Convection in the Sun (mostly what I don’t know)

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based on

Hanasoge, S.M., Duvall, T.L. Jr. & Sreenivasan, K.R.
“Anomally Weak Solar Convection,”

Hanasoge, S.M. & Sreenivasan, K.R.

Hanasoge, S.M., Gizon, L. & Sreenivasan, K.R.
“Seismic sounding of convection in the Sun,”
The Sun

Temperature: at the base of convection ~ $2M$ K; at the surface ~ $6000K$
• Lab perspective: Every convective flow is characterized by unique values of Ra, Pr, Re, Ro, Ek, etc.
• But Solar convection is not---because fluid properties change drastically across the convection layer.
• Global Ra and Re (by taking geometric averages of fluid properties across convection depth) are
  \[ Ra = O(10^{22} \text{--} 10^{24}); \ Re = O(10^{12} \text{--} 10^{14}). \]
• Very vigorous convection with strong fluctuations may be expected: this may mean that the equation
  \[ O - I = N \]
  may be satisfied by \[ O = mN, \ m \gg I \text{ and } I = (m - I)N. \]
• If true, it has implications for the convective structure.
• But we don’t know if this is true.
A major effect of rotation is to increase the critical Rayleigh number (e.g., Cheng et al. 2015, Ecke & Niemela 2014).

For small Ek, as in solar convection, transition to fully turbulent state may occur only at very high Ra. The best estimate is not known; also whether the conditions of the theory hold for Sun.

Yet, for the Ra just estimated, the flow is likely to be turbulent.
Heat transport decreases with rotation but only modestly.

Differential rotation contours are oriented more radially than along the rotation axis (i.e., not Taylor-Proudman).

Intuition for convection at very low Pr and very large Ra is incompletely developed.

More vigorous convection occurs in the bulk.


liquid sodium: with K. Joshi, D. Lathrop

DNS: with R. Verzicco, G. Silano, and others: JFM, 662, 409, 2010
Phys. Fluids 17, 12170, 2005

Ra = $O(10^{22} - 10^{24})$
Pr = $O(10^{-6} - 10^{-3})$

Goldstein

DNS

liquid helium

liquid sodium

Missing!
Density stratification is immense, but the fluid is nearly a perfect gas in hydrostatic equilibrium, and convection is driven by small departures from that state.

But the assumption that the stratification effects can be accounted for entirely by subtracting the adiabatic gradient is almost certainly not true.
Numerical work

• Some (spectacular) large scale computer simulations exist; e.g., Miesch et al. 2008, Ghizaru et al. 2010, Käpylä et al. 2011, Hotta et al. 2014, Arnett et al. 2015.

• Large and extreme parameter regimes: using $L \sim 200$ Mm, one gets $\eta \sim 1 \text{ cm}$ ($\eta_0 \sim 30 \text{ m}$), etc., so that the length and time scale ratios $= O(10^8)$. Not amenable to direct numerical simulations.

• One set of fluid parameters assumed in ASH are: $\nu = 1.2 \times 10^{12} \text{ cm}^2/\text{s}$ (some 15 orders of magnitude larger), $\kappa = 4.8 \times 10^{12} \text{ cm}^2/\text{s}$ (some 12 orders of magnitude larger), $\text{Pr} = 0.25$ (some 3 orders of magnitude larger).

• Play ground for mixing length theories (e.g., Böhm-Vitense 1953, 1958) or its several extensions (e.g., Unni 1961, Gough 1967, Spruit 1977, etc)
Observational Helioseismology

• Sun is nearly opaque to electromagnetic radiation, but is transparent to acoustic waves (and neutrinos).

• Acoustic waves are excited by turbulent convection. The Sun acts as a resonator to a standing wave pattern and the surface continually resonates.

• How to know what happens inside the Sun by observing oscillations on the surface? An inverse method: not unique!
Normal modes of the Sun

Any flow breaks symmetry

$$\delta \tau = t_+ - t_-$$

$$\delta \tau \sim v_\theta \text{ or } v_\phi$$

Cross-correlations!

Any flow breaks symmetry
Some details

Deep-focusing geometry

Imaging the interior using measurements at the surface

$\frac{r}{R_\odot} = 1$

Imaging depth, $\frac{r}{R_\odot} = 0.96$

$\delta T \propto v_\theta$

$\delta T \propto v_\phi$

PNAS paper

Figure courtesy of L. Gizon
Gizon & Birch (2012): PNAS

“The work of Hanasoge et al. is perhaps the most notable helioseismology result since the launch of the Helioseismic and Magnetic Imager…”

Not included in this graph are the helioseismic results of Greer et al., which yield results closer to ASH. That two helioseismic results don’t agree with each other is quite worrisome and suggests that some additional work is needed.
Comments

- Weak Reynolds stresses are consistent with weak poleward meridional motions.
- Despite weak Reynolds stresses, the requisite heat transport is accomplished. That is, momentum transport might be small but not heat transport. This requires special types of large scale correlated motion; and so the convective motion in the Sun is likely to be quite different from standard convection.
- One view is that plumes (with sizes of the order of “supergranules”) descend all the way down to the tachocline, with little mixing despite entrainment (presumably because of high stratification, they get squeezed along the way (which renders them stable). (The complementary rising flow is thought to be diffuse.) See M. Rieutord & J.-P. Zahn, 1995. Each such view brings its own unanswered questions.
Summary

- “How turbulent” is the convective motion in the Sun is not entirely clear (despite high Ra). Nominally, the standard effects of turbulence should operate, but they get modified by the rotating and stratified environments.
- Rotation effects may be benign but not stratification effects (even in deep convection region, the density changes by two orders of magnitude or more).
- Our intuition for low Pr and high Ra convection from laboratory experiments is still inadequate (even allowing for differences in boundary conditions). Simulations still cannot reach the range of parameters.
- Thus, much of what we have learnt from experiment and simulations is helpful in stringing a plausible story, but the knowledge is still far from being causally quantitative (despite some terrific studies).
- One set of helioseismology data suggest that convection in the Sun must possess an unconventional structure---and this poses unanswered questions, e.g., the role of thermal plumes. Theories exist but there is need for more work.