Are Changes in the Solar Meridional Circulation Responsible for the Characteristics of Minimum 23-24?

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What makes minimum 23-24 unusual?

1. Lowest values of solar irradiance (depending on who do you believe).

2. Cosmic ray flux is at it’s highest (since we started measuring it).

3. Solar wind density, temperature and energy at a record low.

4. Low values of the polar field.

5. Large amount of spotless days.
Important Terminology

**Poloidal**: Inside the meridional plane. \( r - \theta \) components

**Toroidal**: Perpendicular to the meridional plane. \( \phi \) component
The Solar Cycle in a Nutshell

Poloidal: $r - \Theta$

Toroidal: $\phi$

Differential Rotation

Poloidal Source

Meridional Flow

Turbulent Diffusivity
The 2.5D Kinematic Dynamo Model

- Based on the MHD induction equation:
  \[
  \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left( \mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B} \right)
  \]

- Expressing the fields in axisymmetric form:

  \[
  \mathbf{B} = B\hat{e}_\phi + \nabla \times \left( A\hat{e}_\phi \right) \quad \text{v} = r \sin(\theta) \Omega \hat{e}_\phi + \mathbf{v}_p
  \]

The poloidal source will be explained later.
Differential Rotation & Meridional Flow

Charbonneau et al. 1999

Muñoz-Jaramillo, Nandy & Martens 2009
The Babcock-Leighton Mechanism


Regeneration of poloidal field through the emergence and decay of tilted bipolar active regions.
• Truer to the discreet nature of the BL mechanism that a continuous poloidal source.

• The most accurate representation of active region emergence and decay in an axisymmetric formulation.
Double Ring Approach

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

Durney (1997), Nandy and Choudhuri (2001)
Double Ring Approach

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Durney (1997), Nandy and Choudhuri (2001)
Understanding this Solar Minimum

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.
Understanding this Solar Minimum
Results

1. Dependence on the meridional flow amplitude in the second half of the cycle:
Results

1. Dependence on the meridional flow amplitude in the second half of the cycle:

- The correlation for both quantities is very weak.
- The flow near minimum does not define the characteristics of that minimum.
Results

2. Dependence on the meridional flow amplitude in the second half of the previous cycle first half of the current:
Results

2. Dependence on the meridional flow amplitude in the second half of the previous cycle first half of the current:

- Polar field gets weaker with strong flow due to surface dynamics.
- Length of the minimum increases with strong flow because less toroidal field is inducted – cycle takes time to pick up.
3. Dependence on the change in meridional flow amplitude in the middle of the cycle:

- Polar field amplifies with a change into a faster flow because the later amplifies the polar field by compression.
Do we reproduce the defining characteristics of this minimum?

4. Polar Field vs. Overlap

- Cycles without overlap consistently have weak polar fields
How do our result compare with observations?

The torsional oscillation associated with cycle 24 (which started at the maximum of cycle 23), is migrating slowly compared with the previous cycle.
How do our result compare with surface observations

- Surface flow observations show a sinusoidal behavior indicating that the flow speed is higher at this minimum compared to the last.
- However...
Near-surface observations capture a only a minute part of the flux transport process...
Final Remarks

• The strength of the polar field is governed mainly by surface dynamics in the early half of the cycle.

• The amount of spotless days is governed by the dynamics deep in the solar interior.

• Without dynamo models is not possible understand the whole story.
So what’s the story?

• A fast meridional flow in the early half of the cycle followed by a slower flow in the later half explains best the characteristics of the current minimum.
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THANK YOU!
Verifying Surface Dynamics

Run a simulation changing the meridional flow randomly from cycle to cycle between 15 m/s and 30 m/s

Using the double ring algorithm we obtain the same correlation between MF and polar field as flux transport simulations.
Changing at Sunspot Min

Run a simulation changing the meridional flow randomly from cycle to cycle between 15 m/s and 30 m/s
Results

1. Dependence on the meridional flow amplitude in the full cycle:

Polar Field

Cycle Overlap
Results

2. Dependence on the meridional flow amplitude of the previous cycle:

Polar Field

Cycle Overlap
Results

3. Dependence on the change in meridional flow amplitude:

![Polar Field](image1)

![Cycle Overlap](image2)
Do we reproduce the defining characteristics of this minimum?

4. Polar Field vs. Overlap
Changing both at Sunspot Max and Min

Run a simulation changing the meridional flow randomly twice per cycle between 15 m/s and 30 m/s

Before

After
Results

1. Dependence on the meridional flow amplitude in second half of the previous cycle:

- Polar Field
- Cycle Overlap
Results

3. Dependence on the meridional flow amplitude of the first half of the cycle:

Polar Field

Cycle Overlap
Results

2. Dependence on the meridional flow amplitude in the second half of the cycle:
Results

4. Dependence on the change in meridional flow amplitude at mid cycle:
Do we reproduce the defining characteristics of this minimum?

4. Polar Field vs. Overlap
Meridional Flow - Helioseismic Data of Irene González-Hernández
Meridional Flow Dependence

Muñoz-Jaramillo, Nandy & Martens 2009

Latitudinal Dependence

Radial Dependence

Helioseismic data of Irene González-Hernández
Meridional Flow – Latitudinal Dependence

Meridional Flow Speed at Different Depths

Density Weighted Meridional Flow Speed at Different Depths
Meridional Flow – Radial dependence
Average Surface Magnetic Field

Image by David Hathaway