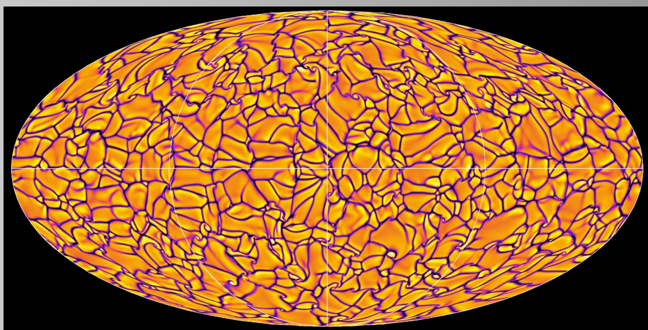
ASTR 7500: Solar & Stellar Magnetism

Hale CGEG Solar & Space Physics



Mark Miesch, Prof. Juri Toomre + HAO/NSO colleagues

Lecture 4 Thurs 31 Jan 2013

zeus.colorado.edu/astr7500-toomre

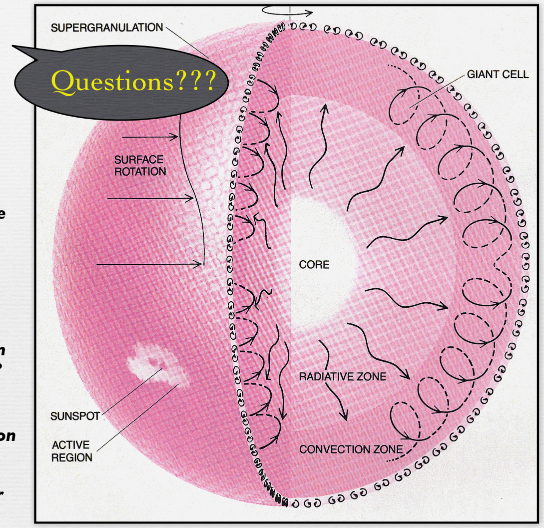
Where did we leave off?

Basic solar structure pretty well established

Outstanding challenges include microphysics/ composition** (equation of state, opacities) **and convection

Why is Convection such a challenge?

turbulence
boundary layers
density stratification
rotation
magnetism
radiative transfer



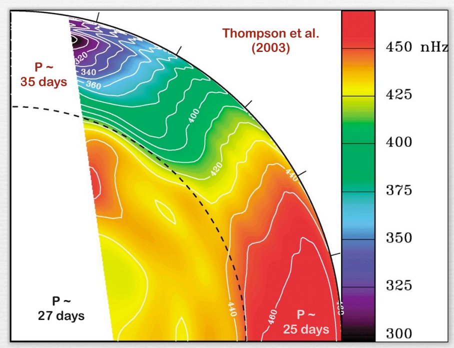
Why study convection?

Where are we going?

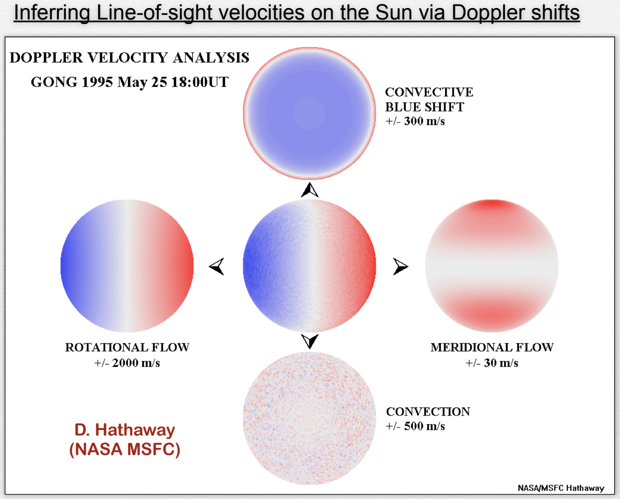
Today: applying fundamentals of convection to what actually occurs in the Sun

Angular momentum transport by global convection, in anticipation of next lecture on mean flows

(differential rotation & meridional circulation)

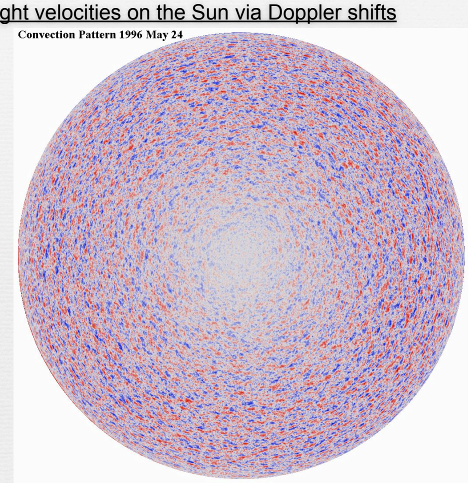


Inferring Line-of-sight velocities on the Sun via Doppler shifts



Inferring Line-of-sight velocities on the Sun via Doppler shifts

Most of what you see are horizontal velocities

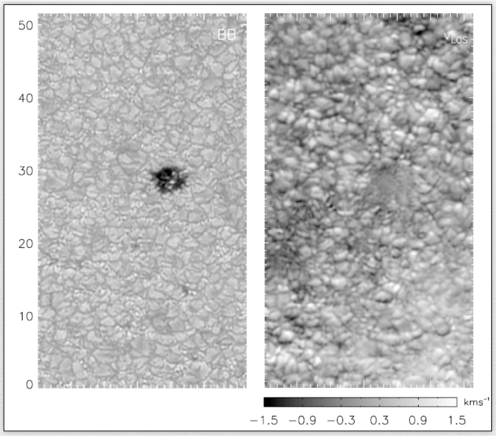


D. Hathaway (NASA MSFC)

Convection (granulation) in Dopplergrams

Can see vertical velocities if you look closely

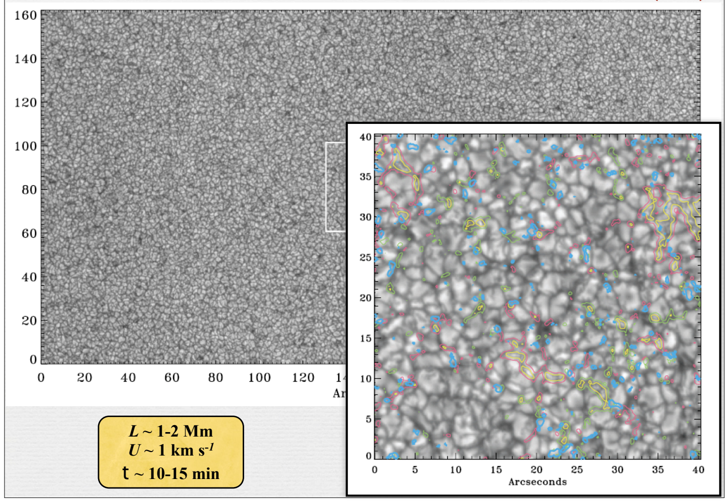
Telltale signature of thermal convection: warm (bright) upflows, cool (dark) downflows



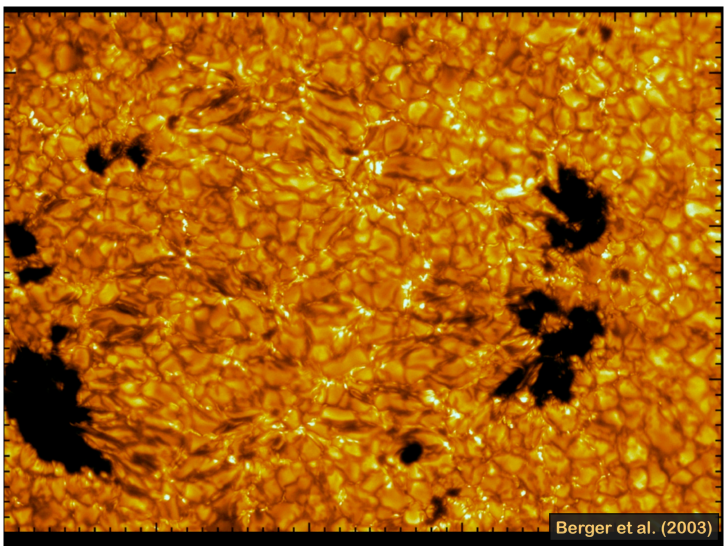
Bello Gonzalez & Kneer (2008)
Vacuum Tower Telescope, Tenerife, Canary Islands
Kiepenheuer-Institut für Sonnenphysik (Freiburg, Germany)
resolution ~ 150 km (0.2 arcsec) using adaptive optics

Granulation in the Quiet Sun

Lites et al (2008)



L ~ 1-2 Mm
U ~ 1 km s^{-1}
t ~ 10-15 min



Radiative MHD Simulations of Solar Granulation

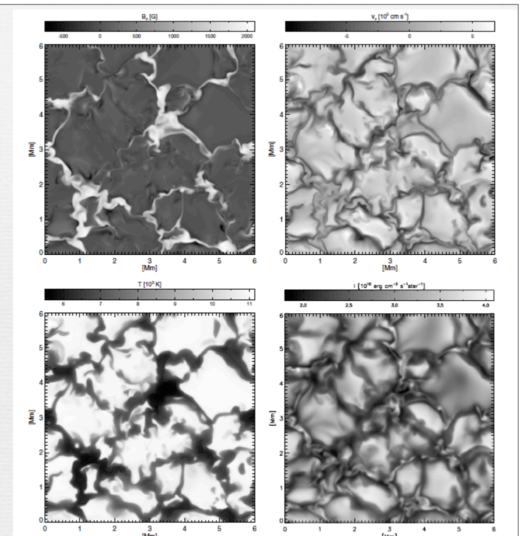
Upflows ***warm, bright***

Downflows ***cool, dark***

Vertical magnetic fields swept to downflow lanes by converging horizontal flows

Bright spots in downflow lanes attributed to magnetism

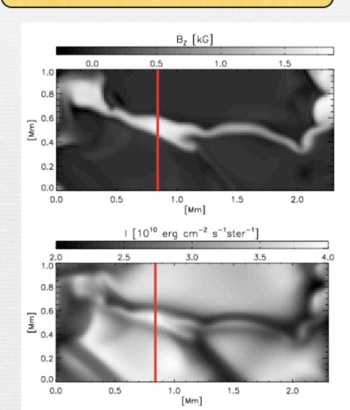
Vogler et al. (2005)

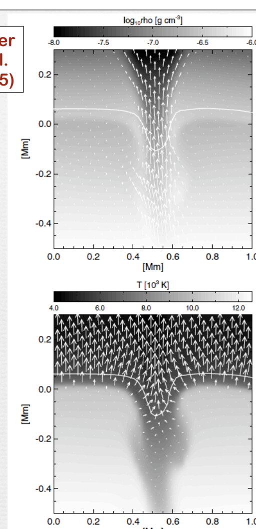


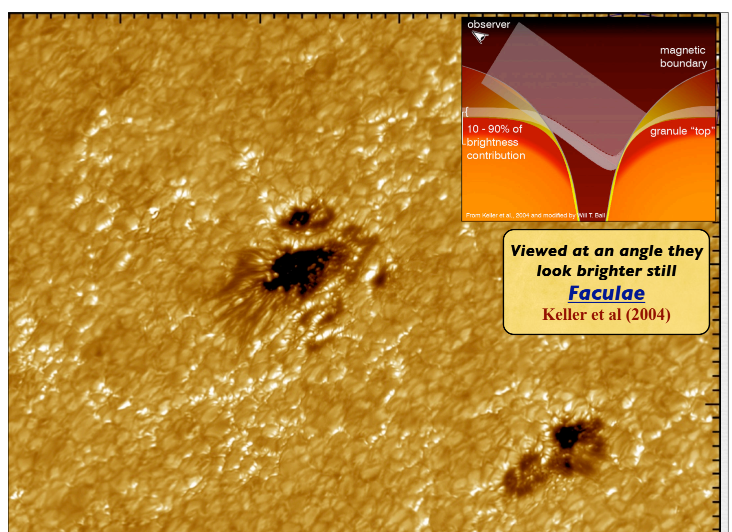
Cool doesn't necessarily mean dark

Channelling of radiation in magnetic flux concentrations ($B_z > 1$ kG)

Vogler et al. (2005)





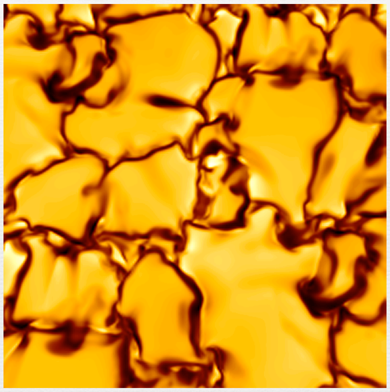


Viewed at an angle they look brighter still

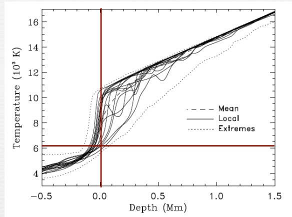
Faculae

Keller et al (2004)

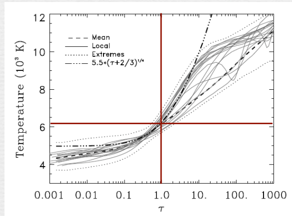
The Surface of the Sun is Corregated!



Carlsson et al. (2004)



Stein & Nordlund (1998)



Photosphere depressed in downflow lanes even without magnetism
Photospheric temperature variations relatively small

H⁻ opacity ~ T⁹

Scale Selection

Granulation is driven by strong radiative cooling in the photosphere

Downflows dominate buoyancy work

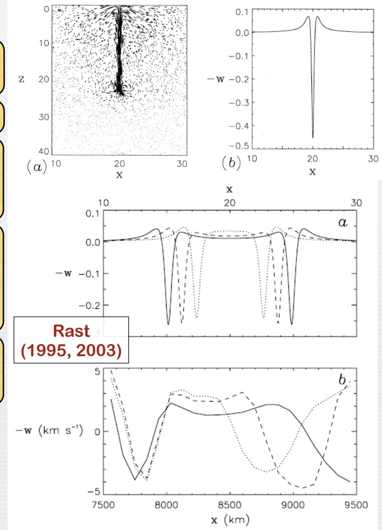
Upflows are largely a passive response induced by horizontal pressure gradients; peak velocities occur adjacent to downflows

When granules get too wide, radiative cooling overcomes the convective flux coming up from below, reversing the buoyancy driving in the center of the granule

Upflow becomes downflow and the granule bisects (exploding granules)

$$\rho v_z y N_A \chi_H \gtrsim \sigma T^4$$

$$L \sim D \frac{v_h}{v_z} \qquad v_h \lesssim c_s \qquad D \sim H_\rho$$



Rast (1995, 2003)

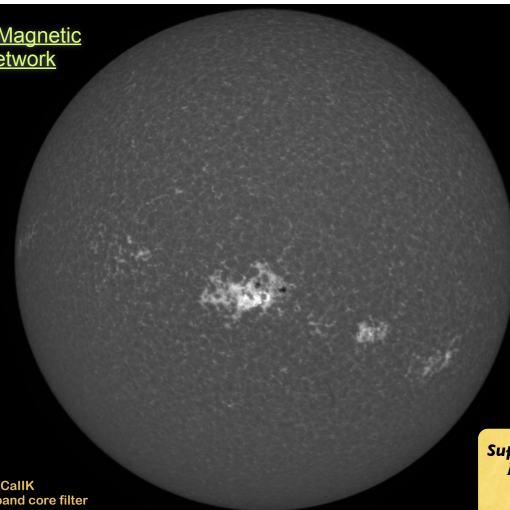
How is solar granulation modified by the rotation of the Sun?

...not much...timescale ~ 10-15 min
is much shorter that the solar rotation period ~ 28 days

implies high Rossby number

$$\mathrm{Ro} = \frac{\omega_{rms}}{2\Omega} \sim (4\pi)^{-1} \frac{P_{rot}}{\tau_c}$$

The Magnetic Network

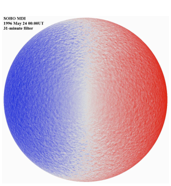


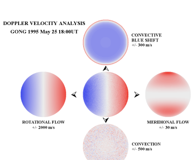
CaIIK
narrow-band core filter
PSPT/MLSO

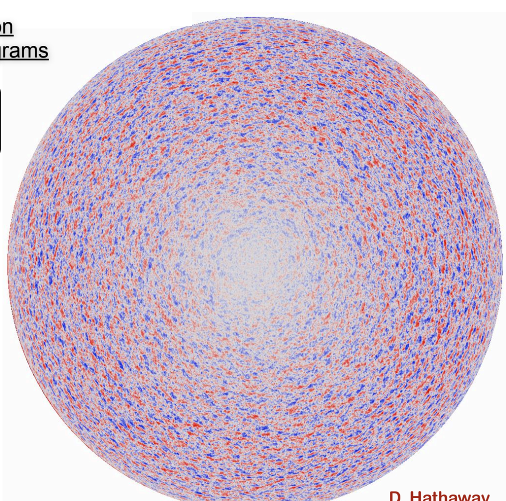
Supergranulation
$L \sim$ 30-35 Mm
$U \sim$ 500 m s⁻¹
t ~ 20 hr

Supergranulation in Filtered Dopplergrams

Most prominent in horizontal velocities near the limb







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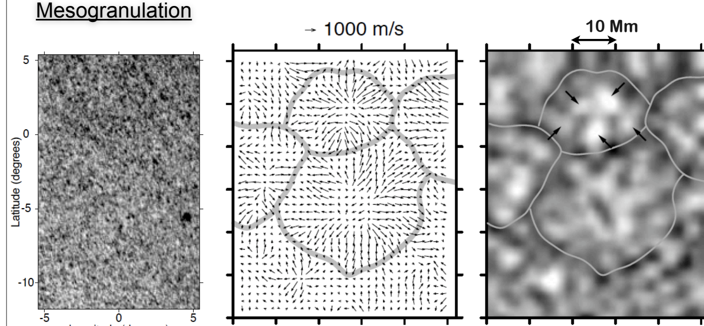
Mesogranulation



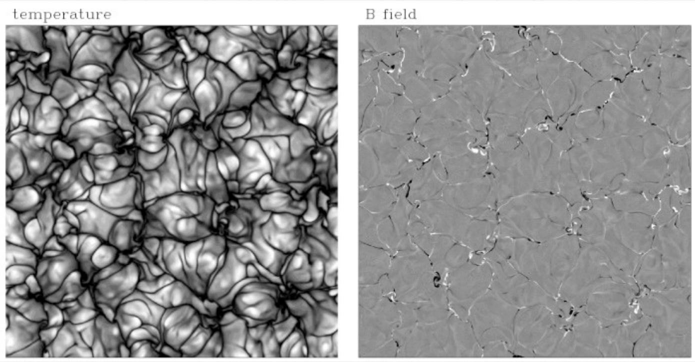
Shine, Simon & Hurlburt (2000)

Most readily seen in horizontal velocity divergence maps obtained from local correlation tracking (LCT)

Vertical velocity and temperature signatures of mesogranulation and supergranulation are still elusive hard to verify that they are convection per se

$L \sim$ 5 Mm
t ~ 3-4 hr

Self-Organization of convective plumes



Cattaneo, Lenz & Weiss (2001)

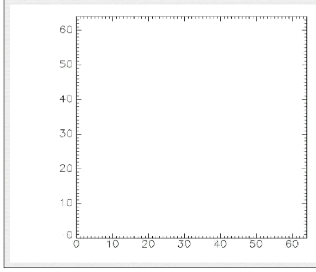
Convective plumes cluster on larger scales due to kinematic advection from the converging horizonal flows that feed them

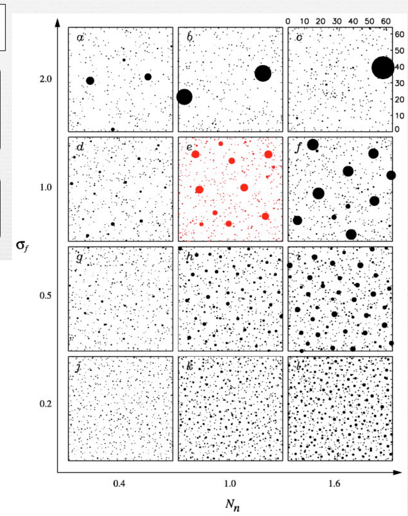
A toy model of interacting plumes

Rast (2003)

Granulation modeled as distributed points of horizontal convergence (representing downflow plumes) on a 2D surface

Kinematic advection and merging produces a larger-scale lattice of stronger convergence points





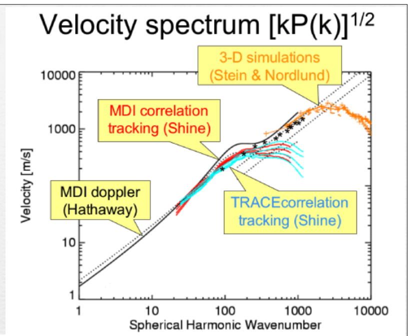
A hierarchy of convective scales

In the Sun, density and dynamical time scales increase with depth

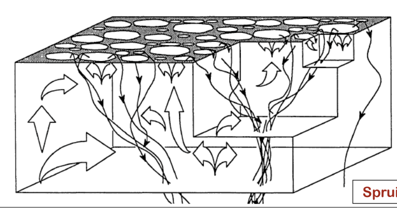
Most of the mass flowing upward does not make it to the photosphere

Downward plumes merge into superplumes that penetrate deeper

Deep-seated pressure variations drive surface flows



Nordlund, Stein & Asplund (2009)



Spruit, Nordlund & Title (1990)

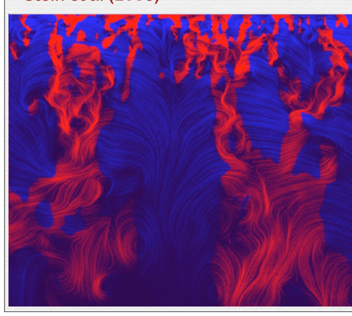
Supergranulation and mesogranulation are part of a continuous (self-similar?) spectrum of convective motions

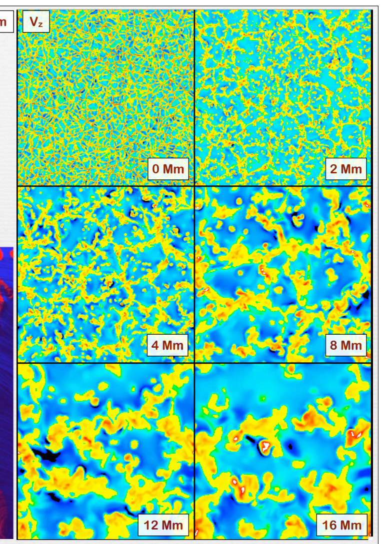
Bigger Boxes

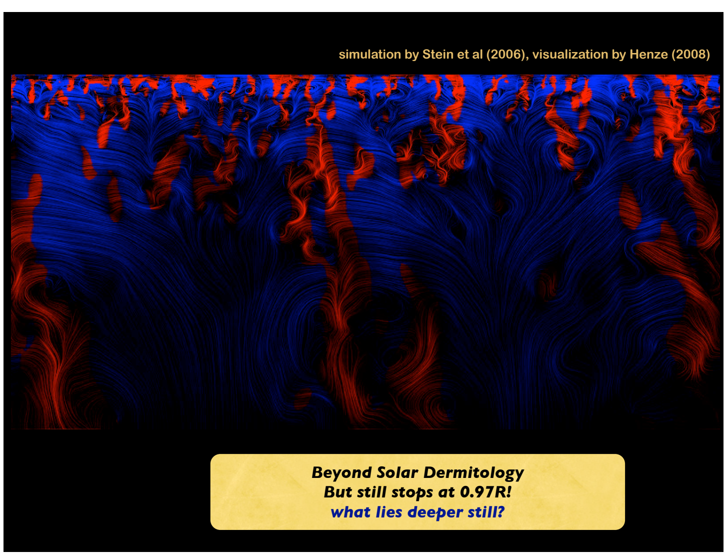
Latest local simulations are now achieving supergranular scales

Size, time scales of convection cells increases with depth

Stein et al (2006)





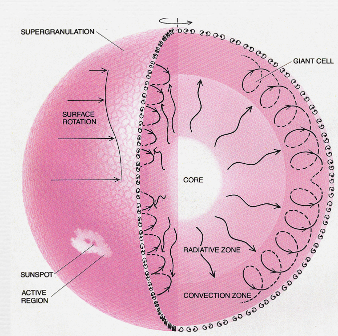


Beyond Solar Dermitology
But still stops at 0.97R!
what lies deeper still?

Eventually the heirarchy must culminate in motions large enough to sense the spherical geometry and rotation

Giant Cells!

How does surface convection influence giant cells?



Mass flux coming down from the granulation layer:

$$\dot{m} = 4\pi r_g^2 f \rho v_r \sim 4.3 \times 10^{21} \mathrm{g\ s}^{-1}$$

Implied Ventilation time for the CZ

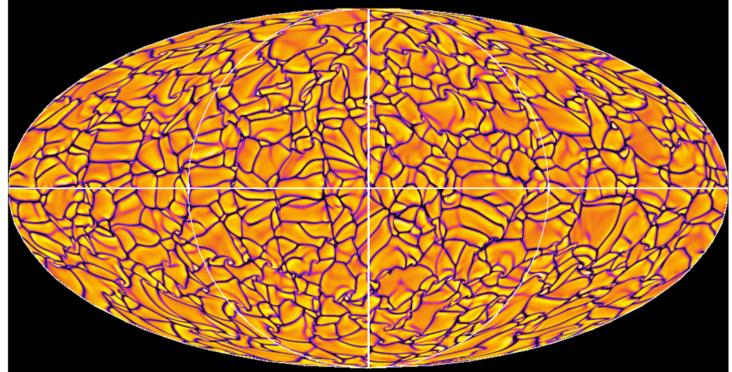
$$\tau \sim M_{CZ}/\dot{m} \sim 370 \text{ years!}$$

Global convection sustained by entropy variations that originate largely (but not entirely) in the surface layers

What should we expect giant cells to look like?

Giant Cells

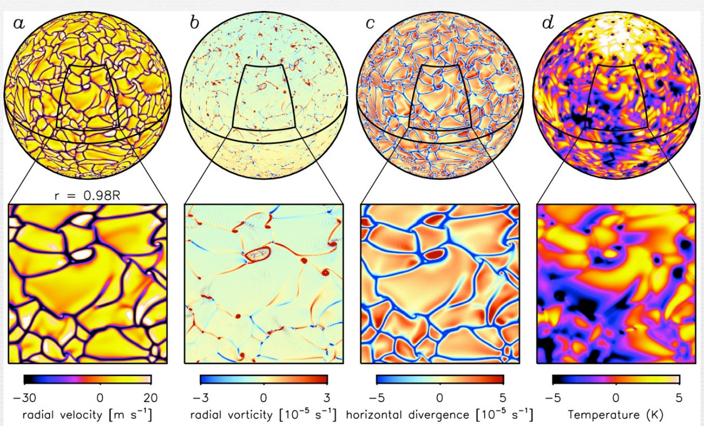
radial velocity, r = 0.98R



Miesch, Brun, DeRosa & Toomre (2008)

ASH

Granulation-like network of downflow lanes and plumes

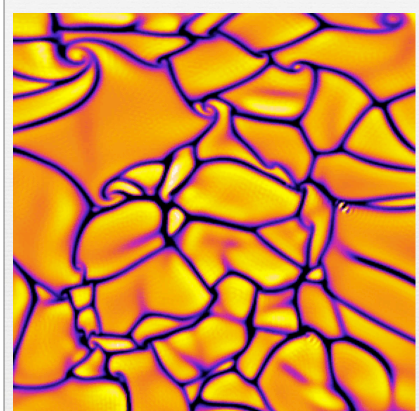


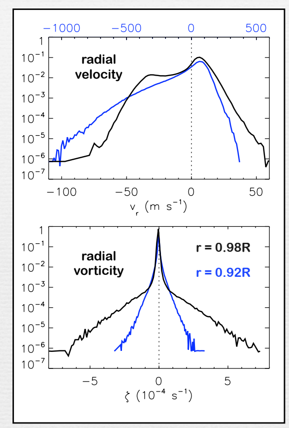
Cool, Helical Downflows

Solar Cyclones

w_r - D anticorrelation

Solar Cyclones are strong, helical, rapidly evolving and highly intermittent

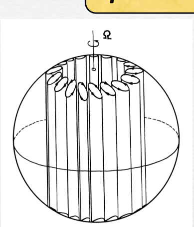




Cells bisect and fragment due to efficient cooling in the thermal boundary layer

Cyclones localized near the surface

Spherical Geometry: Thermal Rossby Waves



Potential Vorticity

$$Q = \frac{\omega_z + 2\Omega}{H\rho}$$

$$\frac{DQ}{Dt} = 0$$

anelastic, adiabatic motions, inviscid, non-magnetic, Ro << 1, $\boldsymbol{\Omega} \cdot \nabla \rho = 0$

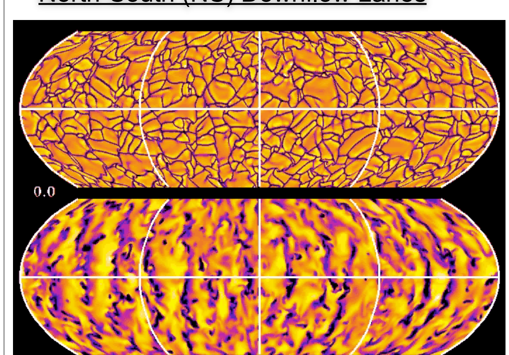
(Glatzmaier & Gilman 1981)

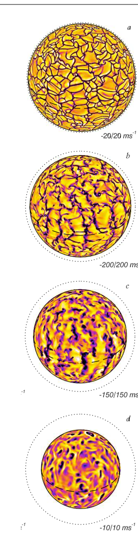
Can be driven either by the spherical curvature of the outer boundary or by the density stratification

Simplest example: Boussinesq fluid, centrifugal gravity, local, linear perturbations, small boundary curvature (Busse 2002)

$$v_p = \frac{4\Omega}{L} \frac{\tan\chi}{(1+P_r)(k_y^2+k_x^2)}$$

North-South (NS) Downflow Lanes

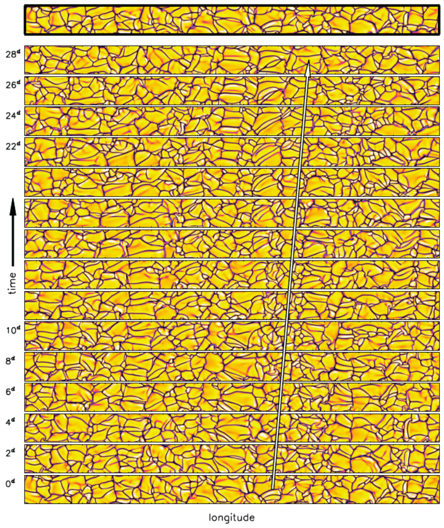


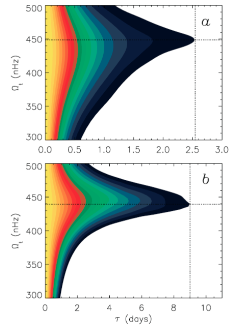


Prograde propagation: Traveling convection modes!

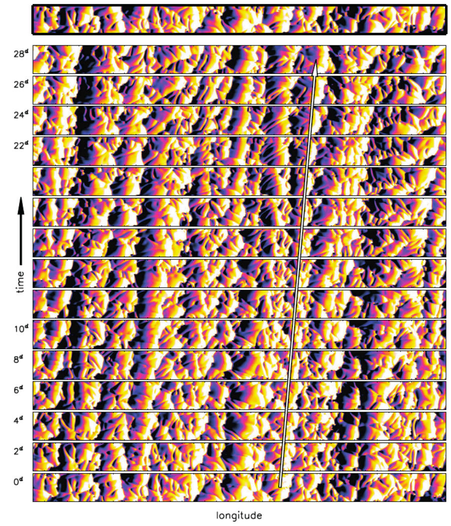
Coherence through most of the convection zone

Turbulent Transport: especially angular momentum!





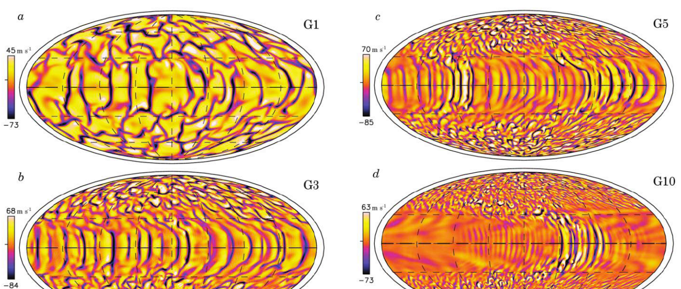
Miesch et al (2008)



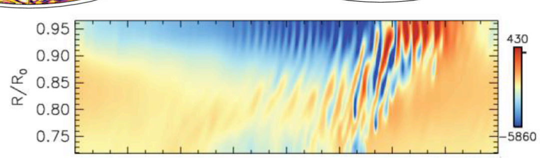
Easier to see converging horizontal flow that feeds the lanes

$$\frac{\partial v_\phi}{d\phi}$$

Modulated Convection at Faster Rotation Rates!



Brown et al (2008)



Summary: Solar Convection

- **Granulation**
  - Driven by radiative cooling in the photospheric boundary layer
  - Strong downflow plumes, lanes
  - Weaker upflows are a passive reponse

L ~ 1-2 Mm
U ~ 1 km s^{-1}
t ~ 10-15 min

- **Supergranulation and Mesogranulation**
  - Self-organization of granular plumes
  - Density stratification, plume interactions
  - Part of a continuous hierarchy (?)

L ~ 5 Mm
U ~ 300 m s^{-1}
t ~ 3-4 hrs

L ~ 30-35 Mm
U ~ 400 m s^{-1}
t ~ 20 hours

- **Giant Cells**
  - Strong downflow lanes & plumes, weaker upflows
  - Propagating NS downflow lanes at low latitudes
  - Solar cyclones at high latitudes (helicity)
  - Modulated convection at high rotation rates

L ~ 100 Mm
U ~ 100 m s^{-1}
t ~ days - months

NCAR

CU, Jan, 2012

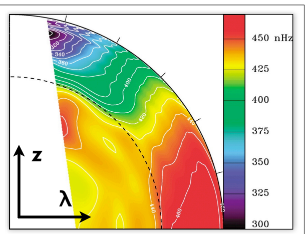
Reynolds Stress

Angular momentum per unit mass

$$\mathcal{L}^* = \lambda v_\phi$$

Average over longitude

$$\mathcal{L} = \langle \lambda v_\phi \rangle$$



Conservation of momentum

$$\frac{\partial}{\partial t}(\rho \mathcal{L}^*) = -\nabla \cdot (\rho \mathbf{v} \mathcal{L}^*) - \frac{1}{r\sin\theta}\frac{\partial P}{\partial \phi}$$

Now average over longitude and write it as follows

$$\mathcal{F}_{mc} = \langle \rho \mathbf{v}_m \rangle \mathcal{L}$$

$$\frac{\partial}{\partial t}(\rho \mathcal{L}) = -\nabla \cdot (\mathcal{F}_{mc} + \mathcal{F}_{rs})$$

Reynolds stress

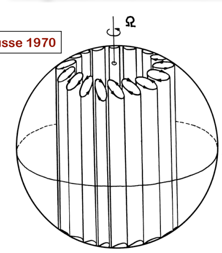
$$\mathcal{F}_{rs} = \langle \rho \lambda \mathbf{v}'_m v'_\phi \rangle$$

Conservation of angular momentum

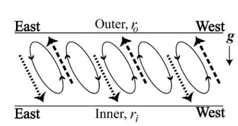
Angular Momentum Transport

Coriolis-induced tilting of convective structures

Busse 1970



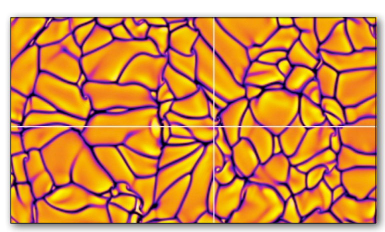
Ro << 1



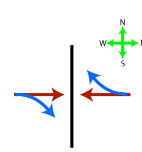
Aurnou et al 2007

$$\langle v'_\lambda v'_\phi \rangle > 0$$

angular momentum transport away from the rotation axis



Ro ~ 1



$$\langle v'_\theta v'_\phi \rangle > 0$$

(NH)

angular momentum transport toward the equator