Solar cycle & Dynamo Modeling

Andrés Muñoz-Jaramillo
www.solardynamo.org

Georgia State University
University of California - Berkeley
Stanford University
THE SOLAR CYCLE: A MAGNETIC PHENOMENON
The solar cycle was discovered by Schwabe 1843 when he found that sunspot numbers change in time.

- Alternating peaks in solar activity (maxima), followed by quiet periods (minima).
- Time variation is predominantly cyclic, mean period is 11 years.
Sunspots are associated with regions of very strong magnetic field (Hale 1908)
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Fields generally appear at the surface in the form of bipolar structures called active regions.
Sunspots are associated with regions of very strong magnetic field (Hale 1908)

Active regions present systematic orientation and inclination
The most visible features of the cycle are associated with active regions

Movie by David Hathaway
The most visible features of the cycle are associated with active regions

- Equatorward migration of active latitudes.
- Poleward migration of their decayed diffuse field
- Polar field reversal at the maximum of the cycle and across hemispheres.
A cycle is not unique to the Sun

HD 30495

Sun
THE STELLAR DYNAMO
What is a Dynamo?

A machine that converts kinetic energy into electric energy by moving a conductor inside a magnetic field.
In stellar dynamos things are much more complicated

- The shape of the current loop can change freely to create very stable magnetic structures.

- The magnetic field restricts the movement of particles resulting in elastic behavior.

- The magnetic field used to induce the current is sustained by the induced current.
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- The shape of the current loop can change freely to create very stable magnetic structures.
- The magnetic field restricts the movement of particles resulting in elastic behavior.
- The magnetic field used to induce the current is sustained by the induced current.
BASIC NECESSARY STEPS FOR A SAFE AND FULFILLING DYNAMO EXPERIENCE
DROP!  COVER!  HOLD ON!  SELFIE!*  *NOT RECOMMENDED IN AN ACTUAL EMERGENCY
Silly Putty Time!
STRETCH!
FOLD!
STRETCH!
FOLD!
STRETCH!
FOLD!
4

SELFIE!
3D STELLAR DYNAMO SIMULATION
Poloidal and Toroidal Fields

Poloidal

$r - \theta$
Poloidal and Toroidal Fields

Poloidal
\[ r - \theta \]

Toroidal
\[ \phi \]
Current understanding of the solar cycle

Poloidal $r - \theta$

Toroidal $\phi$
1

STRETCH!

Schematic by J. J. Love
TWIST!
4

SELFIE!

Schematic by J. J. Love
Small-scale vs. Large-scale “Twist”

Small-Scale and Local
- Helical convection acting on the magnetic field.
- Also known as $\alpha$-effect.
- Limited by the relative amount energy available in convection.

Large-Scale and Global
- Coriolis force acting on rising flux-tubes.
- Also known as Babcock-Leighton effect.
- Limited to strong flux-tubes.
Small-scale vs. Large-scale “Twist”

Small-Scale and Local

$\alpha\Omega$ Dynamo

Large-Scale and Global

Babcock-Leighton Dynamo
BALANCE AND COUNTERBALANCE OF COMPETING EFFECTS
DYNAMO FIGHTER II

THE WORLD WARRIOR

DYNAMO FIGHTER II IS A REGISTERED TRADEMARK OF CAPCOM USA INC

1 PLAYER OR 2 PLAYERS?
Differential Rotation

Stretches poloidal fields. Main source of energy for the dynamo.
Meridional Flow

Connects different layers in the convection zone and drives period.

Jackiewicz et al. (2015)
Spreads magnetic flux, but also leads to flux cancellation.
Spreads magnetic flux, but also leads to flux cancellation.
Turbulent Pumping
Fast downflows and slow upflows result in net downward magnetic transport.
Poloidal Sources

Closes the solar cycle and sets the stage for the next one.
BALANCE AND COUNTERBALANCE OF COMPETING EFFECTS
Magnetic Sources vs. Decay

PLAYER SELECT

1P / 2P

D P D P
Advective vs. Diffuse Transport
Summary

• Solar and Stellar cycles are magnetic in nature and are powered by a dynamo mechanism.

• Differential rotation, helical turbulence, and the twist of emergent flux-tubes by Coriolis are main mechanisms that keep stellar cycles going.

• The relative importance of the different mechanisms involved in magnetic field generation and transport determine the properties of each dynamo.
Solar cycle: Observations and Characteristics

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HOW DOES THE SOLAR CYCLE OPERATE?
Solar Cycle Propagation

Poloidal \( r - \theta \)

Toroidal \( \phi \)

Polar Flux

Sunspot Numbers/Area

Credit: J. J. Love
Solar Cycle Propagation

Poloidal $r - \theta$

Differential Rotation

Toroidal $\phi$

Credit: J. J. Love
Solar Cycle Propagation

Poloidal \( r - \Theta \)

Differential Rotation

Toroidal \( \phi \)

Small-Scale and Local
- Also known as \( \alpha \)-effect.
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- Also known as Babcock-Leighton effect.
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Poloidal $r - \theta$

Differential Rotation

Emergence and Decay of Tilted Active Regions

Toroidal $\phi$

Solar Cycle Propagation

Hale’s Polarity Law
Solar Cycle Propagation

Poloidal \( r - \theta \)

Differential Rotation

Toroidal \( \phi \)

Emergence and Decay of Tilted Active Regions

Joy’s Tilt Law
Solar Cycle Propagation

Poloidal $r - \theta$

Differential Rotation

Emergence and Decay of Tilted Active Regions

Toroidal $\phi$
Solar Cycle Propagation

Poloidal \( r - \Theta \)

Differential Rotation

Toroidal \( \phi \)

Emergence and Decay of Tilted Active Regions
Solar Cycle Propagation

Poloidal $r - \theta$

Differential Rotation

Toroidal $\phi$

Emergence and Decay of Tilted Active Regions

Muñoz-Jaramillo et al. (2013)
THE SOLAR CYCLE AND THE LARGE SCALE SOLAR MAGNETIC FIELD
Active Regions have a very complex magnetic field with a lot of free energy
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Active Regions have a very complex magnetic field with a lot of free energy.
Violent reconfigurations of the solar magnetic field release this energy in the form of:

- **Flares**
- **Coronal Mass Ejections**
These highly energetic events are modulated by the solar cycle.

Both Flares...

Aschwanden & Freeland 2012
These highly energetic events are modulated by the solar cycle

... and CMEs

Owens & Lockwood 2012
The presence of active regions has a strong impact on the connectivity of the solar corona.

Images by Miloslav Druckmüller

Solar Maximum

Solar Minimum
Solar wind properties also change with the cycle

Images by Miloslav Druckmüller
Solar wind properties also change with the cycle at solar minimum.
Solar wind properties also change with the cycle

At solar maximum
Solar wind properties also change with the cycle.

Image taken from ESA.
Solar wind drags the magnetic field outwards forming a Parker spiral.
Changes in the solar wind and solar magnetic field modulate the galactic cosmic ray flux on Earth

- High energy particles coming from outside the solar system.
- Scattered by magnetic irregularities propagating in the solar wind.
- Modulation is weaker for high-energy cosmic rays.
- Cosmic rays generate isotopes that can be used to study long-term solar activity.
Changes in the solar wind and solar magnetic field modulate the galactic cosmic ray flux on Earth.
Apart from the main 11 year oscillation there is a large variability in cycle amplitude.

- Strongest cycle has an amplitude of 270 (14), the weakest has an amplitude of 80 (4).
- Longest (shortest) cycle has a duration of 14 (9) years. Mean is 11 +/- 14 months.
Apart from the main 11 year oscillation there is a large variability in cycle amplitude

- The Sun appears to enter periods in which several cycles have similar amplitudes.
- The most striking is known as the Maunder minimum (1645-1715; Eddy 1976).
A time with few sunspot observations

Ribes & Nesme-Ribes 1993
A time with few sunspot observations

Ribes & Nesme-Ribes 1993
What happened to the cycle during this period?

- Cosmogenic isotopes can be used to study the long term evolution of the cycle.

- Main isotopes used are $^{14}$C (half-life of 5730 years) and $^{10}$Be (half-life of $1.5 \times 10^6$ years).

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Beer et al. 1998
What happened to the cycle during this period?

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- Main isotopes used are $^{14}\text{C}$ (half-life of 5730 years) and $^{10}\text{Be}$ (half-life of $1.5 \times 10^6$ years).

- The solar cycle seems to be working during the Maunder minimum, but perhaps not as a Babcock-Leighton dynamo.

- For the latest work check Vaquero et al. 2015.
RECONSTRUCTION OF PAST SOLAR ACTIVITY USING COSMOGENIC ISOTOPES
There was a major discrepancy between the international sunspot number $R_I$ and the group sunspot number $R_G$.

During the last 5 years the solar community got together and fixed the issues.
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Cosmogenic isotopes can also be used as a proxy of past solar activity

Usosking et al. 2003 & Solanki et al. 2004

- During the last 1200 years there have been 3 grand minima.
Cosmogenic isotopes can also be used as a proxy of past solar activity.
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- Sunspot number distribution shows two significant deviations from normality for grand maxima and minima. Grand maxima may be an artifact!

Usoskin et al. 2007
Cosmogenic isotopes can also be used as a proxy of past solar activity

- Overall the Sun seems to spend $\frac{1}{6}$th of the time in grand minima.

Usoskin et al. 2007
Why is important to study long-term solar variability?

- Grand minima and maxima remain poorly understood and can teach us a lot about the inner workings of the cycle.

- Long-term solar changes are important to understand climate change.

- Long-term proxies increases the data pool we have to understand the cycle.
• The solar cycle is a process that is magnetic in nature.

• Its main characteristics are determined by the emergence and decay of active regions.

• The Sun is currently operating as a Babcock-Leighton Dynamo.

• The solar cycle is the main determinant factor in setting the conditions in the heliosphere.

• The Sun seems to have a long-term evolution involving multi-cycle scales.