Helioseismic Perspective of the Solar Dynamo

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THE SOLAR CYCLE
Constraints imposed by surface observations
Global features of the solar cycle
Global features of the solar cycle

- Equatorward migration of active latitudes.
- Poleward migration of decayed diffuse field.
- Polar field reversal at the maximum of the cycle.
SOLAR DYNAMO MODELS
Some of the tools in our arsenal
Mean-Field Dynamo Models

• Based on the magnetic induction equation assuming axial symmetry.

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

Muñoz-Jaramillo et al. 2010
Mean-Field Dynamo Models

• **Main Advantages:**
  – Relatively inexpensive computations.
  – Self-excited.
  – Very successful at reproducing cycle characteristics.

• **Main Disadvantages:**
  – Large amount of free parameters.
  – Phenomenological approach to modeling.
Full MHD Simulations

• Solutions of the full magnetohydrodynamical (MHD) equations.

• They allow us to study an artificial star inside a computer, see what we can’t see, and go where we can’t go.

Brown et al. 2010
Full MHD Simulations

• **Main Advantages:**
  – Built upon basic plasma physics.
  – Self consistent evolution of both the magnetic and velocity fields.

• **Main Disadvantages:**
  – Very expensive computations.
  – Far from the physical regime in which the Sun operates.
HELIOSEISMOLOGY AND OUR UNDERSTANDING OF THE CYCLE
A semi-chronological perspective
Conceptual Formulation
Larmor (1919), Parker (1955), Babcock (1961), Leighton (1964)

Poloidal
\[ r - \theta \]

Toroidal
\[ \phi \]
Conceptual Formulation

Larmor (1919), Parker (1955), Babcock (1961), Leighton (1964)

Poloidal

\[ r - \theta \]

\[ \text{Differential Rotation} \]

\[ ? \]

Toroidal

\[ \phi \]

Credit: J. J. Love
Conceptual Formulation

Larmor (1919), Parker (1955), Babcock (1961), Leighton (1964)

Interaction with helical turbulence ($\alpha$)

Active region emergence and decay (BL)

Parker (1955)
Propagation of Dynamo Waves

Propagation of Dynamo Waves

Leighton (1969)
The Time of Troubles

- Measurements of the solar rotation showed that active latitudes have positive latitude shear. Thompson et al. (1996); Kosovichev et al. (1997); Schou et al. (1998).
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• Measurements of the solar rotation showed that active latitudes have positive latitude shear. Thompson et al. (1996); Kosovichev et al. (1997); Schou et al. (1998).

• Simulations of rising flux-tubes through the convection zone find them to match surface observations only if they start with super-equipartition field strengths. Fan (2009).

• Interaction of the magnetic field with helical turbulence ($\alpha$) may not be an efficient source of toroidal field.
The discovery of the meridional flow


Data courtesy of Irene Gozález-Hernández
The discovery of the meridional flow

• Systematic poleward flow observed near the surface. Komm, Howard & Harvey (1993).

• Typically modeled in mean-field dynamo as a single cell spanning the entire convection zone.
The discovery of the meridional flow


- Typically modeled in mean-field dynamo as a single cell spanning the entire convection zone.

- A vigorous enough meridional flow can in principle overpower the dynamo wave. Choudhuri et al. (1995).

- The combination of the BL mechanism with a significant role for the meridional flow led to the birth of the modern flux-transport dynamo. Dikpati & Charbonneau (1999).
Poloidal \( r - \theta \) → Differential Rotation → Toroidal \( \phi \) → Emergence and Decay of Active Regions (Sunspots) → Meridional Flow → Turbulent Diffusivity
SOME IMPORTANT DEVELOPMENTS
TORSIONAL OSCILLATIONS
Thinking outside of the kinematic box
“pattern of migrating bands of faster- and slower-than-average zonal flow associated with the equatorward drift of the activity belts during the solar cycle” Howe (2009); Howard and LaBonte (1980).
Can only be modeled in a non-kinematic regime \textsuperscript{Rempel (2006)}

- Lorenz feedback on the differential rotation produces the high latitude branch.

- Enhanced cooling produces the low latitude branch. \textsuperscript{Spruit (2009)}.
The high latitude branch seemed to be absent during cycle 24

Howe et al (2013)

• Models showed that this was caused by a drift of the average differential rotation caused by the weakening of the polar fields. Rempel (2012).
SEISMIC CONSTRAINTS ON INTERIOR SOLAR CONVECTION

Providing observational constraints to global MDH simulations
Why is this important?

• Global MHD simulations provide us with the unique opportunity of studying the self-consistent interaction between convection and magnetic fields.

• Mean field dynamos driven using model ingredients inferred from MHD simulations show remarkable similarities in the evolution of the average magnetic field. Simard et al. (2013).
How it has been done so far?

Hanasoge et al. (2010)

- Careful analysis of the sensitivity of helioseismic techniques (time-distance) places an upper limit on the velocity spectrum of the solar convection.
A DYNAMO THEORIST WISH LIST

How can helioseismology improve our models?
Main ingredients of dynamo models

- Differential Rotation

- Meridional Flow

- Turbulent Convection (diffusivity)

- Magnetic Sources
• Depth dependence.
• Radial component.
• Another time of troubles?
Turbulent convection (diffusivity)

- Constraining convection properties at deeper layers.
- Strong cooperation between helioseismology and global full MHD simulations.
• Hunt for magnetic signatures.
• Impact of magnetic fields on solar and stellar models.
FINAL REMARKS
• Helioseismology has been (and will remain), without a doubt, instrumental in the development of our understanding of the solar cycle.

• The arrival of global MHD simulations and their synergy with helioseismology will be instrumental in advancing our understanding from now on (ASH and EULAG).

• Studying below surface conditions inside the solar convection zone is difficult, but please don’t stop trying.

• Any inference on the properties and location of the magnetic field inside the CZ would be very useful.
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