoing cycle ends early.

A subsequent, slower flow distances the next cycle’s toroidal field, resulting in a large gap between cycles.
Solar study sheds light on sunspot doldrums

An image from November 2010 shows an active sunspot 1123, which unleashed a solar flare toward the Earth. Solar activity such as sunspots and flares are more common during the peak of the solar cycle. ((NASA))

Unusually low sunspot activity in the past solar cycle may be due to changes in the flow of plasma deep below the sun's surface.
Acknowledgements

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- Dana Longcope, Paul Charbonneau, Aad Vanballegooijen.
- The NASA Living with a Star program.
Thank you!
By driving our dynamo model with active region data we can study the role that active regions have in the propagation of the cycle.
Comparing with Surface Observations

Given the surface dynamics, do the interior dynamics arise naturally?
The double ring algorithm is able to successfully capture the essence of surface flux transport...

However, we also find that active region emergence and decay alone is not enough to sustain the magnetic cycle.
Constraining the Helioseismic Meridional Flow

- Traditionally, in the dynamo community, the meridional flow is expressed as the curl of a stream function combined with mass conservation:

\[ \vec{v}_p (r, \theta) = \frac{1}{\rho(r)} \nabla \times \left( \Psi (r, \theta) \hat{e}_\phi \right) \]

- The stream functions we all use have a very important characteristic – their radial and latitudinal dependences are separable:

\[ \Psi (r, \theta) = v_0 F(r) G(\theta) \]

- This is very handy when maximizing the information that can be taken from the data.
Assimilating the Helioseismic Meridional Flow – Latitudinal dependence
Assimilating the Helioseismic Meridional Flow – Radial dependence
How do our result compare with observations?

The torsional oscillation associated with the magnetic field of cycle 24 (at the bottom of the CZ) is migrating slowly compared with the previous cycle.
How do our results compare with observations?

Hathaway & Rightmire 2010

Basu & Antia 2009
A small trip through Colombian music

By Andrés Muñoz-Jaramillo

Tomorrow Friday
9:30am

Here in this room