Active regions as sites of enhanced surface cooling.

Irradiance variation due to a surface effect:

A Enhanced / reduced emissivity
faculae, network — spots

as opposed to:

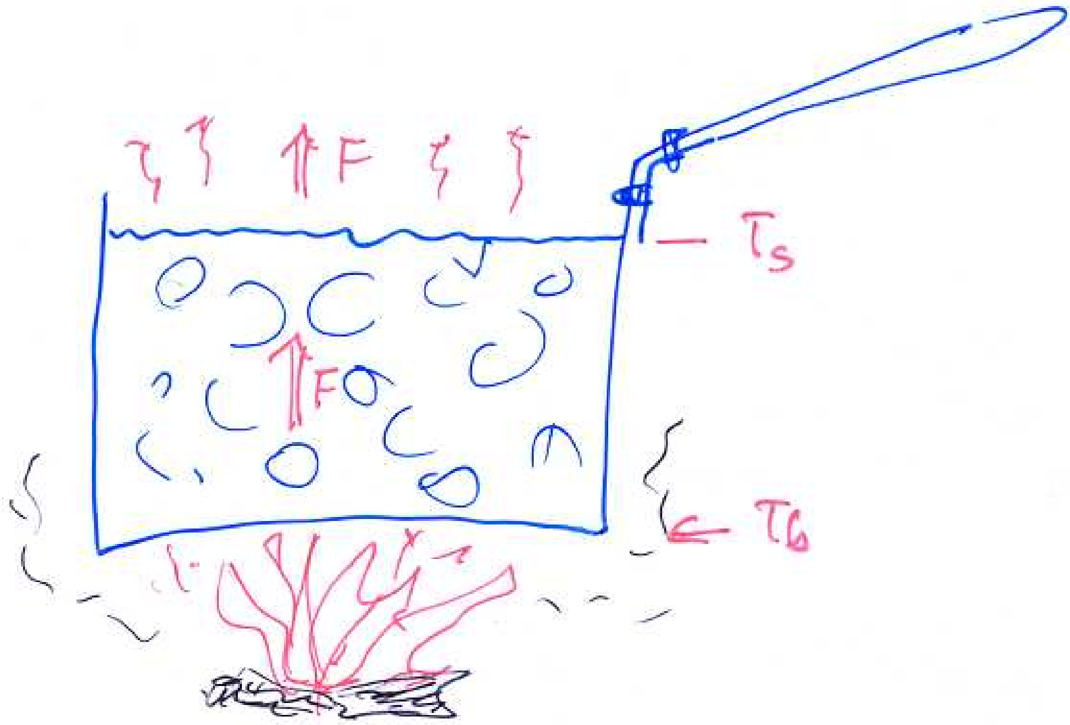
B Enhanced / reduced heating from below

- What's the difference A ↔ B ?
- Observational evidence (classical)
- Evidence from helioseismology
- Further tests: large scale flows
- Theoretical evidence.

Summary.

- Emissivity changes due to surface magnetic fields explain > 80% of irradiance variation. PSPT: 86%
- For remaining < 20% no plausible "deep seated" mechanism known.
- Increasingly tight obs. constraints on deep-seated sources.
- Importance of large scale flows as diagnostic.

Solar convection: the stove-top-analogy.



More heating below → more heat flux at top

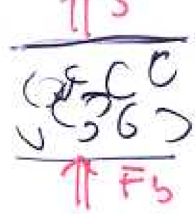
☉ : - Heated from inside
? → Higher surface flux → more heat from below. ?
wrong: → need higher temperatures (T_b) below.

1. Is higher T_b necessary? (No)

2. Is it likely? (No)

Heating from below vs cooling @ top:
kitchen vs. ☉

In stationary state: $F_b = F_s$



In heating phase: $F_b > F_s$

cooling phase kitchen: $F_b = 0$, $F_s \neq 0$ ($\tau_{cool} \sim$ minutes)

☉: $\tau_{cool} = E_{thermal} / L_{☉} = 3 \cdot 10^5$ yrs

: - very high density & temperature

⟹

1. changing surface temperature
   - requires huge amounts of energy
   - is slow

(slide!) 2. Convective flows driven by cooling @ surface, not heating from below.

$F_{☉} \rightarrow (\Delta\rho/\rho)_s \sim 0.3$

$(\Delta\rho/\rho)_b \sim 10^{-6}$

Higher temperatures from below (ctd')

1. Necessary ?

$$F = \sigma T_s^4$$

but:

Only for black body surface s

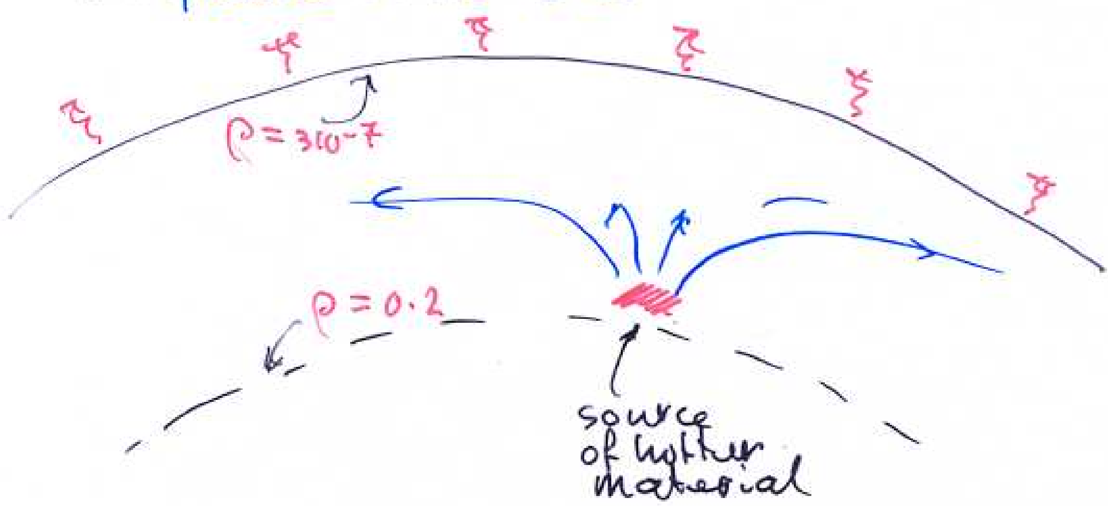
$$F = f \sigma T(z_s(\psi, B \cdots))$$

$f < 1$ — not isotropic limbdarkening

↑ dependence on magnetic structures

2. Likely ?

- (theory) what kind of sources? (cycle @ base)
- observations : close correlation with magnetic structures



* Obs. evidence > 80% of irradiance var. due to small scale B-field

  - Perhaps more (indicators / decomposition not perfect)

  - Remaining < 20% : No good physical ideas

    (↔ Kuhn, Sofia, Demarque, Schatten, Walton ....)

  - Why bother about remaining 20% ?

    A: Could be different in past / future

  - Theory : Unlikely to be "deep seated sources"

    - - - - - - - -

  - More observational constraints : helioseismology.

    * ΔT below surface from time-distance

    * $\frac{\Delta\Omega}{\Omega}$ from cycle variation ν's.

Limits on $\frac{\Delta R}{R}$ → limit on $\frac{\Delta T}{T}$

* On timescales $\gtrsim$ 1 day: ☉ in perfect hydrostatic equilibrium.

  ↓

  expansion when T ↑.

* MDI images (Scherrer): $\lesssim$ 7 mas $\triangleq$ 10^{-5}

* Mode frequency shifts: ⇒ $\frac{\Delta R}{R} \lesssim 3\,10^{-6}$ (Antia 2003)

quantitative:

If $\Delta T/T$ cst with depth:

$$\frac{\Delta R}{R} \simeq 0.1 \frac{\Delta T}{T}$$

$$\Rightarrow \quad \frac{\Delta F}{F} \simeq 4 \frac{\Delta T}{T} \simeq 40 \frac{\Delta R}{R}$$

⇒ Scherrer : $\frac{\Delta F}{F} \lesssim 4\,10^{-4}$

Antia : $\lesssim 10^{-4}$

Potential for spatially resolved tests of subsurface ΔT with time-distance helioseismology:

Higher T : sound speed ↑ → ν ↑
$c_s \sim T^{1/2}$ Δt ↓

expansion of strat. → ν ↓
$\Delta z \sim T$ Δt ↑

For $\frac{\Delta R}{R}$: expansion effect dominates.

AR-size structures : depends on ray path.

(Brüggen & Spruit Sol Phys.)

((Not taken into account in current time-distance inversions !

Enhanced emission from surface structures

* How does it work ?
* Consequences: cooling

Dark structures (pores, spots) : (easy)

Interference of $\vec{B}$ with convection.

Theory (.......) : no bright rings.
Observations : $\lesssim 10\%$
(⇔ Rast, Kuhn ......)

Bright structures (faculae, pores-near-the-limb)

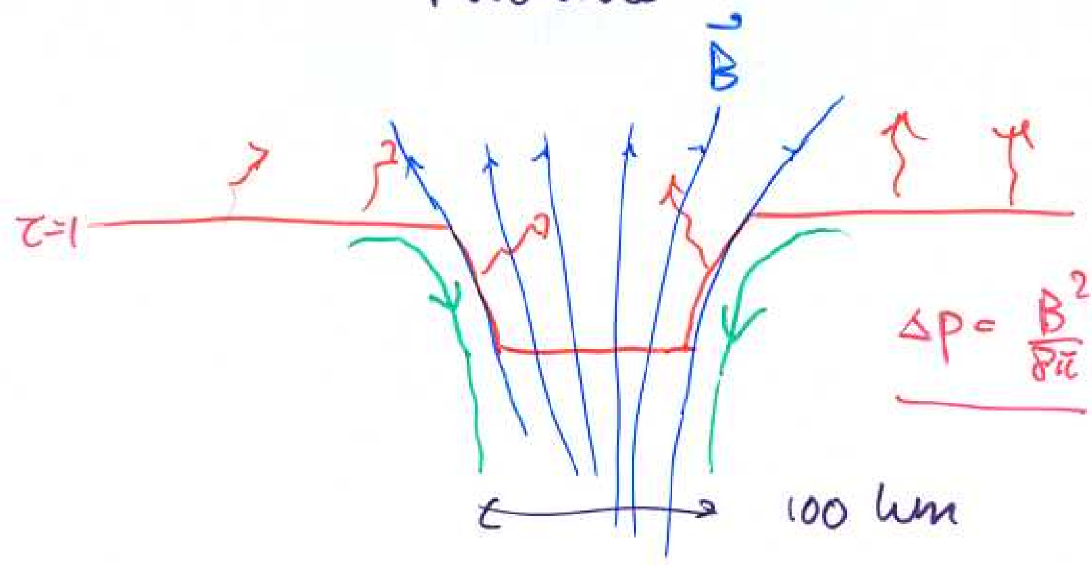
Radiative transfer :

1. More isotropic emission
2. More transparent atmosphere

$$F_s = f \sigma T^4$$ $f < 1$: non-black

structures : higher (f) higher (T) (transparency)

Faculae

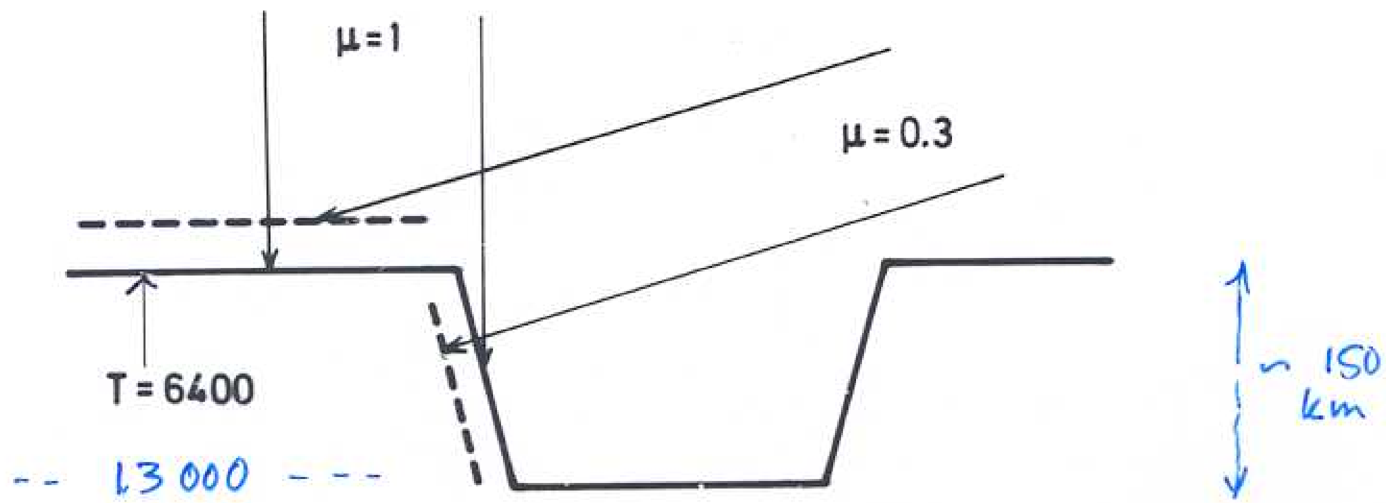


Enhanced emission from small scale field (Spruit '77)

Numerical flow simulations:
Schüßler et al. 1986 – 1997.
Keller et. al. 2004
Steiner 2004

Explains:
- Why facular brightness peaks near solar limb (emission more isotropic than normal ⊙-surface)

"Bright-wall-effect"



Enhanced surface emission: consequences

- Increased emission in AR →

⇒ increased cooling

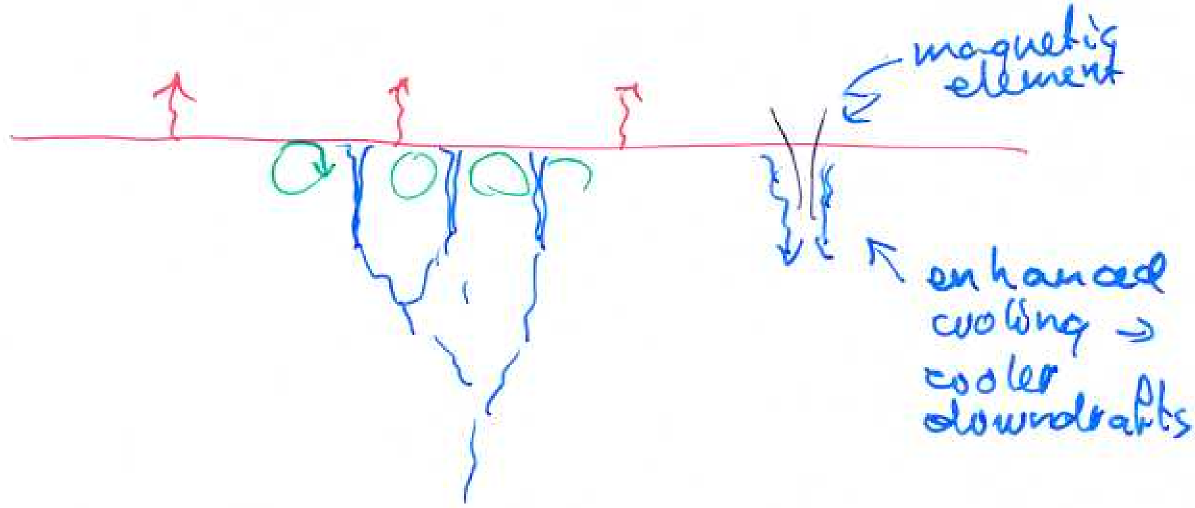
⇒ lower T below surface ....

1. * In principle detectable with time-distance helioseismology

$\langle \Delta F/F \rangle \sim 10^{-3} \rightarrow \langle \Delta T/T \rangle \simeq -10^{-3}$

2. * Causes large-scale flows associated with AR.

Cooling at surface → lower temperatures below an AR



Amplitude of effect ?

$(\Delta I)_{tube} \sim 0.1 - 0.3$

filling factor : $f \sim 0.01$

↓

$\frac{\Delta T}{T} \sim -10^{-3}$

Vertical hydrostatic balance →

$$\frac{\Delta P}{P} = \frac{\Delta T}{T} n$$

↑ no of scale heights, $n = \ln \frac{P_1}{P_0}$

→ $\frac{\Delta P}{P} \sim$ few $\times 10^{-3}$

⇒ AR is a low-pressure system

Geostrophic flows.

Examples : - weather systems
- ocean circulations

slowly changing flows in a rotating system :

$$0 = -\nabla p + 2 v \times \Omega + \rho \vec{g}$$

Horizontal components :

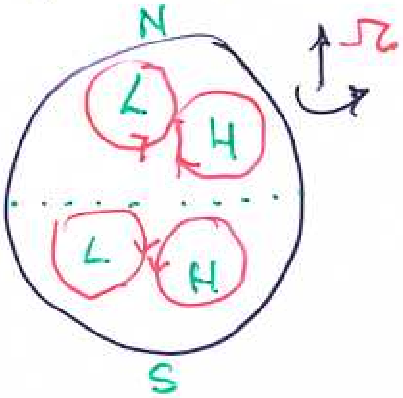
$$0 = -\nabla_h p + 2(v \times \Omega)_h$$

At pole : $\Omega = \Omega \hat{z}$

$$0 = -\partial_x p + 2 v_y \Omega$$
$$0 = -\partial_y p - 2 v_x \Omega$$

$\rightarrow$ $\underline{v_h \perp \nabla_h p}$; $|v| \sim \frac{\Delta p}{L \Omega}$

Low pressure system $\rightarrow$ cyclonic flow
High " " anticyclonic flow.

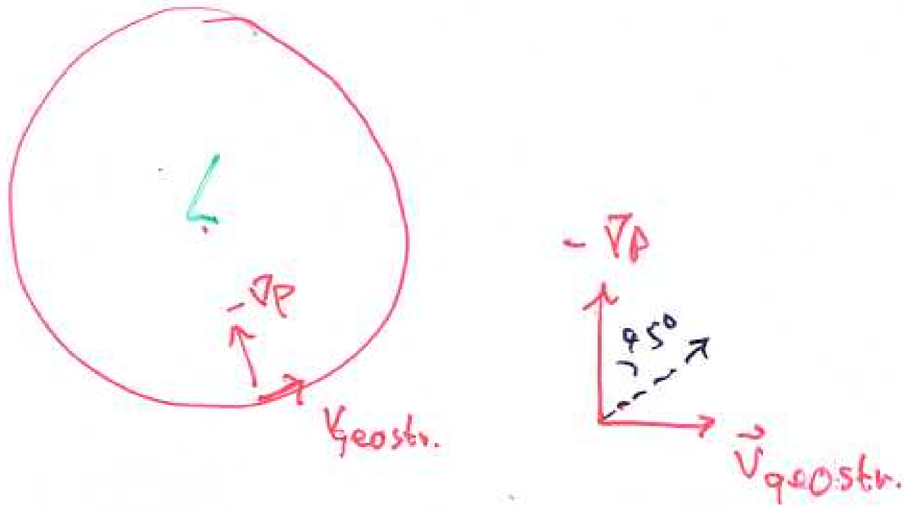


Ekman layer.

Flows are not exactly geostropic:

at boundary : an Ekman layer

$$0 = -\nabla p + \rho 2 v \times \Omega + \rho \nu \nabla^2 v$$



Ekman layer thickness

$L_E = (\nu/\Omega)^{1/2} \sim 10^9$ cm

width of active latitude belt $\sim 3\,10^{10} \gg L_E$

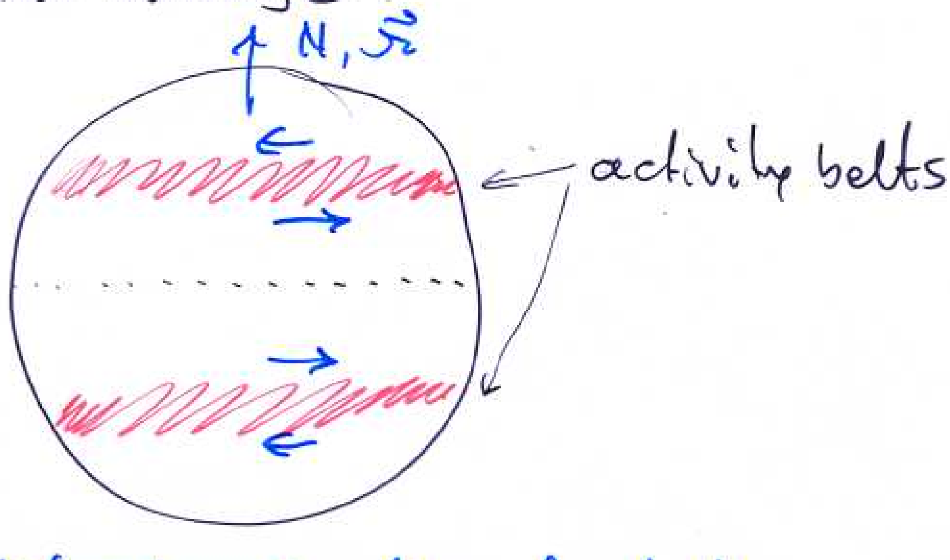
→ Prediction :

Enhanced cooling causes

- cyclonic flow ~ 5 ms^{-1} around
+
- flow into AR ~ 5 ms^{-1}.

- declining with depth.

Azimuthal average :



- Flow in direction of rotation on equator-side
- opposite rotation on pole-ward side

⇒ "torsional oscillation"
(HCS, 2003, Sol. Phys 213, 1)

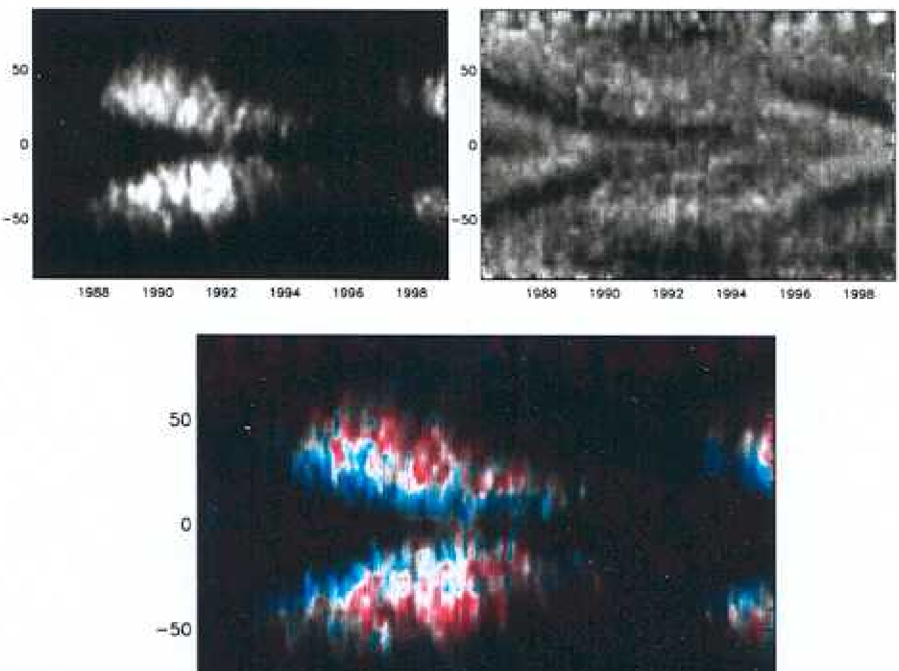


Figure 1. Top panels: synoptic maps of the absolute value of the magnetic field (left) and azimuthal velocity residual (right) measured at Mt. Wilson Observatory (Ulrich, 2001). Bottom panel: composite map in which the absolute value of the magnetic field is shown in intensity and deviations in rotation velocity in color, with blue (red) for faster (slower) rotation than the mean. Color saturation codes for the velocity amplitude. Data have been averaged over 3 rotations.

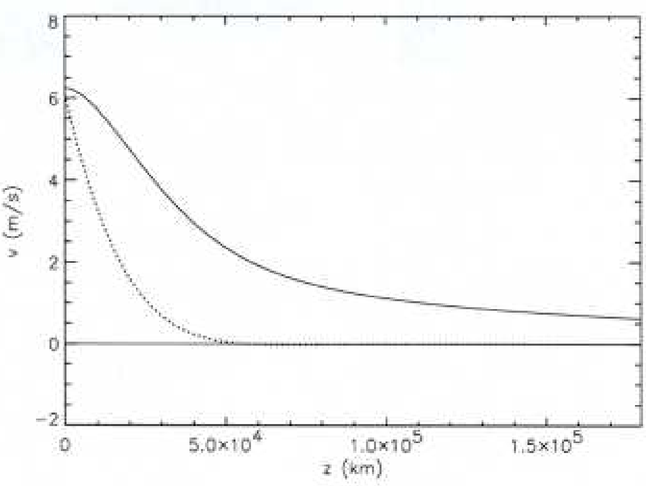


Figure 2. Depth dependence of the Ekman flow. Solid: azimuthal (zonal) component, broken: latitudinal component.

The velocity pattern produced by the model is in agreement with the observation that the flow is concentrated at the *boundaries* of the main activity belt (see Fig. 1). The *sign* of the flow agrees, provided we accept that the small flux elements in an active region acts as 'leaks' by which an enhanced heat flux passes through the surface, as discussed in section **??**. The consequence of this leak is additional *cooling* below the surface in active regions, the opposite of what would be the case if they were heated from below.

The model makes a few testable predictions.

5.1. PREDICTIONS

5.1.1. *Meridional component of the Ekman flow*

A generic feature of an Ekman spiral is the direction of the flow at the surface, which is at an angle of nearly 45° to the direction of the driving force. In our application, this means that there must be a flow directed from the edges towards the center of the main activity belt. Its amplitude must the same as that of the torsional oscillation. This feature has, in fact, been observed (Komm, Howard and Harvey 1993, Komm 1994). From data obtained at Kitt Peak these authors find a pattern of meridional flow in just this sense, directed towards the center of the active latitude zone at an amplitude of about 5 m/s.

Large scale temperature inhomogeneities lasting > months must have large scale flows

- more easily detectable than the ΔT itself

- Average effect identifiable with "torsional oscillation" pattern

(- "Heating from below" would have flow of wrong sign !)

- Right amplitude

- Right depth dependence

Evolution of thermal disturbances.

$\vec{F}_c = - \kappa \rho T \vec{\nabla} S$ convective heat flux

$\kappa \sim \frac{1}{3} \ell v$

$\rho T \frac{\partial S}{\partial t} = - \mathrm{div}\, \vec{F} = \mathrm{div}(\kappa \rho T \nabla S)$

1st law thermod.

$\partial_t S = \frac{F}{\rho T H} + \kappa \partial_{zz} S$

thermal timescale

diffusive time scales

$\odot$: $t_{Th} = \frac{U_{th}}{L} \sim 10^5$ yr

$t_D = \frac{D^2}{\kappa} \lesssim 1$ yr

→ convection zone is "superconductor" for thermal (entropy) disturbances

Enhanced emission @ surface by magnetic structures: an analogy

Metal sphere (Al) heat from inside

① "Looking deeper"