Understanding the Interior of the Sun

Pascale Garaud
Astrophysical & Geophysical Fluid Dynamics

Applied Mathematics and Statistics
Baskin School of Engineering
UC Santa Cruz
The equations of Fluid Dynamics

\[
\begin{align*}
\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u &= -\nabla p - \rho \nabla \Phi + \rho \nu \nabla^2 u \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) &= 0 \\
p &= p(\rho, T) \\
\rho T \frac{\partial s}{\partial t} + \rho T u \cdot \nabla s + \nabla \cdot F &= 0
\end{align*}
\]
The equations of Fluid Dynamics
THE EQUATIONS OF FLUID/GAS DYNAMICS
The equations of Magneto-HydroDynamics (MHD)

\[
\begin{align*}
\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u &= -\nabla p - \rho \nabla \phi + \rho \nu \nabla^2 u + j \times B \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) &= 0 \\
p &= p(\rho, T) \\
\rho T \frac{\partial s}{\partial t} + \rho Tu \cdot \nabla s + \nabla \cdot F &= 0 \\
\frac{\partial B}{\partial t} + \nabla \times (u \times B) + \nabla \times (\eta \nabla \times B) &= 0
\end{align*}
\]
Astrophysical Fluid Dynamics
The challenge

• Real physical systems exhibit a formidable range of complex behavior.

• Solving the MHD equations is a correspondingly complex problem.
The challenge

- Progress can be achieved by synergy between
  - Idealised, analytical models
  - Large-scale numerical simulations
MHD of The Solar Interior
Magnetic properties of the Sun

- The Sun is an "active" star.
- Its magnetic activity is modulated by an 11-year cycle.

http://science.msfc.nasa.gov/sol/pas/solar/images/hfx.gif
Magnetic properties of the Sun

October 7th, 2008
Magnetic properties of the Sun
MAGNETIC PROPERTIES OF THE SUN
Magnetic properties of the Sun

- **Solar Activity can be harmful for space-based equipment and humans.**
NASA GOALS

• To understand the origin of the solar magnetic cycle.
• To predict future solar weather.
Before Helioseismology...

"I think you should be more explicit here in step two."
Helioseismology

- Infers properties of the interior of the Sun from measurements of pressure waves (sound waves).
  - Solar structure
  - Internal flows

- SOHO data analysis @ Stanford (Solar Oscillation Investigation).
Interior structure
Interior dynamics
The solar “Dynamo”
AMS Research Goals

• To understand the origin of the observed rotation profile (Garaud et al.)

• To understand the origin of small-scale and large-scale solar magnetic fields (Brummell et al.)
THE SOLAR ROTATION PROFILE
The solar rotation profile
The solar rotation profile

- The magneto-hydro-dynamics of the solar interior are complex!
  - Nonlinear / chaotic
  - Small ↔ large scales

- Can we model such a system?
  - Use approximate “closure” model for small/turbulent scales
  - Solve exact equations for largest scales
The solar rotation profile

- **What is the nature of the solar tachocline?**
  - A dynamical transition?
  - A thermal/chemical transition?

- **Can we understand observables ...**
  - The thickness of the tachocline?
  - The rotation rate of the interior?
THE SOLAR ROTATION PROFILE
The solar rotation profile
Magnetic field generation

- Nature of solar dynamo
- Origin and rise of large-scale magnetic structures
Magnetic field generation