Turbulent Convection and Dynamo Processes in the Solar Interior

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Symposium on Turbulence and Dynamos at Petaspeed
NCAR, Boulder, CO
Colleagues

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Outline

- The Dynamic Sun
- Probing the Solar Interior
- Computational Challenges and Tools
  - The ASH code
- Simulations of Solar Convection
- The Solar Dynamo
- Other Stars
  - Summary and Outlook
Sunspots reflect cyclic magnetic activity

D. Hathaway (NASA MSFC)

22-year activity cycle
Sunspots reflect cyclic magnetic activity and the 22-year activity cycle.
The Solar Butterfly Diagram

SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)

AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)

D. Hathaway (NASA MSFC)

Order amid Chaos
How does it arise?
Convection

Differential Rotation

Meridional Circulation

Magnetism
Convection

Differential Rotation

Meridional Circulation

Magnetism
The Sun rings like a bell!
The Solar Internal Rotation

Local Helioseismology

Peering beneath sunspots
Far-side imaging
Solar Subsurface Weather (SSW)

D. Haber, B. Hindman & J. Toomre
(Univ. of Colorado)
The Challenge

Now How do we go about modeling this mess??

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 Length Scales

 ‣ Solar radius: 700 Mm
 ‣ Tachocline width: 20 Mm
 ‣ Viscous dissipation scale: 1 cm

 Time Scales

 ‣ Period of sound waves: 5 min
 ‣ Period of gravity waves: 1.5 hours
 ‣ Rotation period: 1 month
 ‣ Activity cycle: 22 years

 Other nastiness

 ‣ Spherical geometry
 ‣ Stratification, rotation, magnetism, shear
 ‣ Boundary layers
   ◦ Top: Granulation, ionization, compressibility, radiative transfer
   ◦ Bottom: Tachocline, convective penetration, instabilities, waves
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The Challenge

Turbulent!!
The ASH Code

**LES/SGS Strategy**
- Eddy viscosity, diffusivities
- shave off granulation layer

**Anelastic approximation**
- perturbations about a hydrostatic reference state
- filters out acoustic waves
- density stratification
- streamfunction formulation

**Pseudospectral**
- Spherical Harmonic
- Stacked Chebyshev
- Crank-Nicholson/Adams-Bashforth

**Parallel**
- FORTRAN 90 / MPI
- serial transforms, transposes
- optimal data decomposition
radial velocity, $r = 0.98R$

Miesch, Brun, DeRosa & Toomre (2007)
Solar Cyclones

$\alpha$ $b$

$r = 0.98R$

pdf

$\xi \left(10^{-4} \text{s}^{-1}\right)$
North-South Downflow Lanes

Equatorward Angular momentum transport
Differential Rotation, Meridional Circulation

![Diagram](image)

- **a**: Contour plot showing the differential rotation with angular velocity $\frac{\Omega}{2\pi}$ in nHz.
- **b**: Graphs indicating the rotation rate at different latitudes ($0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$).
- **c**: Contour map highlighting the meridional circulation with colors indicating clockwise (CCW) and counterclockwise (CW) flow.

$r/R$ represents the radial distance from the center.
The Solar Dynamo

The Solar Dynamo

M. Dikpati & P. Gilman (HAO/NCAR)

Y. Fan (HAO/NCAR)

SOHO/ESA/NASA

N. Brummell (UCSC)
Dynamo Processes

Brun, Miesch & Toomre (2004)

Case M3, t = 567.7 days
Intricate, intertwined field lines and ribbons
Tachocline

Pumping, amplification, organization of toroidal magnetic fields

Browning, Miesch, Brun & Toomre (2006)
So Many Stars ...and so little time

Convective Cores
Convective Envelopes
Fully Convective

Magnetism inferred in an M dwarf

M Stars

Small (0.3 $M_{\odot}$), Cool (3000K)
Fully Convective

Browning (2007)
A Stars

Big (2 $M_{\odot}$), Hot (8000K)

Convective Core

N. Featherstone (Univ. of Colorado)

Featherstone, Brun, Browning & Toomre (2007)
Summary and Outlook

~ A Vibrant Sun
  ‣ Magnetism!
  ‣ SOHO, TRACE, SST, Hinode, Stereo, SDO
  ‣ Helioseismogy: Peering inside a star

~ Convection and Dynamo Processes
  ‣ Solar Cyclones, NS lanes
  ‣ Differential rotation, meridional circulation
  ‣ Sustained magnetic field generation
  ‣ Pumping of fields into a *tachocline*
  ‣ Amplification, organization by rotational shear

~ A Universe of Stars
  ‣ Astroseismology: CoRot, Kepler

~ Big computers may be used to tackle big problems!
Next Generation ASH

- Scalably Parallel
  - High Resolution
  - Long time integrations
  - Finite elements?

- Non-uniform grid
  - Spherical geometry
  - Photosphere
  - Overshoot region & Tachocline
  - Time splitting?

- Subsonic
  - Poisson equation
  - Multigrid?

- MHD
  - $\text{Div}(B) = 0$