THE RAILS INSIDE THE SUN AND THE BUTTERFLIES THAT RIDE THEM

Andrés Muñoz-Jaramillo

www.solardynamo.org

Georgia State University
University of California - Berkeley
Stanford University
SOURCES OF INSPIRATION (AND TAKE HOME MESSAGE)
• All hemispheric cycles follow the same latitudinal path (Hathaway 2011, Ivanov & Miletsky 2014).

• All hemispheric cycles decline in the same way (Cameron & Schüssler 2016).

• The amplitude of the solar cycle is strongly determined by the position of the cycle within this universal latitudinal path.

• Toroidal belts are subject to very high diffusivity and are transported by a steady flow (or dynamo wave).
HOW DOES THE SOLAR CYCLE OPERATE (WHAT WE KNOW)?
SOLAR CYCLE PROPAGATION

Poloidal $r - \theta$ \quad \rightarrow \quad Toroidal $\phi$

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 $\phi$

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SOLAR CYCLE PROPAGATION

Poloidal $r - \theta$  \[\rightarrow\]  Toroidal $\phi$

Muñoz-Jaramillo et al. (2013)

![Graph showing solar cycle propagation](image)

Amplitude Next Cycle (mHem) vs. Average Polar Flux During Min ($10^{22}$ Mx)

$rho = 0.6$, $pval = 99\%$
SOLAR CYCLE PROPAGATION

Poloidal $r - \theta$

Differential Rotation

Toroidal $\phi$

Emergence and Decay of Tilted Active Regions

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

Emergence and Decay of Tilted Active Regions

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Emergence and Decay of Tilted Active Regions

Muñoz-Jaramillo et al. (2013)

- Graph showing average polar flux during minima versus maximum cycle A times AWNL average tilt.
- Correlation with $\rho = 0.74$, $p$-value $= 99\%$.

Diagram illustrating the relationship between poloidal and toroidal components.
WHAT IS OUR BIGGEST SOURCE OF UNCERTAINTY?
THE FLUX-TRANSPORT DYNAMO

\[ \frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B} + \eta \nabla \times \vec{B}) \]

\[ \vec{v} = r \sin(\theta) \Omega \hat{e}_\phi + \vec{V}_p \]
WE DON’T KNOW WHAT ARE THE MAIN MECHANISMS OF FLUX TRANSPORT

Meridional Flow Penetration

Turbulent Diffusivity Profile

Jackiewicz et al. (2015)
WE DON’T KNOW WHERE IS THE SEAT OF THE DYNAMO

Surface

or Tachocline?
SUNSPOTS, ACTIVE REGIONS, AND THE INTERNAL MAGNETIC FIELD
The most visible features of the cycle are associated with active regions
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- Equatorward migration of active latitudes.
- Poleward migration of their decayed diffuse field.
- Polar field reversal at the maximum of the cycle and across hemispheres.
ACTIVE REGIONS AND THE TOROIDAL FIELD

Nelson et al. (2014)

Weber, Fan, & Miesch (2011)

Jouve, Brun, & Aulanier (2013)

Fan (2008)

Yeates & Muñoz-Jaramillo (2013)
A Gaussian is fitted to the latitudinal distribution of all observed groups within a 24 month window.
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THE RAILS INSIDE THE SUN
(HATHAWAY 2011, 2015).
ALL HEMISPHERIC CYCLES FOLLOW DIFFERENT PARTS OF A UNIVERSAL PATH

Charles Darwin sails with the H.M.S. Beagle
American civil war begins

First use of anesthetics
Italian and German unifications completed
ALL HEMISPHERIC CYCLES FOLLOW DIFFERENT PARTS OF A UNIVERSAL PATH

First Opium War

Meiji Restoration begins

Second Opium War
ALL HEMISPHERIC CYCLES FOLLOW DIFFERENT PARTS OF A UNIVERSAL PATH
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Bell Curve Area = 19.18 mHem*Yr

Years from the belt reaching 15°
ALL HEMISPHERIC CYCLES FOLLOW DIFFERENT PARTS OF A UNIVERSAL PATH

Cycle 19-North

Bell Curve Area = 19.18 mHem*Yr

Latitude (°)

Years from the belt reaching 15°
ALL HEMISPHERIC CYCLES FOLLOW DIFFERENT PARTS OF A UNIVERSAL PATH
IMPLICATIONS FOR THE SOLAR DYNAMO

• Under the flux transport dynamo paradigm these results mean that the equatorward component of the meridional flow doesn’t change in time.

• These results are also compatible with a shallow dynamo whose equatorward migration is driven by a dynamo wave.

• Studies invoking deep meridional flow variations to explain solar variability need to be revised.
ALL CYCLES DECAY IN THE SAME WAY (CAMERON & SCHÜSSLER 2016).
REFERENCING THE CYCLE TO LATITUDE

Latitude of centroid can be used as reference instead of time

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• Cameron & Schüssler (2016) estimate a turbulent diffusivity of the same magnitude as mixing-length estimates.

• The toroidal belts are probably not located in the stable layer underneath the convection zone.

• Active longitude inflows are probably necessary to sustain the toroidal belt integrity.

• We need a new generation of flux transport dynamos that can operate at high diffusivity values.
DEFINING A MINIMUM UNIVERSAL TIME
(IVANOV & MILETSKY 2014).
TIMING THE CYCLE TO SOLAR MINIMUM IS SUB-OPTIMAL

Using centroid latitude captures much better the individual nature of each cycle than using minimum
WING CENTROID LATITUDE CAN BE USED TO TIME MINIMA
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THERE IS AN OPTIMUM LATITUDE FOR USING THE POLAR FIELDS TO PREDICT THE CYCLE

The optimum intervals for predicting cycle 25 for the northern (southern) hemispheres using polar fields are Jul-2016 to Mar-2017 (Feb-2018 to Aug-2018).
THE SOLAR CYCLE’S MISSING CHUNKS (SOLVING THE MYSTERY OF CYCLE 16).
CONNECTING THE DOTS

Muñoz-Jaramillo et al. (2013)
QUANTIFYING THE MISSING PART

- I fitted all cycles to a skewed Gaussian ignoring the serrated part.
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- Cycle amplitude is correlated with rise rate.
- We calculate rise rate using the beginning of the cycle and the first local maximum.
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WHY IS A PIECE MISSING?

For any given amplitude, the closer the wing is to the equator, the larger the chunk that is missing.
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THIS EXPLAINS THE DIFFERENCE BETWEEN THE SPACE AGE AND THE EARLY 1900s

Space age cycles are farther from the equator.
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Space age cycles are farther from the equator
• Cycle amplitude is limited by the ability of the wings to grow without cancelling across the equator.

• Further evidence of a high diffusivity regime.

• The polar fields are not the only thing determining cycle amplitude.

• In order to make better predictions we need to get a better handle on the timing of the cycle.
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