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 $r - \theta$

Toroidal $\phi$

Muñoz-Jaramillo et al. (2012)
Solar Cycle Propagation

Poloidal \( r - \theta \)

Differential Rotation

Toroidal \( \phi \)

Credit: J. J. Love
Poloidal $r - \theta$

Differential Rotation

Toroidal $\phi$

Solar Cycle Propagation

Muñoz-Jaramillo et al. (2013)
Poloidal \(r - \theta\) 

Small-Scale and Local
- Also known as \(\alpha\)-effect.
- Limited by the relative amount energy available in convection.

Differential Rotation

Large-Scale and Global
- Also known as Babcock-Leighton effect.
- Limited to strong flux-tubes.

Toroidal \(\phi\)
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 $r - \theta$

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Differential Rotation

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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Violent reconfigurations of the solar magnetic field release this energy in the form of:

**Flares**

**Coronal Mass Ejections**

2010-08-01 07:00
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 wind properties also change with the cycle.

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

At solar maximum
Solar wind properties also change with the cycle.
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.
LONG-TERM CYCLE VARIABILITY
Apart from the main 11 year oscillation there is a large variability in cycle amplitude

- **Strongest (weakest) cycle** has an SSN amplitude of 188 (43). Mean is 90 +/- 41.

- **Longest (shortest) cycle** has a duration of 14 (9) years. Mean is 11 +/- 14 months.

- Data taken from Hathaway (2010).
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 (global maxima and minima).
- 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 C\textsuperscript{14} (half-life of 5730 years) and Be\textsuperscript{10} (half-life of 1.5 x 10\textsuperscript{6} years).

[Graph showing oscillations with years and isotopic abundance from 1600 to 1760.]

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

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- Main isotopes used are C\textsuperscript{14} (half-life of 5730 years) and Be\textsuperscript{10} (half-life of 1.5 x 10\textsuperscript{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.
Cosmogenic isotopes can also be used as a proxy of past solar activity.

During the last 1200 years there have been 3 grand minima.

Usosking et al. 2003 & Solanki et al. 2004
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.
SUMMARY
• 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.

• Some cycle properties change in time-scales spanning multiple cycles.