Improving our knowledge of the Near Subsurface Shear Layer: the special case of the leptocline

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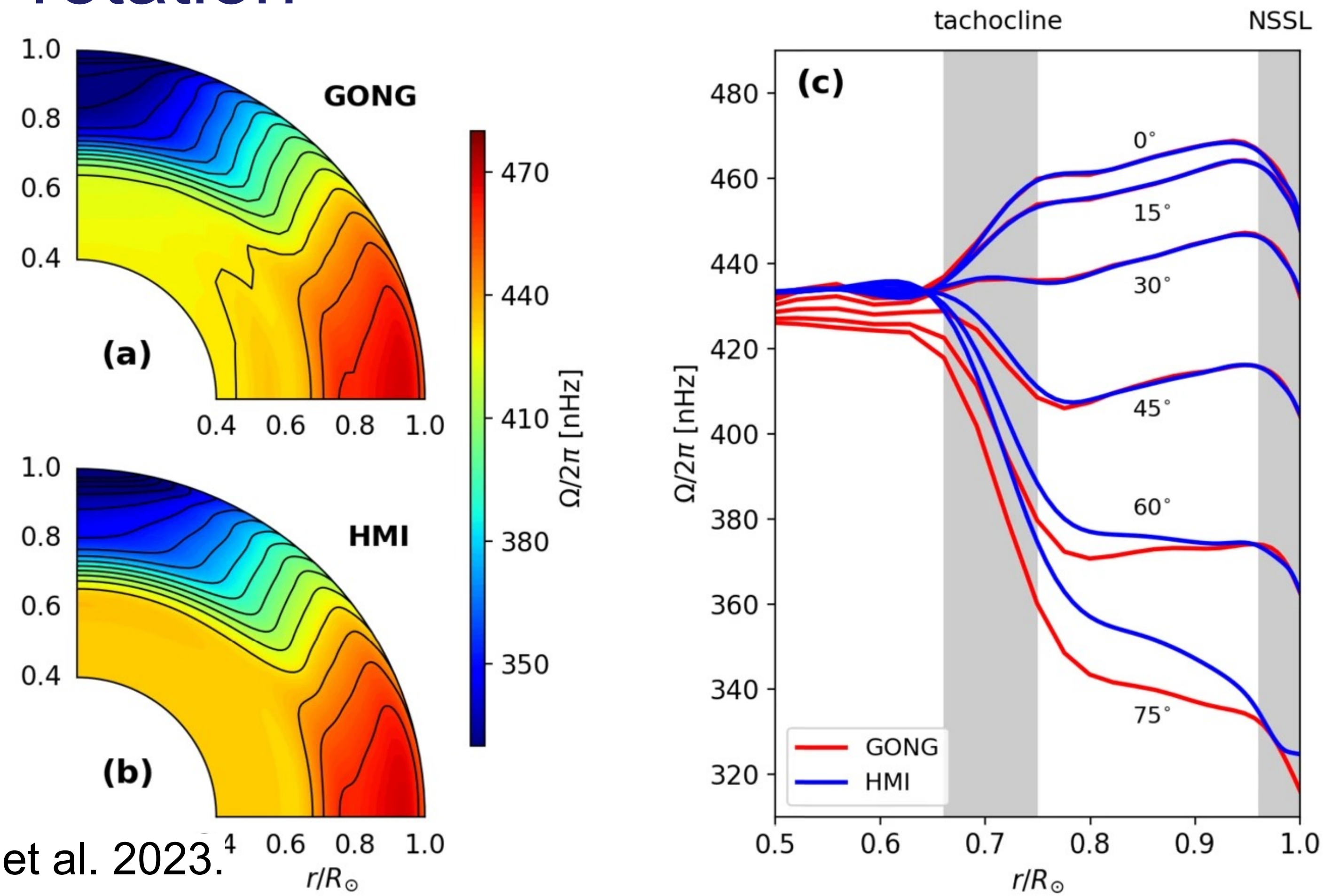
IAU-GA, Focus meeting 8, 13-14 August 2024

Solar rotation



Hotta et al. 2023.

Internal profile of the solar differential rotation deduced from global helioseismology and averaged from April 2010 to February 2021. Panels (a) and (b) show the results obtained by the Global Oscillation Network Group (GONG) and the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO). Panel (c) shows the radial differential rotation at selected latitudes. Grey shades denote the layers of strong radial rotational shear known as the tachocline and the near-surface shear layer (NSSL);

Solar rotation

Main points:

- The radiative interior rotates almost rigidly.
- In the convection zone, the equator rotates about 30% faster than the poles.
- The transition from uniformly-rotating radiation zone to differentially-rotating convection zone occurs in a thin layer from 0.68 $R_\odot$ to 0.73 $R_\odot$. This layer is called the **tachocline.**
- In the bulk of the convection zone (0.73 $R_\odot < r <$ 0.96 $R_\odot$), the rotation rate varies strongly with latitude.
- In a shallow layer > 0.96 $R_\odot$ up to 1 $R_\odot$, the rotation rate decreases by about 5% at all latitudes.
  This layer is called the **Near Subsurface Shear Layer (NSSL)**
- A substructure of NSSL, so-called **leptocline**, covers about 5% of the convection zone.
- The contours of constant angular velocity are inclined by about 25° with respect to the rotational axis over a wide range of latitudes, i.e. rotation does not follow the Taylor-Proudman theorem.
- Within the leptocline: a complex behavior of the variation of the radial gradient $\partial \log \Omega / \partial \log r$, in latitude and in time.

Solar rotation: Key points

- Coupling of large-scale flows are crucial for maintaining the Sun’s global magnetic field.
- How rotational affected by subsurface magnetic fields ?
- What is the influence of magnetic fields on acoustic waves excitation and propagation?
- Theories about formation, subsurface structure, thermal properties and topology of active regions are still controversial.

→ The growth of supercomputers enabled better simulations.

Historically speaking,

The «leptocline» has been evidenced since 1999 *(Armstrong and Kuhn, ApJ, 525):*

Solar limb shape variations

$$s(r,\theta) = r\left[1 + s_2(r)P_2(cos\theta) + s_4(r)P_4(cos\theta) + s_6(r)P_6(cos\theta) + (...)\right]$$

The s_n functions (**shape parameters or asphericity coefficients)** are determined for a given rotation velocity ω and density profile $\rho(r)$.

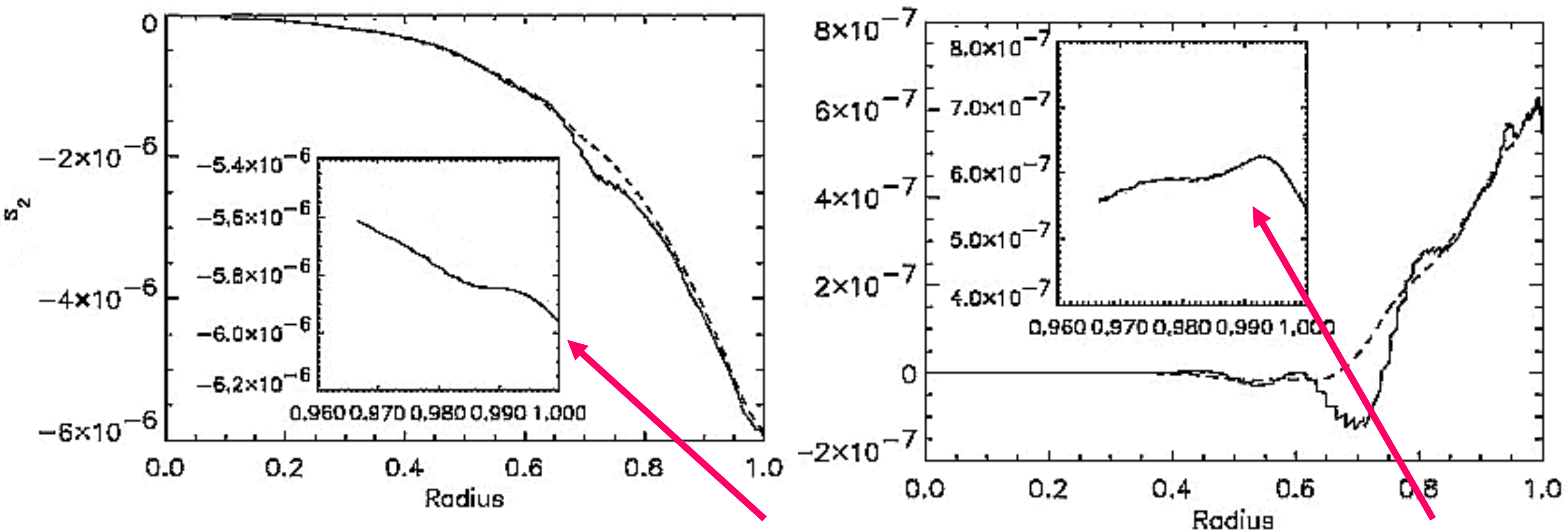
Taking a rotation law of the form:

$$w(\theta) = A + B\sin^2(\theta) \quad [+ C \sin^4(\theta)]$$

→ s_2 *and* s_4

Solar limb variations

- Solar shape:



Near Sub-surface Layer, called «**leptocline**»
(not really recognized as such at the time)

→ By analogy to **the tachocline**, greek "tachos" = speed

leptocline: "leptos" = thin and "klinô" = slope.

Godier & Rozelot, Sol Phys, 199 (2001)

Solar radius

From MDI (SoHO) and HMI (SDO):

«conventional» helioseismological inversions lead to a resolution of the so-called «seismic» solar radius.

$$\frac{\delta \nu_{n,l}}{\nu_{n,l}} = \int K^{(n,l)}_{\psi,\rho} \; f(\psi, G, \rho, x) \; \mathrm{d}x + S_{n,l}$$

relative frequency variations

seismic radius relative variations

surface term

variations

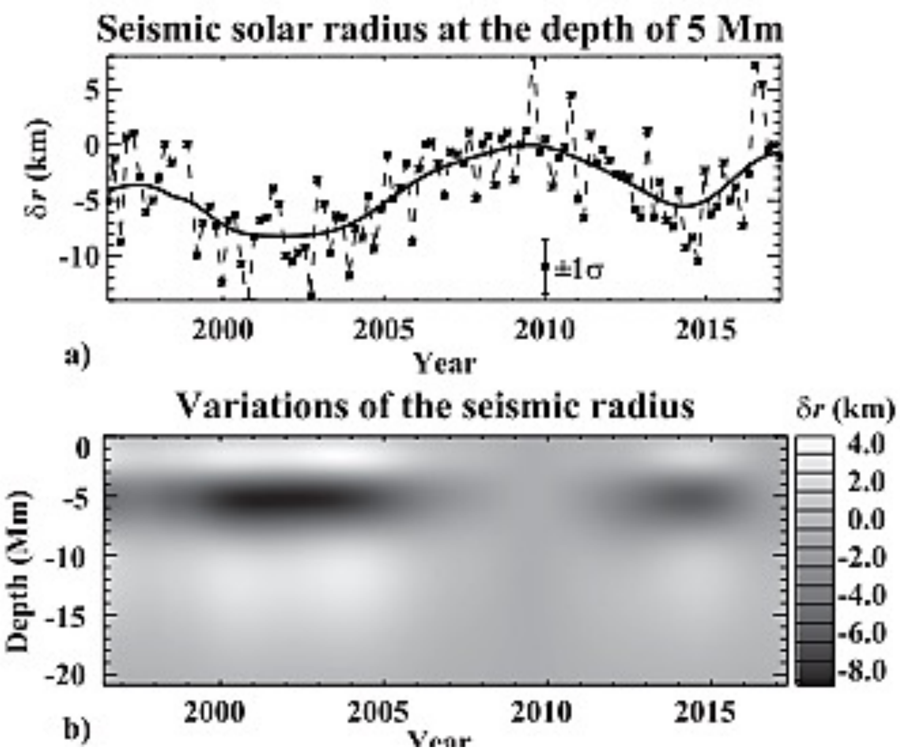
(data kernels)

x is the fractional radius r / R , where R is a fiducial radius

→ The surface term, S_n introduced to take account of uncertainties in the near-surface regions of the Sun

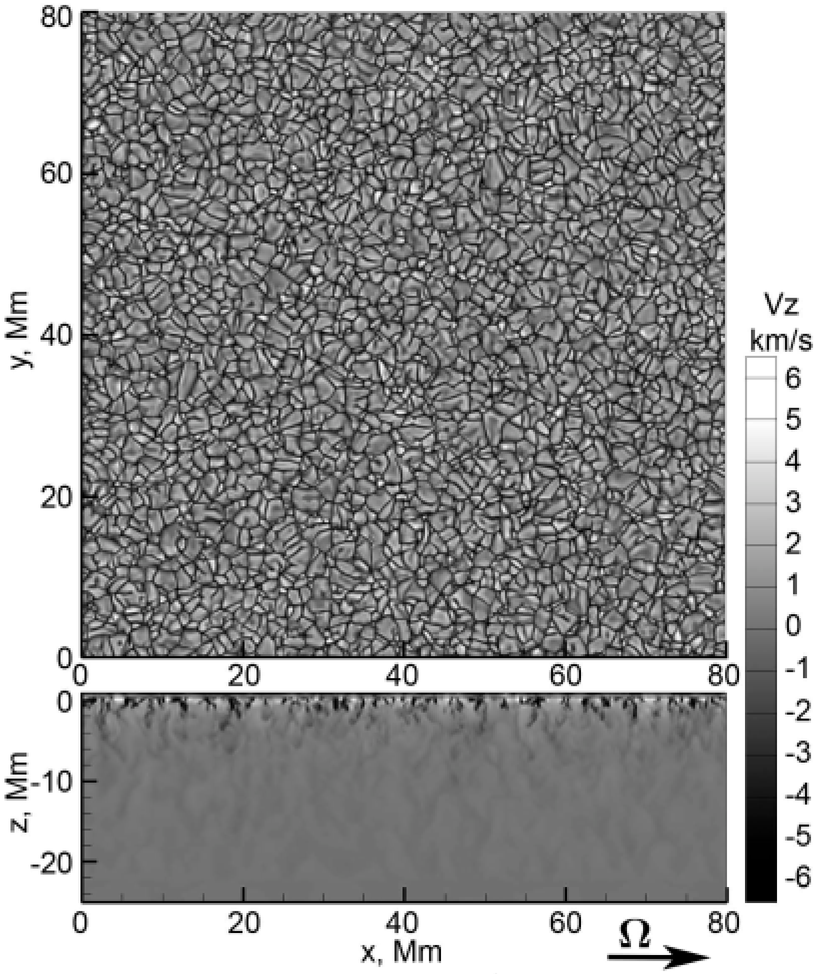
Solar radius

f-mode-based radii are well below the subphotospheric superadiabatic boundary layer: to be about 11 and 4 Mm below the photosphere for *l* = 100 and 300, respectively.



Variations of the seismic radius:
(a) changes of the seismic radius at the depth of 5 Mm
(b) variations with time and depth beneath the solar surface.
The dark color (negative values) corresponds to contraction and the light color (positive values) corresponds to expansion of subsurface layers

Simulation 3-D (1)



Model: The horizontal size of the computational domain is 80 Mm × 80 Mm, and the vertical domain extends to a depth of 25 Mm.

The grid resolution is 100 km in the horizontal directions; the vertical resolution varies from 50 km in the photosphere and low atmosphere to 82 km near the bottom boundary.

The extended duration of the simulation, over 250 hours, permits to reach dynamically stationary conditions before investigating the influence of rotational effects.

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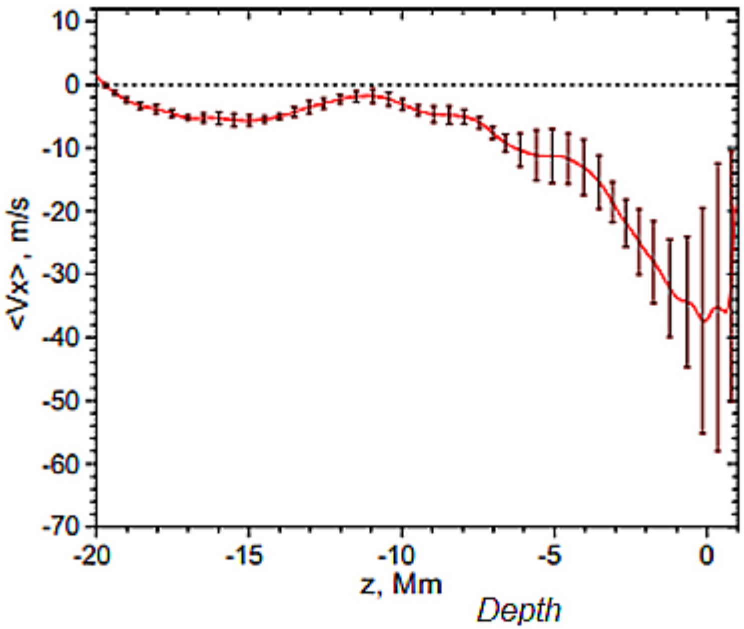
Simulation 3-D (2)

Differential rotation
at 30 degrees latitude.



Results: a significant decrease in the azimuthal velocity with depth by 38 m/s in a 2 Mm deep layer below the photosphere.
Below 7 Mm, the rotation rate is slower than the imposed mean rotation rate by about 5 m/s.
The rotation rate increase with depth is not uniform: from the sub-photospheric layers to about 4 Mm below, the velocity increases by 6 − 7 m/s per Mm, while below 4 Mm the flow accelerates by about 2 m/s per Mm.

The identified 0-10-Mm thick near-surface shear layer, or 'leptocline' is clearly visible in the relative differential rotation profile.

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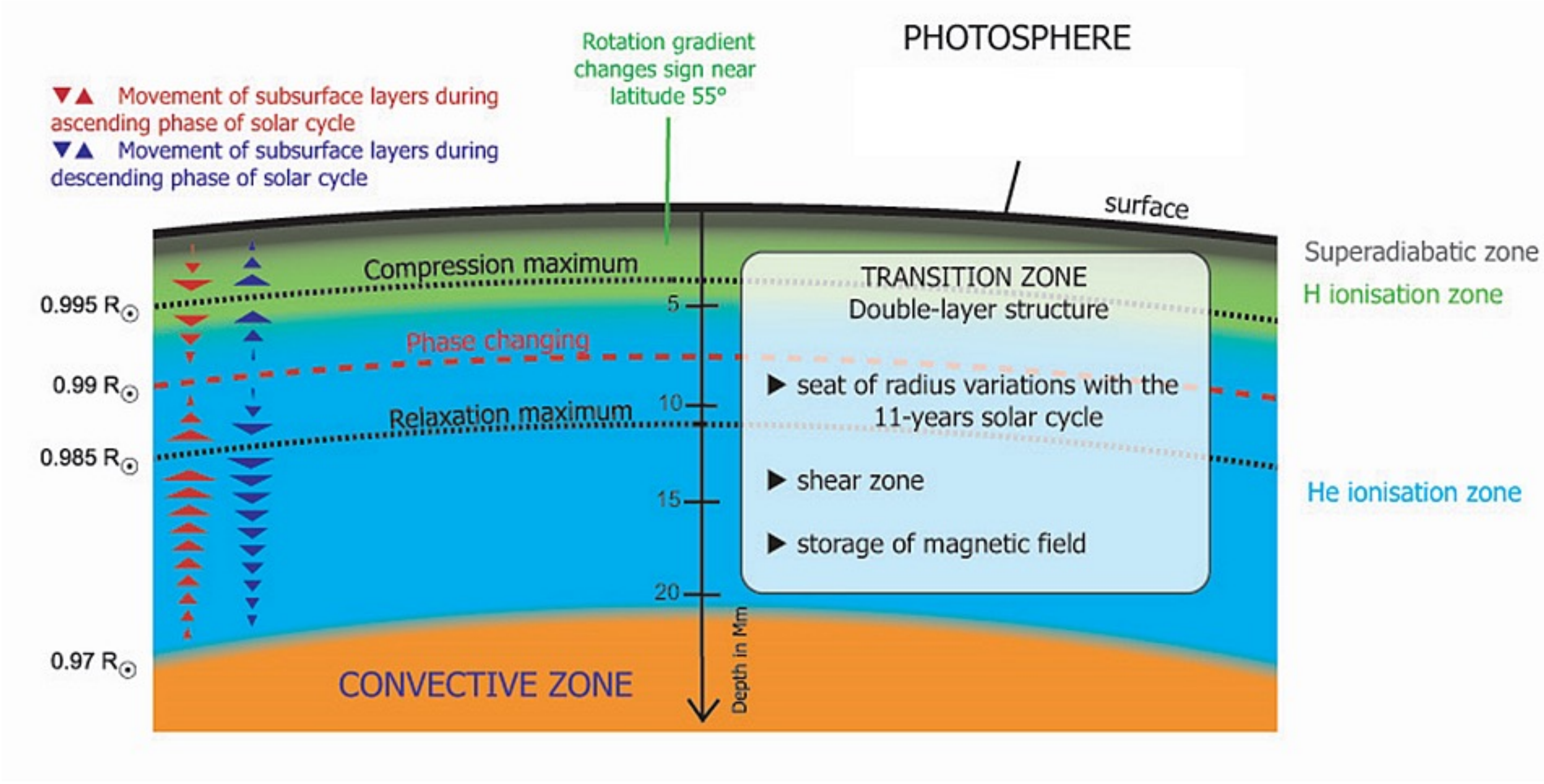
Conclusions (1) schematic view of the leptocline



Conclusions (2)

The “Leptocline” (from the greek "λεπτοσ" = thin and “κλιν” = slope) is a shallow double-structure shear layer, centered at $0.99R_\odot$:

- just beneath the base of the convection zone, where the latitudinal differential rotation rapidly decreases with depth to converge to a uniform rotation of the radiation core,

- right beneath the solar surface. A relatively thin (~ 3 Mm) layer with a rotation rate sharply increasing with depth.

➢ at .996 $R_\odot$ (or 3.1 Mm in depth): this depth coincides with the maximum of the flow divergence of quiet regions, which represents supergranular flows, and the divergence decreases to half its maximum amplitude by a depth of about 8 Mm. The upper layer of the leptocline is heavily influenced by supergranules.

➢ In the deeper part, between 0.97 $R_\odot$ and 0.99 $R_\odot$, the radius to vary in phase with the solar cycle, whereas this is opposite in the upper part above 0.99 $R_\odot$, where the variability becomes in antiphase.

➢ Likely two regimes? Dominant processes in the boundaries could be different from those in the main body of the leptocline.