Imaging Convection in the Solar Interior

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The Study of Convection

1. Motivation and Objectives

Convection in the Sun, the process by which the heat flux of the solar luminosity is transported outwards by motions of plasma, directly and indirectly drives the external magnetic manifestation of the Sun, which in turn affects life on Earth (see Figure 1). Convection in the Sun is a highly non-linear phenomenon (and hence termed 'turbulent') and because a typical characteristic of astrophysical turbulence is the extreme parametric regime which it inhabits, we have very limited ability in describing it using theoretical, computational or laboratory means. Seismology is the only way to image interior turbulence.

The proposed project will be to analyze, using techniques of time-distance helioseismology, extended sequences of observations taken by the Helioseismic and Magnetic Imager onboard the Solar Dynamics Observatory. These measurements will be interpreted using a combination of techniques, ranging from adjoint optimization, high-performance computing and inverse theory to the mathematical theory of homogenization and Wigner transforms. I identify four major tasks in section 2, that will be executed in order to achieve this goal. The successful completion of this project will:

- shed light on the nature of turbulent convection and the distribution of Reynolds' stresses over large spatial scales in the interior of the Sun (using helioseismology),
- attempt to discern the elusive and long-sought-after signals of large-scale convection (there is faint evidence of this in our measurements, private communication, T. Duvall 2012),
- incorporate methodologies of wave propagation in random media (such as homogenization), uncertainty estimation and non-linear inverse theory, of relevance to helio- and asteroseismology.

I am the lead author of an article that demonstrated that over large scales, the power spectrum of convective flows in the interior of the Sun is anomalously weak (Hanasoge et al. 2012), challenging existing

Figure 1: Convection is at the heart of it all. Convection drives turbulence, which in turn is thought to prop up differential rotation and meridional circulation, i.e., large-scale fluid dynamical motions in the Sun (e.g., [3], [22], [20]). These are believed to play a central role in generating and

Convection is one of the least understood aspects of stellar models
Numerical Simulations

- Detailed physics (anelastic/compressible dynamics)
- Hypothesis testing

E.g., ASH, from Miesch (2005) radial velocity
Measurements: Wave travel times as proxies

HMI dopplergrams

900 billion wavefield measurements

Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA

~ 3 billion cross correlations

~ 5 million travel times
Sensitive to 3-flows
Imaging

Aperture at the surface through which interior dynamics are observed

Deep-focusing geometry

Imaging the interior using measurements at the surface

Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA

Figure courtesy of L. Gizon
ASH Convective flows

- Test: How do waves perceive a snapshot of anelastic convection (from the ASH code)
- To determine signatures, we simulate wave propagation through these complex flows in spherical geometry (Hanasoge et al. 2006)
- Figure from Hanasoge, Duvall, & DeRosa (2010)
- Are observations as striking?
OBSERVED MAPS OF TRAVEL TIMES

No obvious large-scale structure (noise)

Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA
Upper bounds

Finite frequency effects are accounted for

Wave \textit{``PSF''} deconvolved from the measurement

\[
Ro = \frac{U}{2\Omega L}
\]
The Nature of the Result

• Non-detections are hard to explain

• The analysis is complicated

• The recognition that non-detections can be profound too (e.g., Birch, Braun, Cameron, Duvall, Gizon, Hanasoge)

• It is ultimately not vastly surprising; few prior detections (notable exception of Hathaway et al. 2013)
THERMAL AND MOMENTUM TRANSPORT

• How to transport a solar luminosity with very low turbulent kinetic energy?

• How is differential rotation sustained? i.e., how is angular momentum transported? Reynolds’ stresses not high enough? Meriodional circulation? (Miesch et al. 2012)

The excess low wavenumber power we find in both our simplified model and realistic simulations adds to other recent evidence that large scale flows deep in the solar convection zone are weaker than previously thought. It supports suggestions that numerical simulations more generally may have difficulty matching solar observations if they are required to carry all of the solar energy flux in the resolved modes (Featherstone 2014). Helioseismic observations (Hanasoge et al. 2010, 2012) yield estimates of flow velocities that are an order of magnitude or two below those found in either global (e.g. Miesch et al. 2008) or local area (Lord et al. 2014) sim-
Directions Forward

• Address systematics more fully

• Comprehensive single study of near-surface and deeper layers (e.g., Gizon & Birch 2004)

• Homogenization (wave propagation through spatio-temporally fluctuating medium)

• Alternate phenomenology? (e.g., Spruit 1997, Miesch et al. 2012, Lord et al. 2014)
SEISMIC WAVES

• Excited by near-surface granulation
• Sources are band-limited spatio-temporally stochastic processes
• Finite samples of stochastic process, correlations contain intrinsic noise
• Waves have finite sizes, infinite frequency asymptotics do not apply
What Is A Detection?

- The seismic wavefield is all stochastic, so there is only noise
- Distinguish correlated and uncorrelated noise (Gizon & Birch 2004)
- Correlated noise could be a convective structure