Why was the Sun so quiet?

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THE SOLAR CYCLE
A brief introduction of its main features
Discovered by Schwabe (1843) while trying to find an intra-mercurial planet.

- Alternating peaks in solar activity (maxima), followed by quiet periods (minima).
- Time variation is predominantly cyclic, mean period is 11 years.
Known to be Magnetic in Nature

Hale (1908)
Its most important characteristics are nicely summarized on the butterfly diagram.

- Equatorward migration of Active Regions.
- Poleward migration of their decayed diffuse field
- Polar field reversal at the maximum of the cycle.
WHY WAS SOLAR MINIMUM 23 SO INTRIGUING?

Main magnetic characteristics and their consequences
1. Large number of spotless days

- Almost three times longer than other minima in the space age.
- Last observed a hundred years ago
1. Large number of spotless days

- Decrease in solar irradiance.

Relevant for solar forcing of climate and structure of Earth’s Atmosphere
2. Weak polar field strength

- Weakest polar field of the previous three solar minima.
2. Weak polar field strength

- Solar wind speed, density and temperature at record low.
2. Weak polar field strength

- Solar wind speed, density and temperature at record low.
2. Weakest Polar Fields Measured

- Highest values of cosmic ray flux directly recorded.

Relevant for cloud formation and a hazard for polar flight passengers and astronauts.
CURRENT UNDERSTANDING OF THE CYCLE
The Solar Cycle in a Nutshell

Poloidal: \( r - \theta \)

Toroidal: \( \phi \)
The Solar Cycle in a Nutshell

Poloidal $r - \theta$

Toroidal $\phi$

Differential Rotation

Images by J. J. Love
The Solar Cycle in a Nutshell

Poloidal - Toroidal

Differential Rotation
Active Region Emergence and Decay

r - θ
φ
The Solar Cycle in a Nutshell

Poloidal $r - \theta$

Differential Rotation

Toroidal $\phi$

Active Region Emergence and Decay

Meridional Flow

Turbulent Convection
MODELING THE SOLAR CYCLE
Surface flux transport simulations and kinematic dynamo models
The MHD induction equation

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

\[ \overline{v} = r \sin(\theta) \Omega \hat{e}_\phi + \overline{v}_p \]
Surface Flux Transport Simulations

• Based on the induction equation and limited to the surface of the Sun.

• They allow us to study the evolution of the surface magnetic field and its interaction with the corona and solar wind.
Kinematic Dynamo Models

• Based on the induction equation assuming axial symmetry.

• They allow us to study a self-excited cycle with freedom to explore different regimes thanks to inexpensive computations.

Images taken from Muñoz-Jaramillo et al. 2011
Important Features of our model

The closest representation of active regions in an axisymmetric formulation (double-ring algorithm).

Durney (1997), Muñoz-Jaramillo et al. (2010)

This implementation resolves a long-standing discrepancy between surface flux transport simulations and kinematic dynamo models.
Important Features of our model

The closest representation of active regions in an axisymmetric formulation (double-ring algorithm).

Durney (1997), Muñoz-Jaramillo et al. (2010)

This discrepancy concerns the surface dynamics and how the meridional flow affects the polar fields.
How does our model compare with observations and other models?

Observations of Surface Magnetic Field

Traditional Models

Improved Model
Main Magnetic Characteristics of the extended minimum

1. Large number of spotless days. ✓

Our model includes a realistic algorithm for sunspot eruption.

2. Weak polar field strength.

Our model captures successfully the dynamics of polar field generation ✓
UNDERSTANDING THE EXTENDED MINIMUM
What does the model tell us?
Which Dynamo Ingredient is likely to be responsible for the characteristics of minimum 23?

- **Differential Rotation**
- **Meridional Flow**
- **Turbulent Diffusivity**
- **Active Region emergence and decay**

Schrijver & Liu 2008
Meridional Flow Variations

- The amplitude of the flow is varied randomly between 15—30 m/s
- This random change is made to occur at sunspot maximum
  - maximum feedback expected from magnetic fields on flows
  - coincides with the induction of next cycle toroidal field belt
Solar Cycle Simulations
Nandy, Muñoz-Jaramillo & Martens (2011)

- 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?

Dependence on flow speed during declining-phase of cycle

![Polar Field](image)

![Cycle Overlap](image)

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

Dependence on flow speed during the 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?

Dependence on change in flow speed

Significant correlation: Change from a fast to a slower meridional flow generates a deeper minimum
Defining characteristics of cycle 23 minimum:

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

Our model finds that deep minimums also have weak polar fields (but the reverse is not true).
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 result compare with observations?

The amplitude of the second order component in a Legendre polynomial expansion drops at the maximum of cycle 23.

Basu & Antia 2009
SUMMARY
A recipe for a deep 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)
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• Fast flow also inducts less internal toroidal field – ongoing cycle ends early.
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• 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.
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谢谢
Thank you!
How do our result compare with observations?

Hathaway & Rightmire 2010

Basu & Antia 2009
How do our result compare with observations?

- Surface Doppler measurements indicate flow speed at surface higher at this minimum compared to earlier minimum – conflicting

- However: Surface measurements/variations are superficial!
  - Also supported by conclusions of Jiang et al. 2010