Helioseismic Constraints on Large-Scale Convection

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Convection at the surface

Granulation (1500 km) supersonic flows (8 km/s)

What about large-scale, interior convection? (solar radius = 700,000 km)

Typical supergranule (35000 km, 300 m/s horizontal velocity)

Solar convection parameters
Re ~ $10^{16}$  Ra ~ $10^{22}$  Pr ~ $10^{-6}$
Measurements: Wave travel times as proxies

HMI dopplergrams

900 billion wavefield measurements

~ 3 billion cross correlations

~ 5 million travel times

Sensitive to 3-flows

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

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

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
A variety of constraints

ASH at \( r/R = 0.97 \)

SG tracking (Hathaway, HMI)

Stagger (Stein and Nordlund simulations), \( r/R = 0.98 \)

Granulation tracking (MPS pipeline, HMI)

Seismology constraints at \( r/R = 0.96 \)

Arrow Miesch et al. 2012 phenomenology

Greer et al. (not shown) consistent with ASH

Figure from Hanasoge, Gizon & Sreenivasan (2015), Annual Reviews of Fluid Mechanics
**Convective flows are likely weak**

- Surface power is about 30 m/s at $l \sim 30$ (supergranulation tracking and Doppler)
- Convective flow magnitudes decrease with depth
- Granulation tracking at slightly higher $l$ also shows velocities (shallower measurement)
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) spectra of the simulations and observations. These separate lines of evidence all suggest that the Sun transports energy through the convection zone while maintaining very low amplitude large scale motions. Something is missing from our current theoretical understanding of solar convection below $\sim 10\text{Mm}$.

Numerical models are unable to reproduce the linear fall-off of convective power at low wavenumbers.
Implications for Thermal and Momentum Transport

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

• How is near-solid-body rotation sustained? i.e., how is angular momentum transported? Reynolds’ stresses not high enough? Meridional circulation? (Miesch et al. 2012)
What next

• Appreciating the relationship between the various constraints
• Better forward models (kernels)
• Greater attention to systematical biases (measurement and instrumental)
• Incorporate noise-covariance modeling
• Extend granulation tracking to lower $l$
ALL ABOUT THE PLUMES

• Not convection but magneto-convection?
• Magnetism stabilizes the plumes, increasing the effective Prandtl number
• Similar to high-Prandtl number Earth convection?

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Re $\sim 10^{16}$  Ra $\sim 10^{22}$  Pr $\sim 10^{-6}$