STELLAR MAGNETIC ACTIVITY

(PAP351)

Lecture 2, 23.1.2024

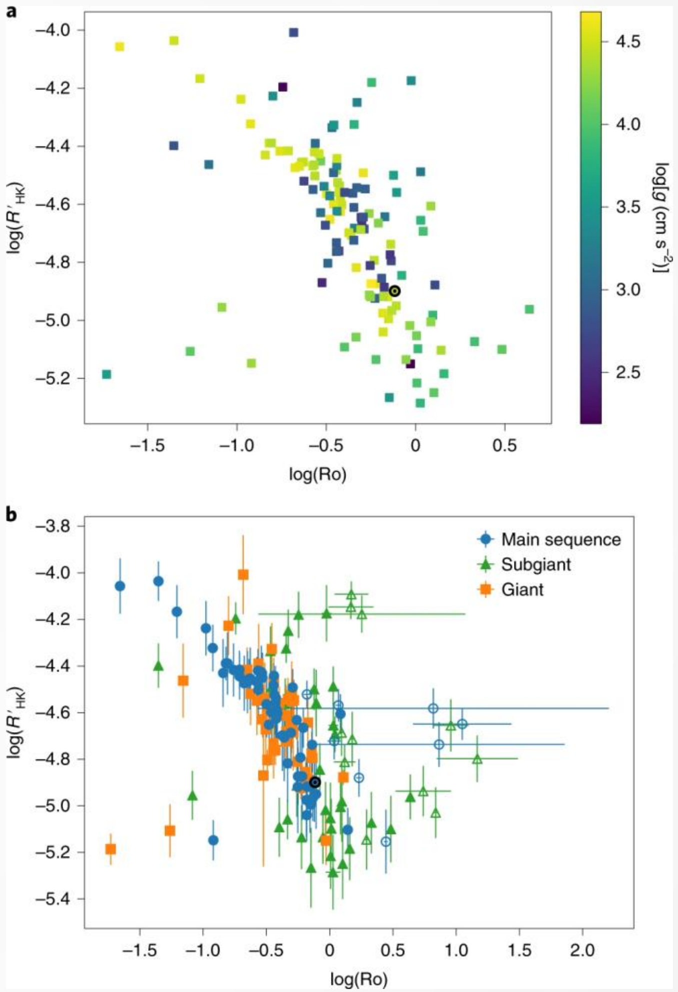
Thomas Hackman

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

2.4 CAUSE OF MAGNETIC ACTIVITY

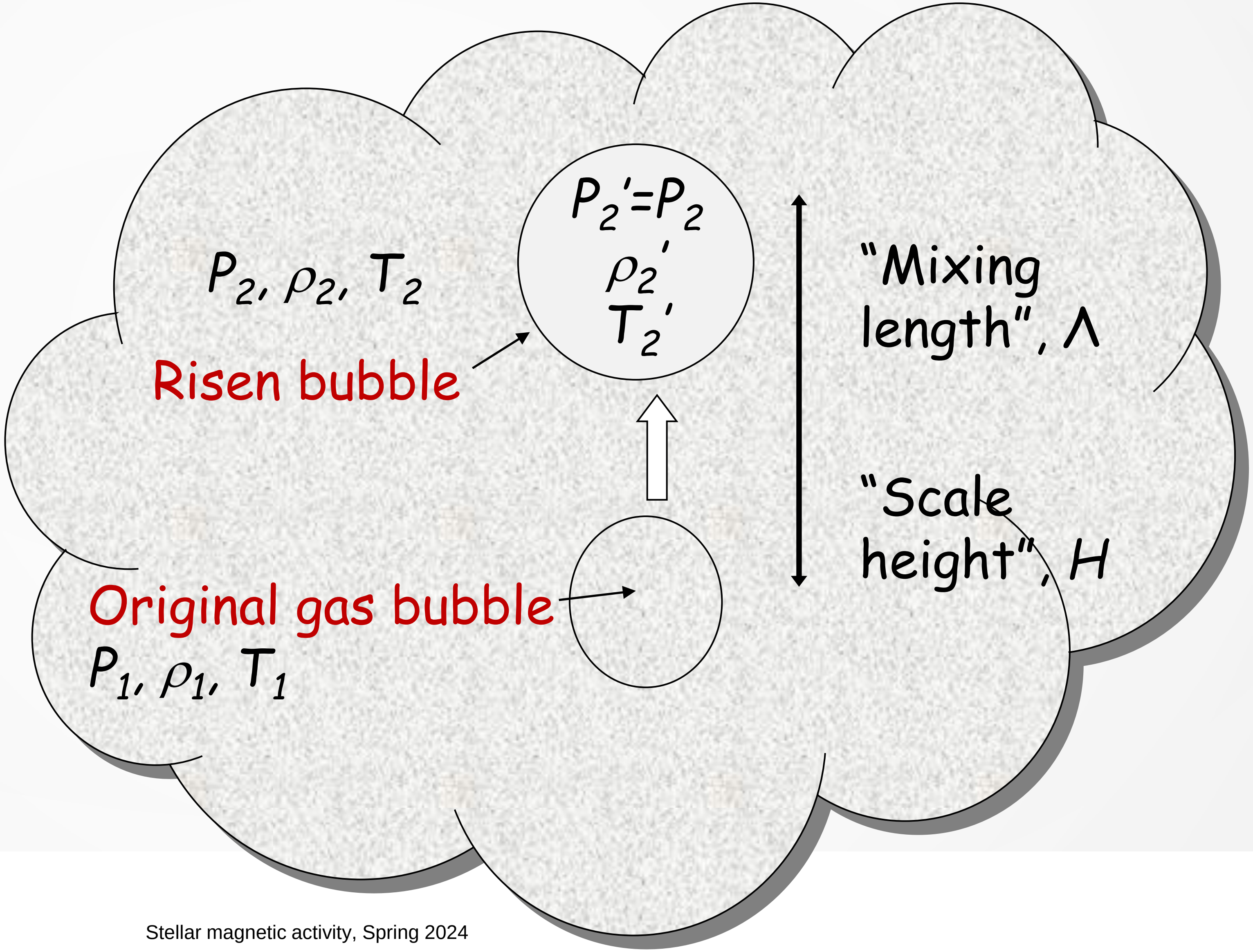
- Late type stars cannot have significant fossil magnetic fields.
- ↦ Dynamo-model:
    - Convective turbulence
    - (Differential)rotation
- Stars with spectral class F2 or later have convective envelopes.
- Activity increases with decreasing Rossby number (Noyes et al. 1984):

$$\boxed{Ro = \frac{P_{\mathrm{rot}}}{\tau_{\mathrm{conv}}}}$$



Lehtinen et al. 2020

2.5 STELLAR CONVECTION



P_2, ρ_2, T_2

$P_2'=P_2$

ρ_2'

T_2'

Risen bubble

“Mixing length”, Λ

“Scale height”, H

Original gas bubble

P_1, ρ_1, T_1

- Convection starts, when displaced ”bubble” does not return.

2.5.1 DIFFERENT TEMPERATURE GRADIENTS

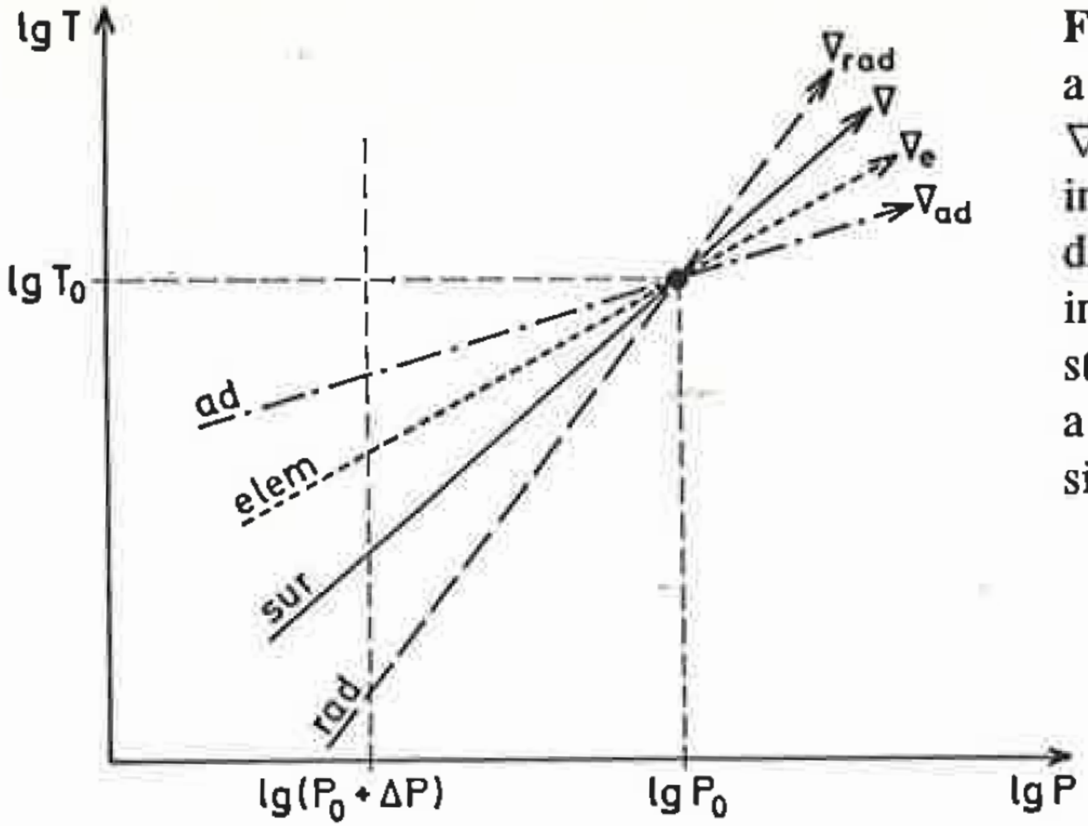


Fig. 6.2. Temperature–pressure diagram with a schematic sketch of the different gradients $\nabla(\equiv \partial \ln T/\partial \ln P)$ in a convective layer. Starting at a common point with P_0 and T_0, the different types of changes (adiabatic, in a rising element, in the surroundings, for radiative stratification) lead to different temperatures at a slightly higher point with $P_0 + \Delta P$ ($< P_0$, since P decreases outwards)

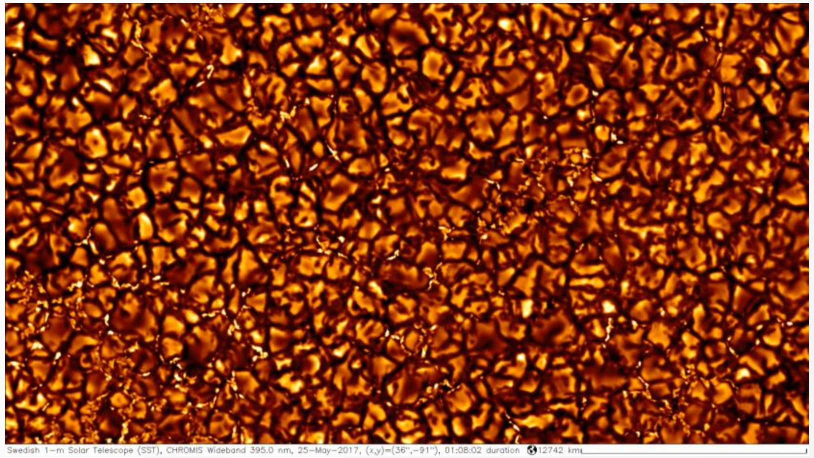
Figure 6.2 (KW)

2.6 STELLAR CONVECTION CONT.

- Schwarzshcild criterion for convection: $\nabla_{\mathrm{rad}} < \nabla_{\mathrm{ad}}$ => $\boxed{\left.\frac{d\log P}{d\log T}\right|_{\text{radiat}} < \frac{\gamma}{\gamma - 1}}$

$$\gamma = C_P / C_V$$

- Ledoux's criterion: $\nabla_{\mathrm{rad}} < \nabla_{\mathrm{ad}} + \frac{\varphi}{\delta}\nabla_\mu$
  where $\begin{cases} \delta = -\dfrac{\partial ln\rho}{\partial lnT} \\ \varphi = \dfrac{\partial ln\rho}{\partial ln\mu} \end{cases}$
- Usual reason for convective envelope
  - T decreases outwards $\mapsto$ stronger absorption
- Solar convection $\mapsto$ granulation

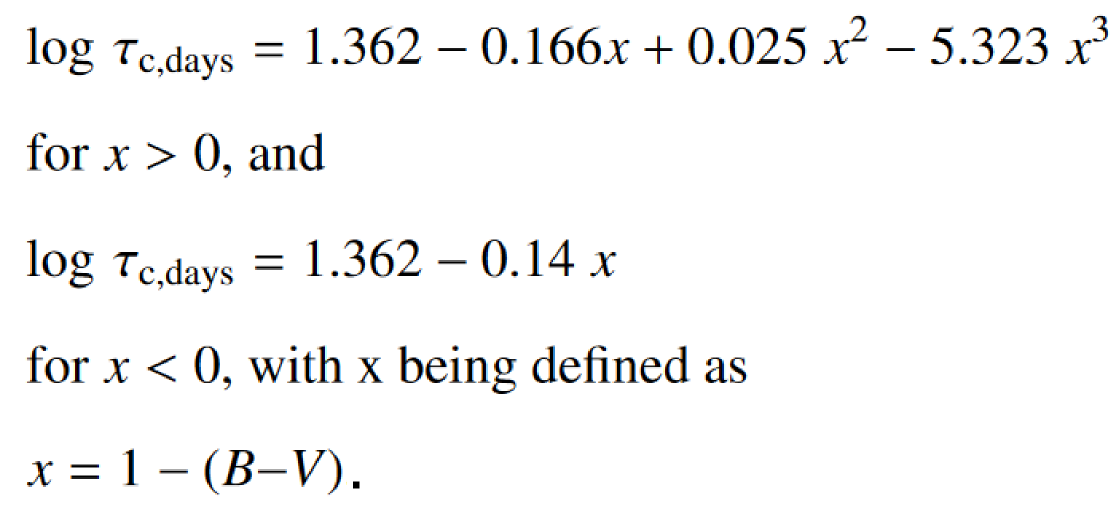


Swedish 1-m Solar Telescope (SST), CHROMIS Wideband 395.0 nm, 25-May-2017, (x,y)=(36",-91"), 01:08:02 duration 🌍12742 km

Solar granulation (Swed. Solar Telescope/ V. Henriques & A. Drews)

2.7 CONVECTIVE TURNOVER TIME

- τ_{conv} is the typical timescale for a convective cell to rise in the stellar plasma
- Estimated, e.g., through mixing length theory:
- $\tau_{\mathrm{conv}} = \frac{\Lambda}{v_{\mathrm{conv}}}$, where Λ is the mixing length and v_{conv} the convective velocity.
- τ_{conv} varies strongly in the convection zone
- At the base of the solar convection zone $\tau_{\mathrm{conv}} \sim 25\ \mathrm{d}$



$$\log \tau_{\mathrm{c,days}} = 1.362 - 0.166x + 0.025\, x^2 - 5.323\, x^3$$

for $x > 0$, and

$$\log \tau_{\mathrm{c,days}} = 1.362 - 0.14\, x$$

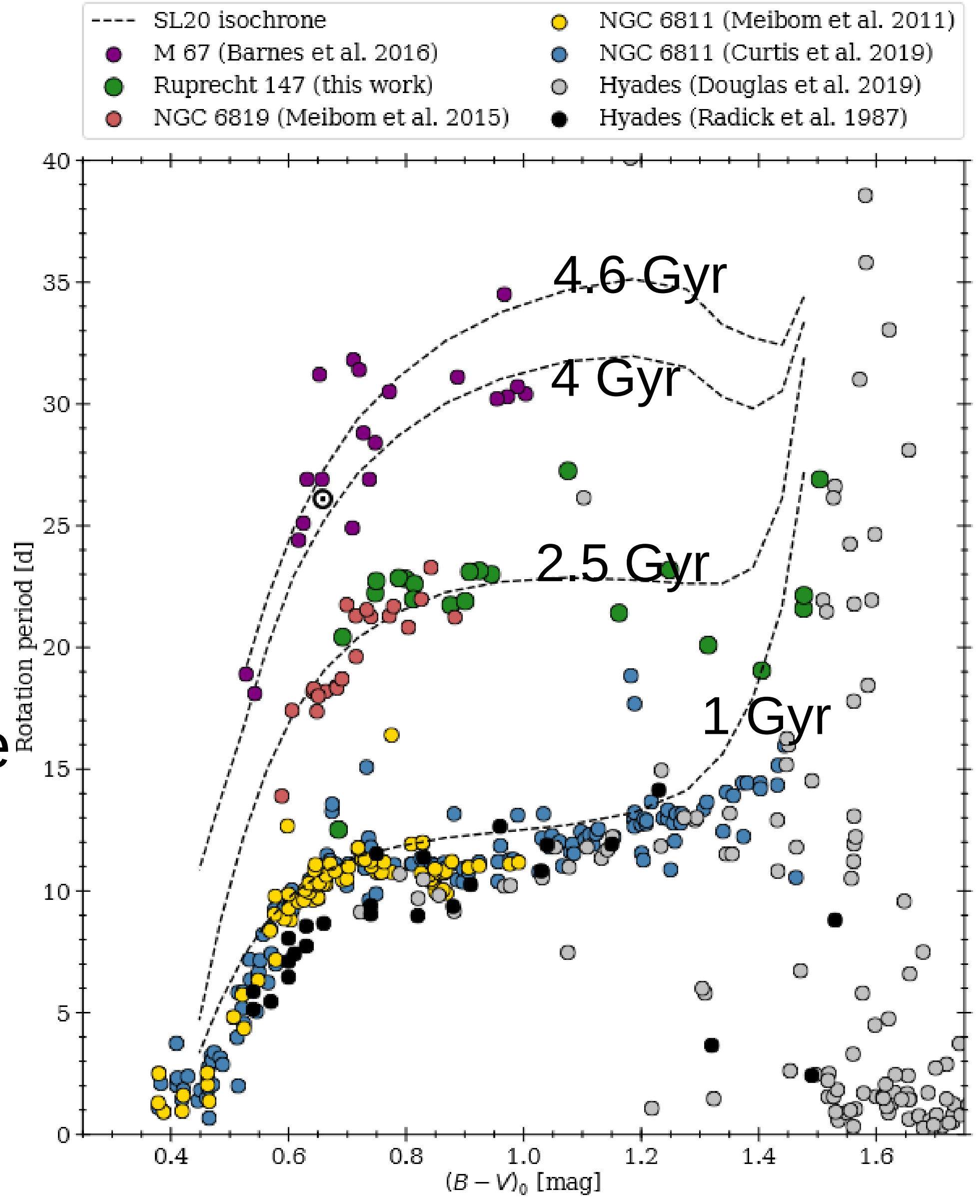
for $x < 0$, with x being defined as

$$x = 1 - (B{-}V).$$

Empirical formula for τ_{conv} (Noyes et al. 1984).

2.8 STELLAR ROTATION

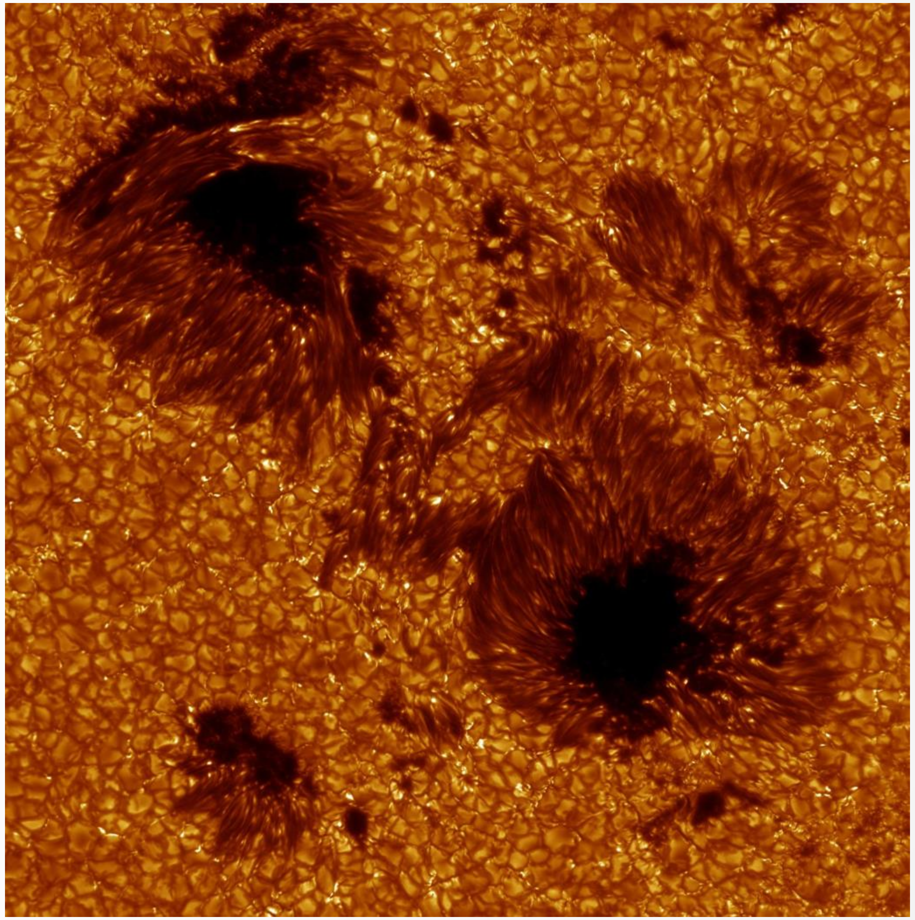
- Star forming clouds rotate slowly
- Contraction ↦ increased rotation
- ↦ Young stars rotate fast: Strong activity
- Magnetic breaking ↦ old late type stars rotate slowly
    - E.g., solar rotation period ~ 30 days
- Close binaries ↦ tidal forces ↦ synchronised rotation maintains fast rotation
- Convection => differential rotation



Different stellar clusters and the Sun (Gruner & Barnes, 2020)

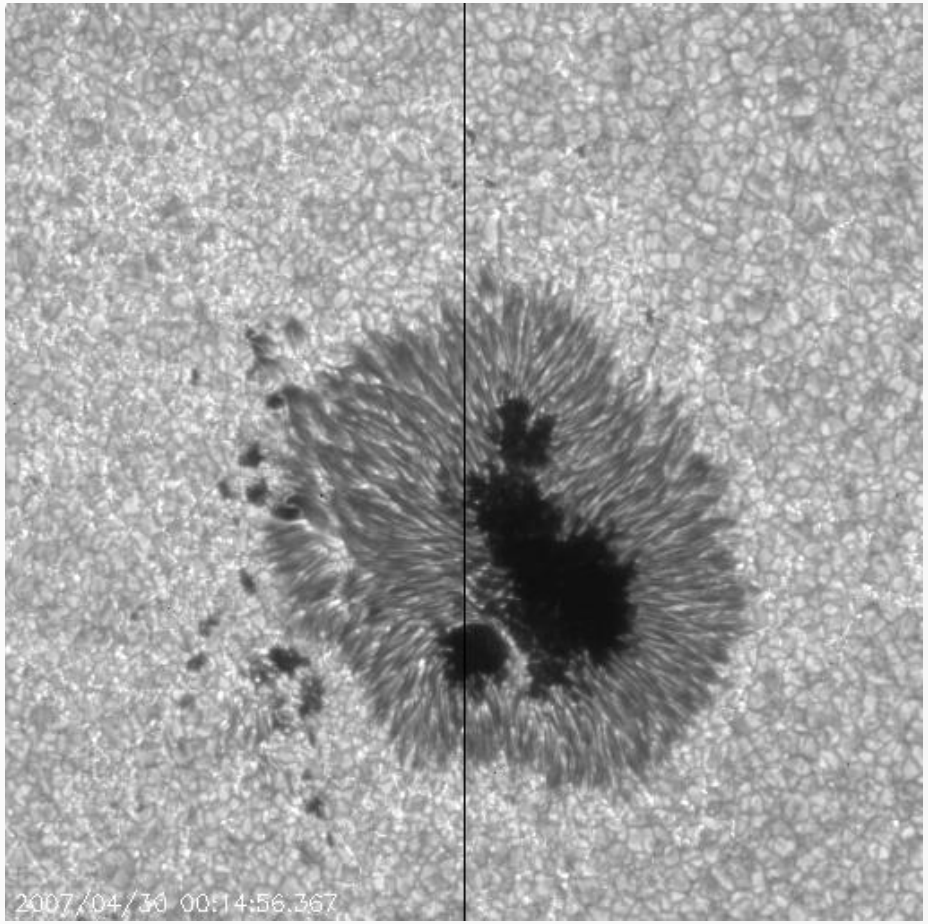
3. SUNSPOTS

- Structure
  - Umbra ~ 4000 K
  - Penumbra ~ 5500 K
  - ”Wilson depression” <= optical depth)
- Sunspot groups:
  - Leading and trailing spots
- Magnetic field:
  - Radial in umbra
  - Turns towards horisontal in penumbra



Sunspots in 430.5 nm by Swedish Solar Telescope (Sharmer & Langhans / Royal Swed. Acad. of Sciences)

3.1 SUNSPOT EVOLUTION



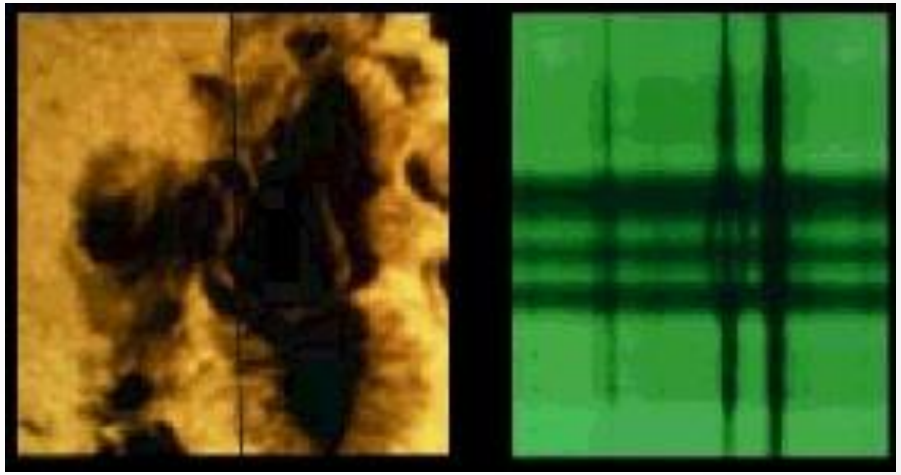
Spot eveolution ~ 2 h (30 April, 2007 Hinode SOT, G-band)

3.2 SUNSPOTS AS A INDICATORS OF SOLAR ACTIVITY

- Link with magnetic fields:
  - Magnetic fields penetrate the solar surface ↦ convection is locally inhibited ↦ cool spot
- Sunspots are easy to observe => cycle is clearly visible
- The Wolf (or Zürich) relative sunspot number:

$$R_Z = k(10g + n),$$

  - k = ”observer factor”
  - g = number of sunspot groups
  - n = number of sunspots



Zeeman effect in sunspot (NSO/AURA/NSF)

3.3 SUNSPOT CYCLES

- Schwabe cycle ~ 11 years, Hale cycle: ~ 22 years:
  - Rise 3-6 years, decline 5-8 years
  - Cycle numbers: No 1 Starting 1755
  - Magnetic polarity reversal each cycle
- Gleissberg cycle: ~ 80-120 years
- Suess cycle: ~ 210 years
- Hallstatt cycle: ~ 2100 years

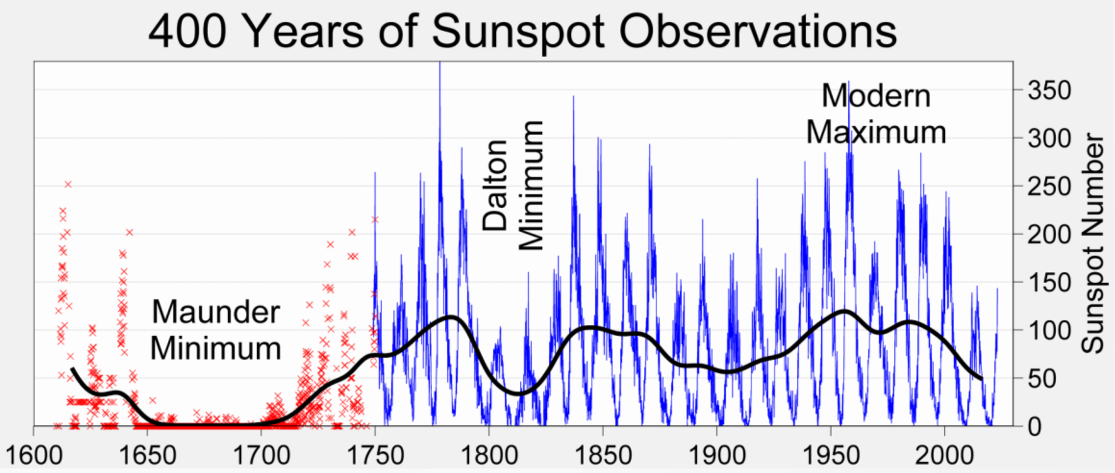


Figure: Wikipedia

3.4 LONG TERM VARIABILITY

- Long-term cycles known through abundances of radioisotopes:
  - ^{10}Be (ice)
  - ^{14}C (three rings)
  - ^{44}Ti (meteorites)

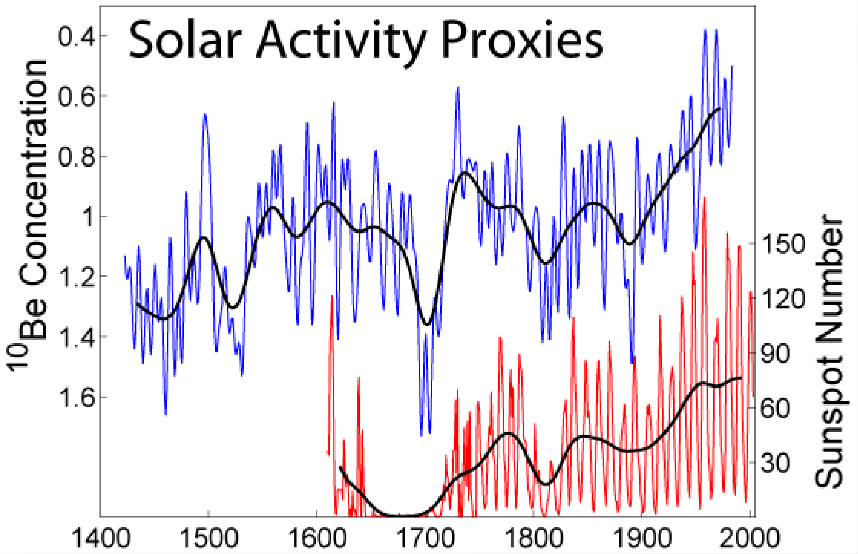
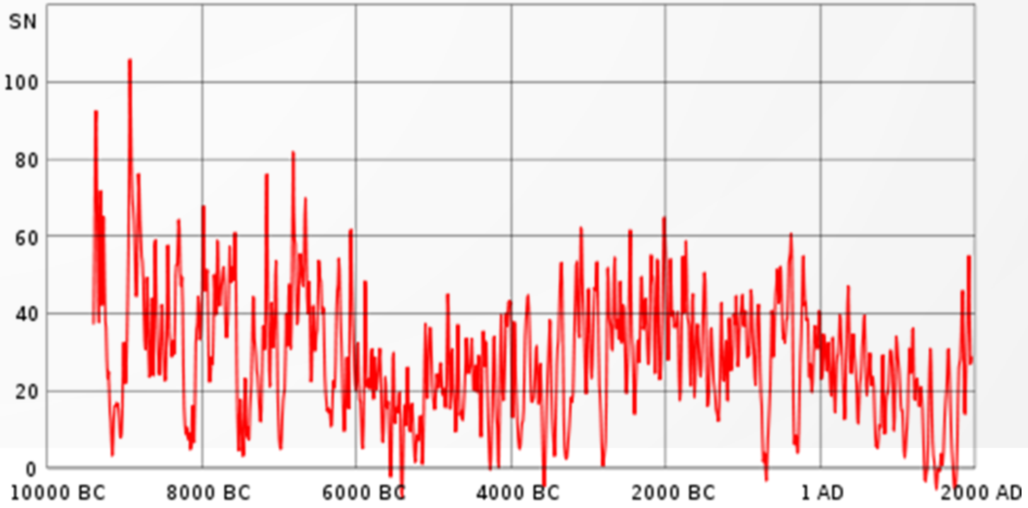


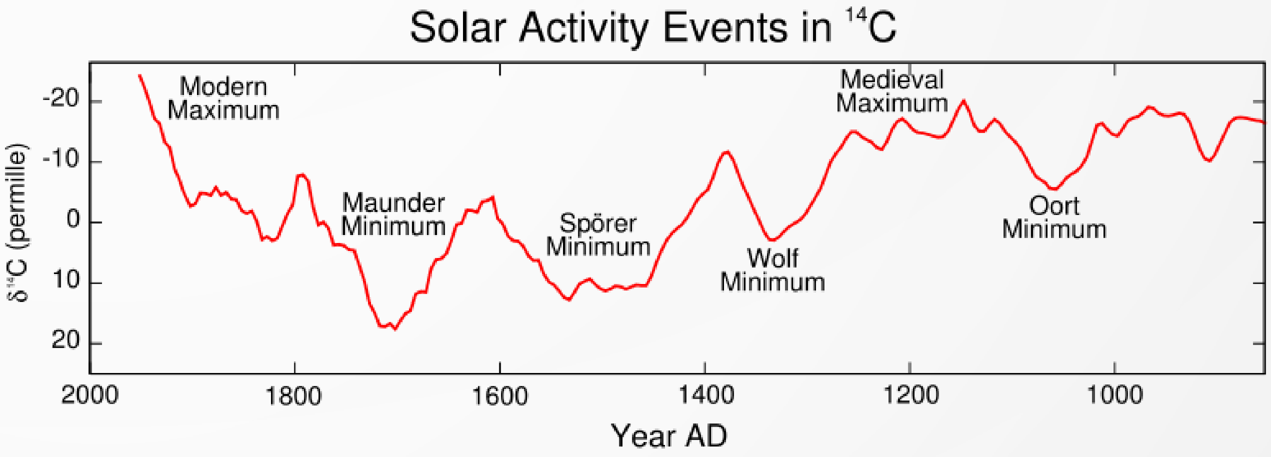
Figure: Wikipedia



Sunspot reconstruction from ^{14}C data (Solanki et al. 2004, Nature 431, 1084)

3.5 GRAND MINIMA

- Long term periods of minimum activity:
  - Dalton minimum ~ 1795 – 1823
  - Maunder minimum ~1645 – 1715
  - Spörer minimum ~ 1420 – 1530
  - Wolf minimum ~ 1280 – 1340
  - Oort minimum ~ 1010 – 1050

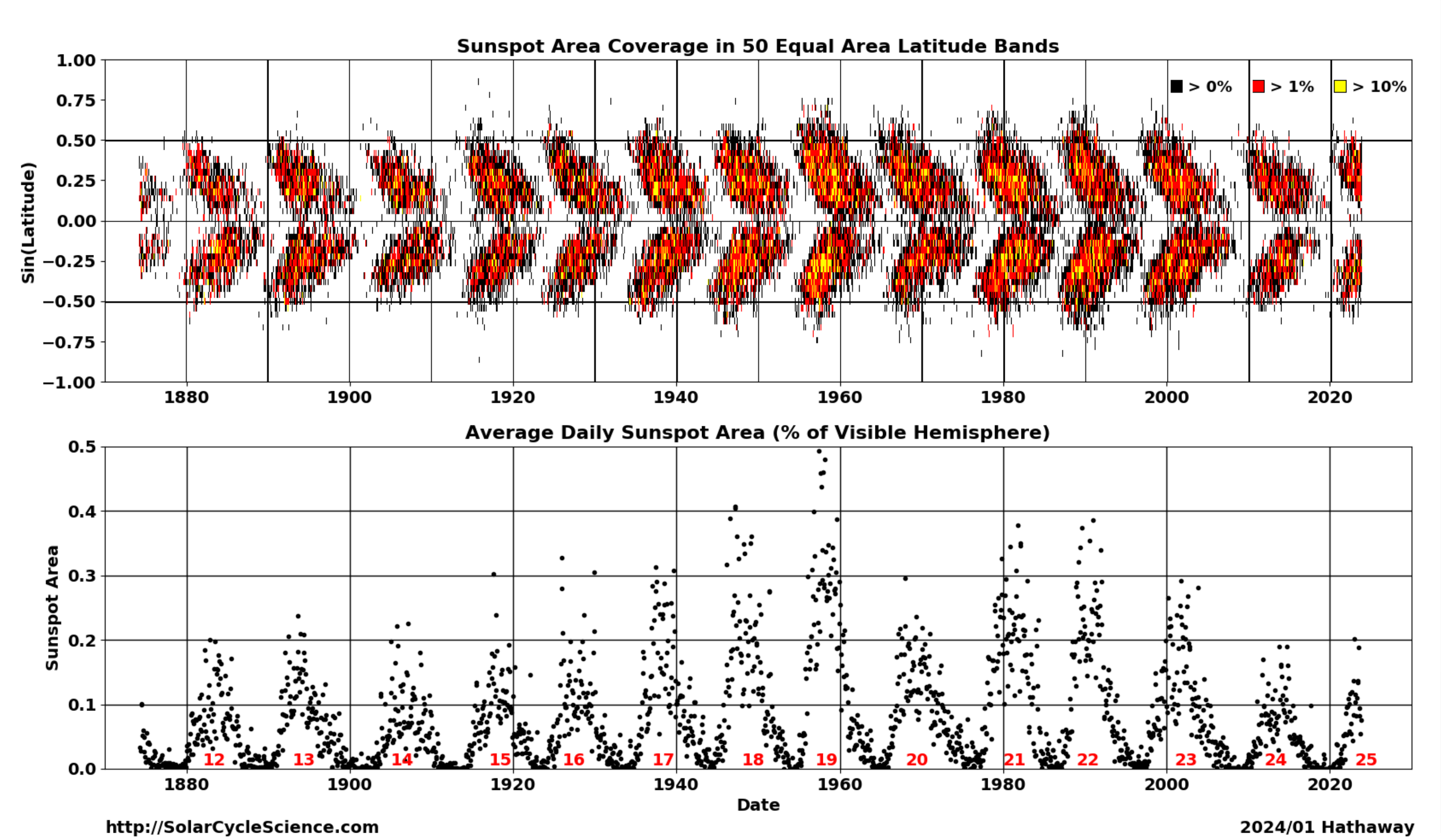


Leland McInnes, Wikipedia

3.6 REGULARITIES OF SUNSPOT CYCLES

- Spörer 's law:
  - In the beginning of cycle spots appear at around solar latitude $\phi \sim 30^{o}$, end the end at $\phi \sim 7^{o}$
  - $\mapsto$ butterfly diagram
- Waldmeier's rule:
  - Duration of rise anticorrelated with amplitude
- Gnevyshev-Ohl –rule:
  - The amplitude of an odd-numbered cycle usually exceeds that of the proceeding even-numbered cycle: North – South asymmetry

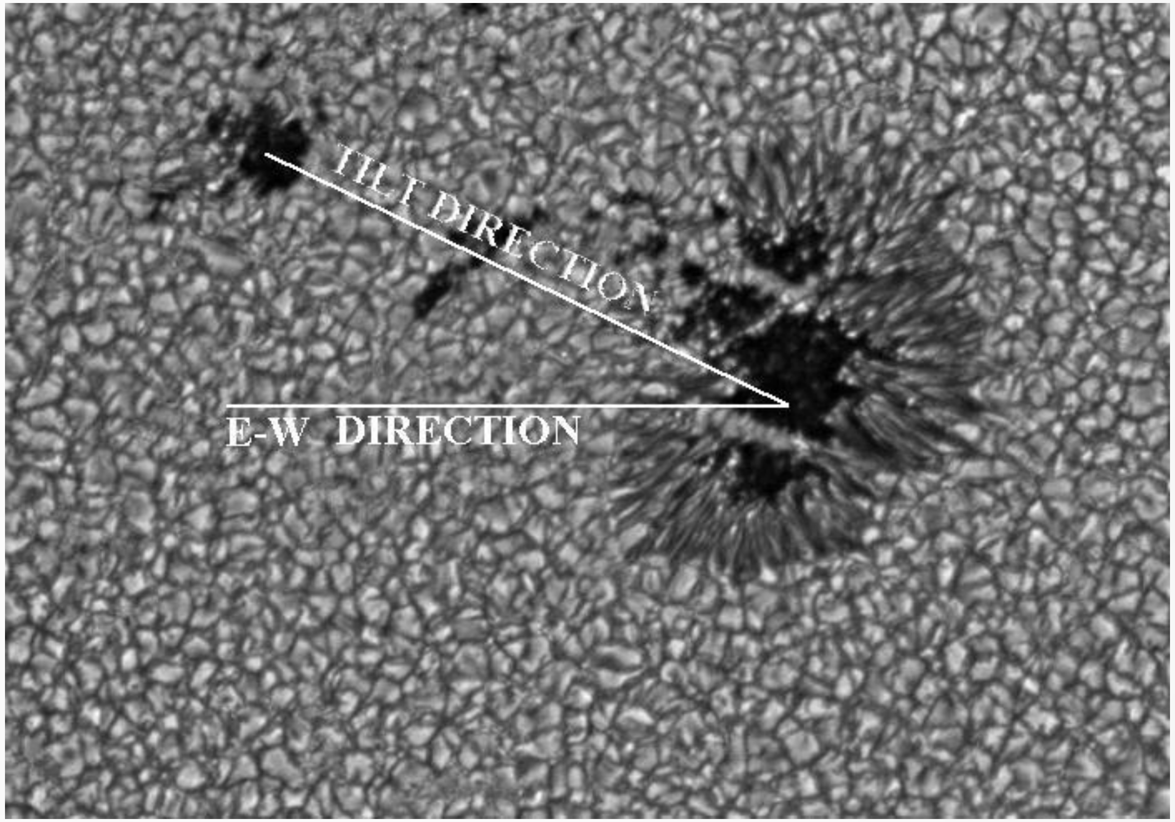
3.7 BUTTERFLY DIAGRAM



3.8 MORE SUNSPOT REGULARITIES

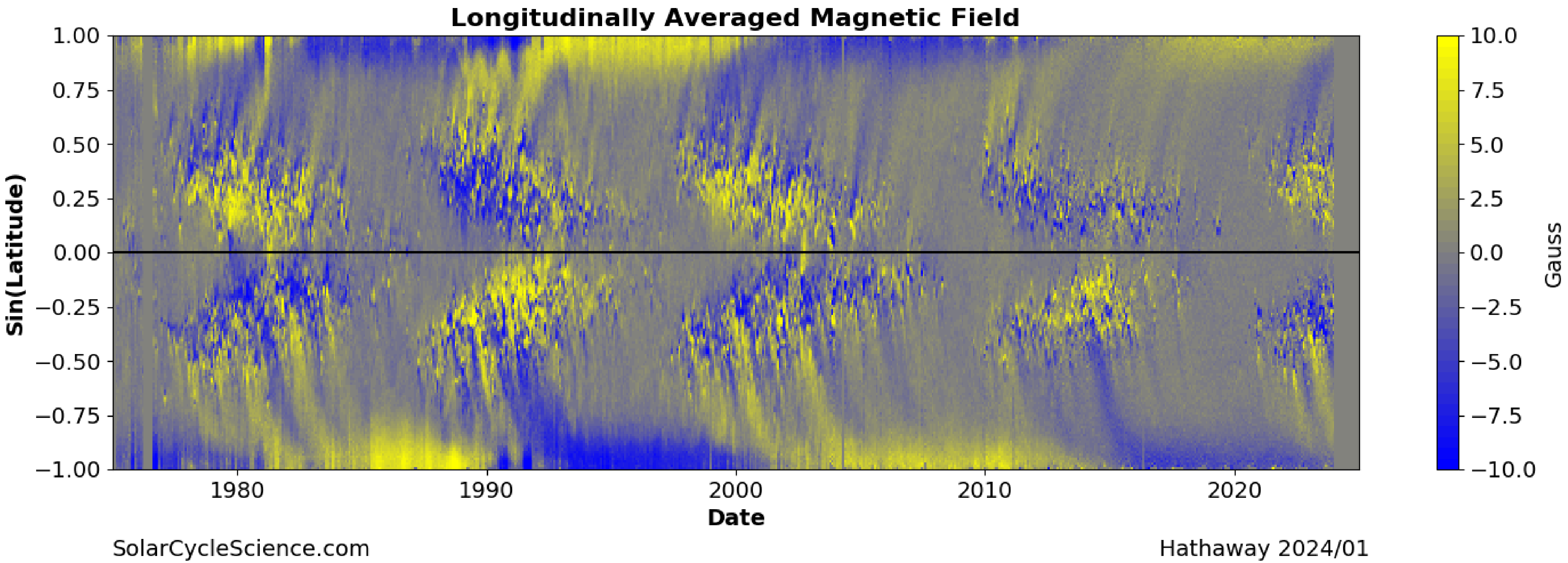
- Hale-Nicholson polarity rules:
  - The polarities of ”leading” and ”trailing” spots:
    - Opposite polarities of leading and trailing spots
    - Reversed polarities at northern and southern hemispheres
    - Polarity reverses after the sunspot minimum
- Joy’s rule:
  - Axis of bipolar sunspots tilted, the leading spot is nearer to the solar equator
- Overlap of cycles:
  - New cycle begins on higher latitudes before old cycle ends at lower latitudes

3.9 JOY’s RULE

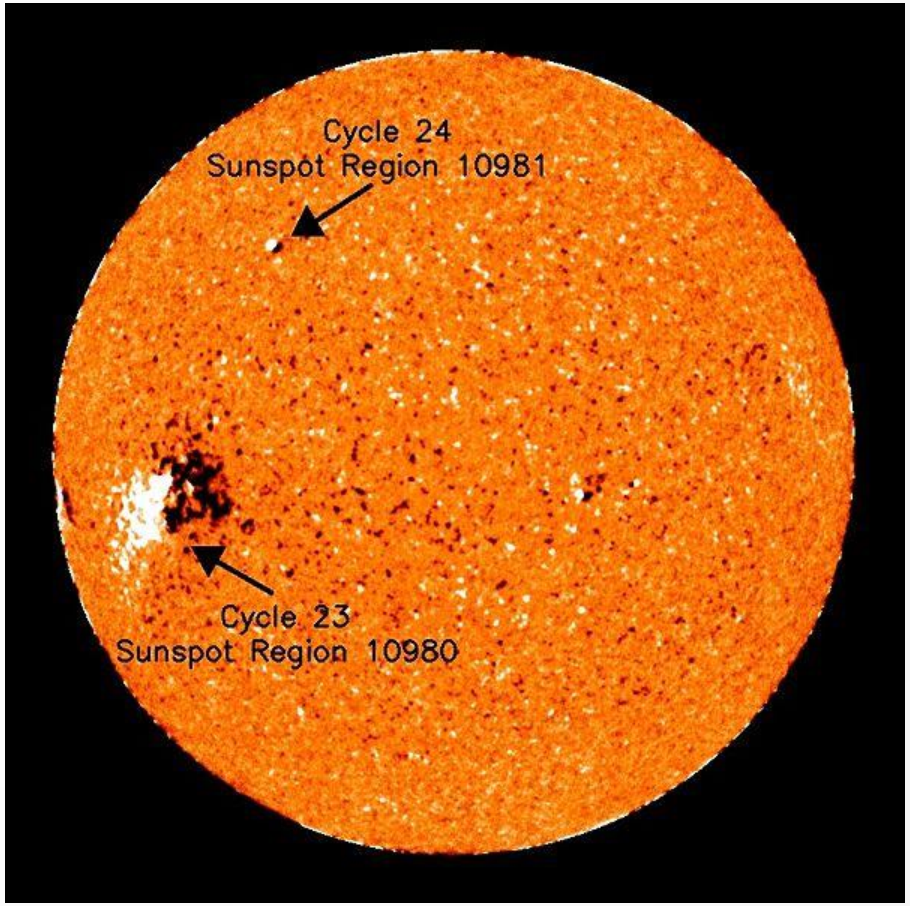


Joy’s rule (McClintock, 2016, Univ. of South Queensland)

3.10 MAGNETIC POLARITY CHANGES



3.11 OVERLAPPING CYCLES



Start of cycle 24 8.1.2008:
Spots of two cycles visible simultaneously (NOAA)

3.12 ACTIVE LONGITUDES

- Active longitudes: Active regions concentrated to certain longitudes in a rotation frame
- Complication: Differential rotation
- Active regions certainly exist, but lifetime of active longitudes is under dispute.

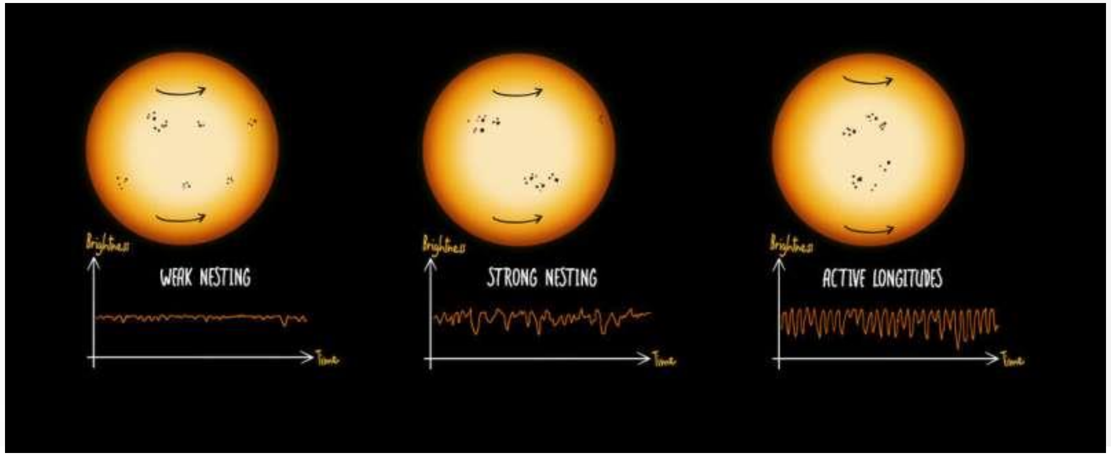
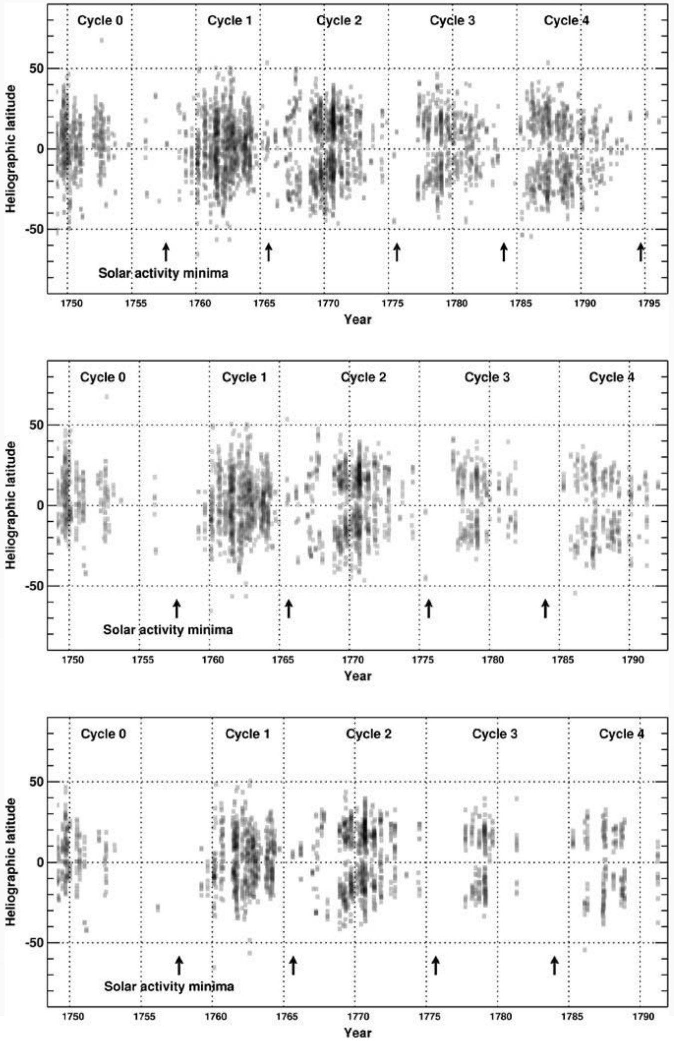
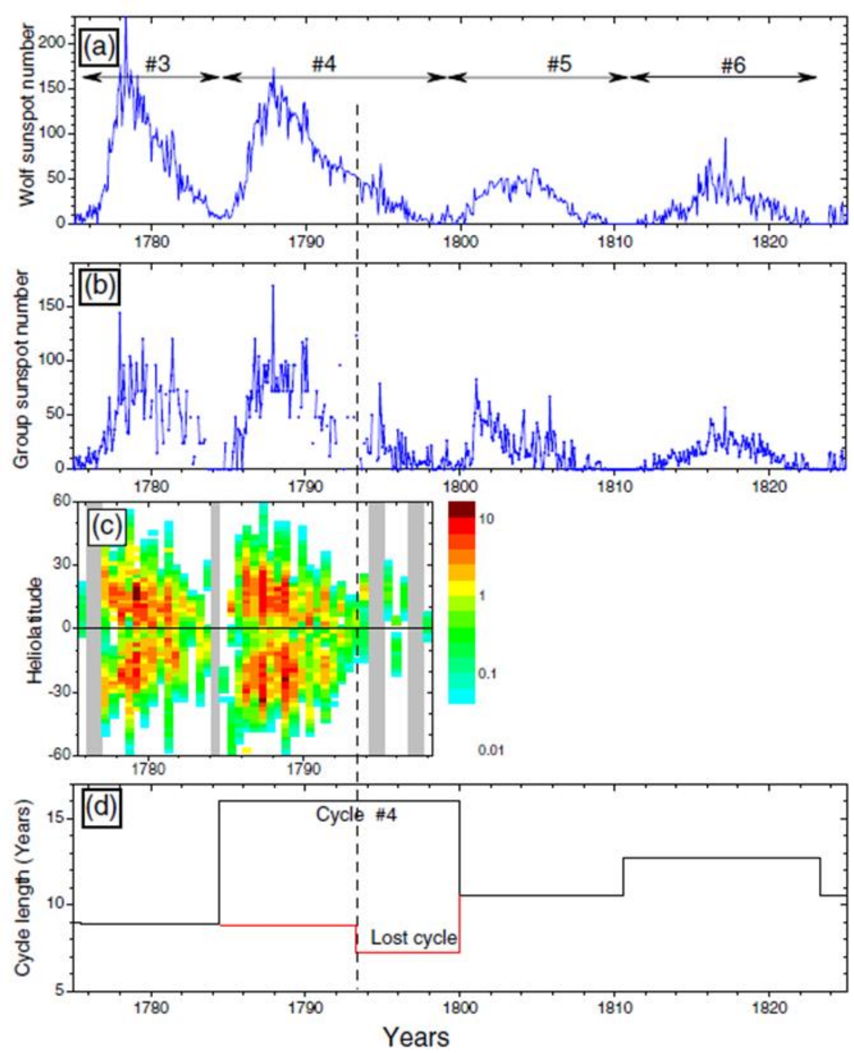


Figure: MPS/Taylan Ayık

3.13 IRREGULARITIES IN SUNSPOT CYCLES

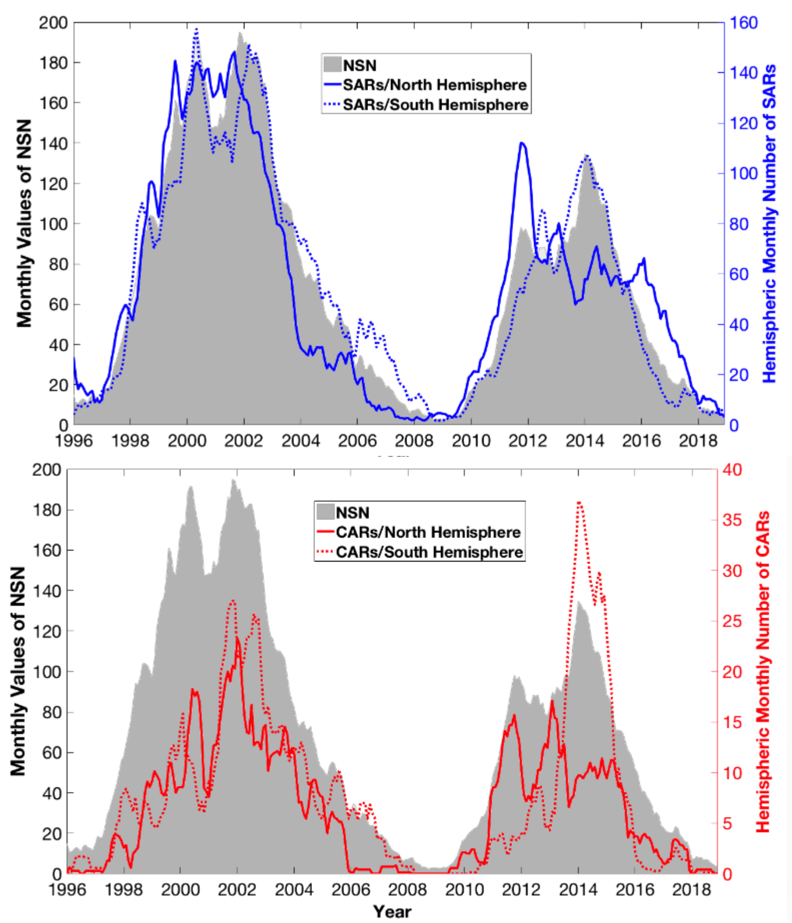
- E.g. reconstruction of sunspot data from 18th century shows irregularities near grand minima
    - No clear ”butterfly diagram”
    - ”Lost cycle” within cycle 4

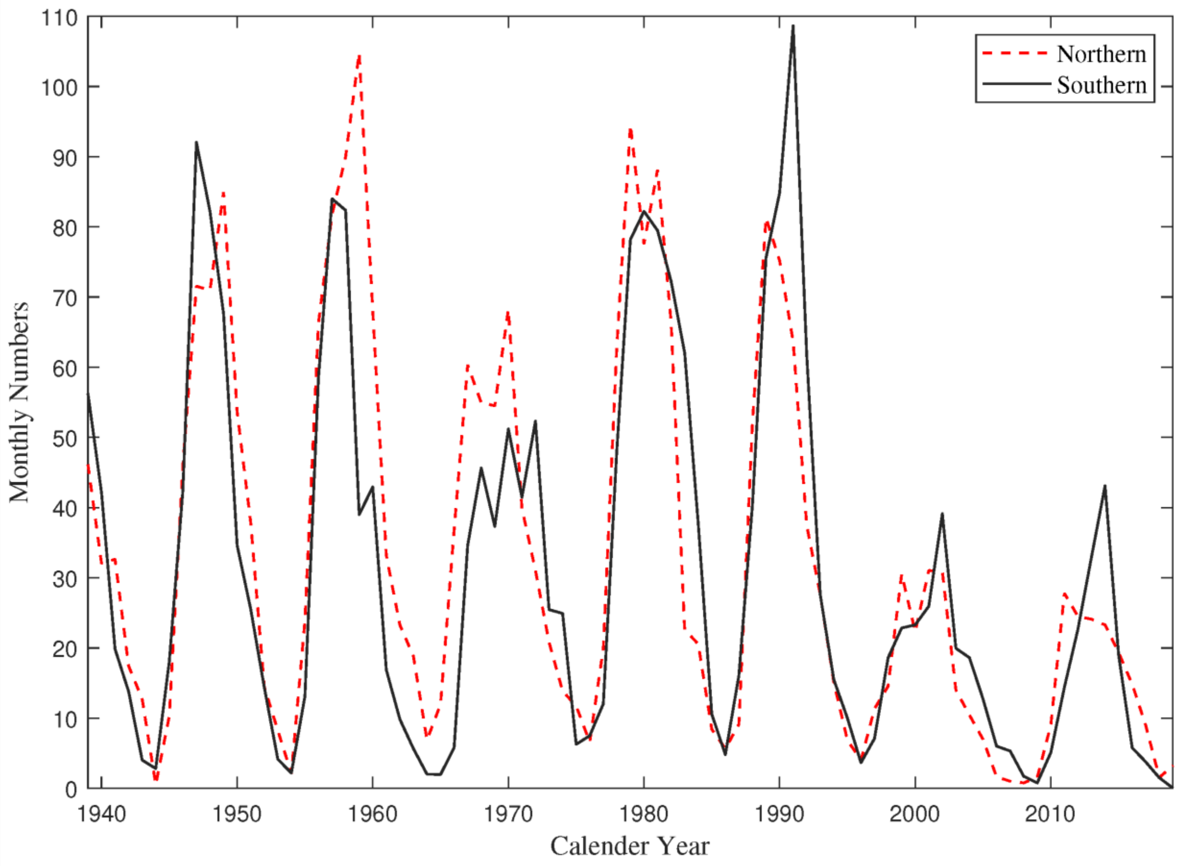




Reconstructed butterfly diagrams (Arlt, 2009; Usoskin et al. 2009)

3.14 NORTH – SOUTH ASYMMETRY IN SUNSPSOTS AND ACTIVE REGIONS





Nikbakhsh et al. 2019 and Xu et al. 2021

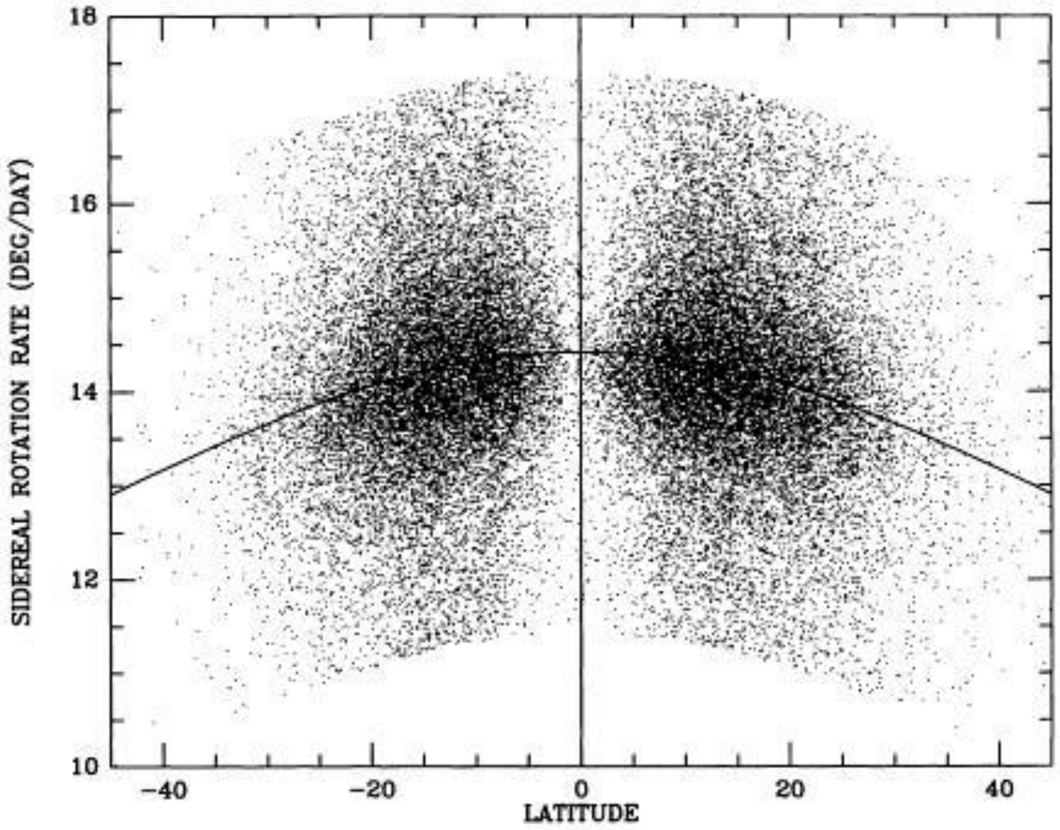
HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

3.15 SOLAR SURFACE DIFFERENTIAL ROTATION

- Angular rotation vs. latitude (36708 sunspot groups, Howard 1994)
- Differential rotation model:

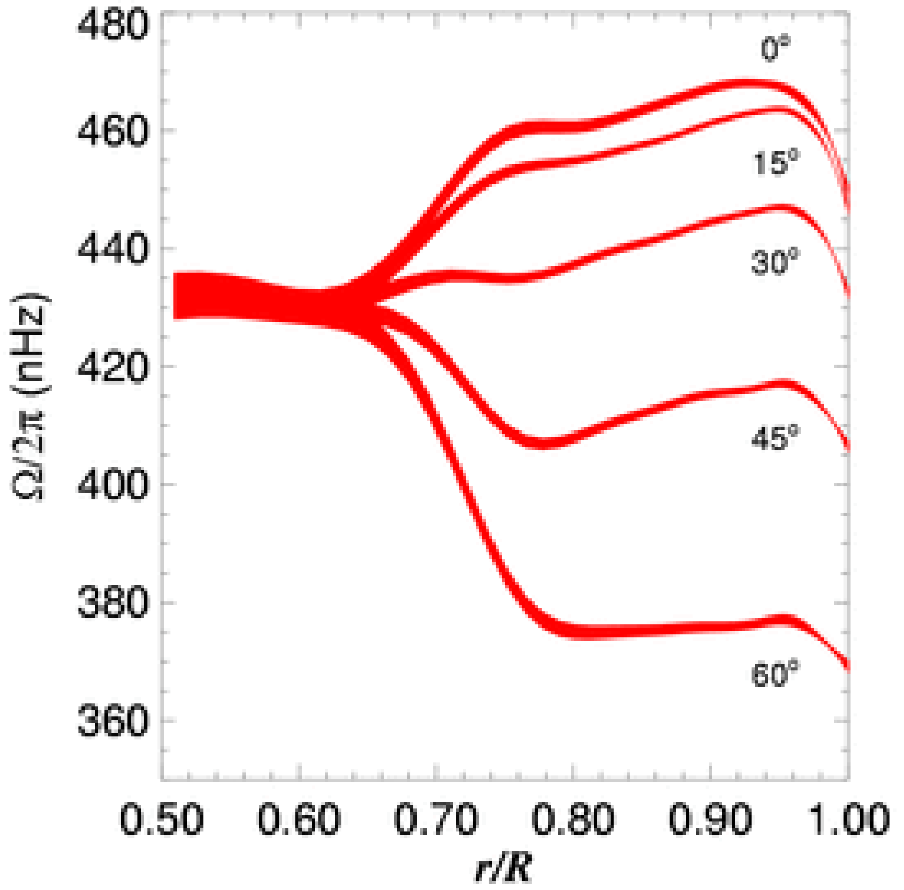
$$\Omega(\phi) = \Omega_{\text{eq}} + \beta \sin^2 \phi + \gamma \sin^4 \phi \Rightarrow$$

$$\Omega(\phi) \approx \Omega_{\text{eq}} (1 - \alpha \sin^2 \phi)$$



3.16 DIFFERENTIAL ROTATION IN DEPTH

- Differential rotation as function of depth ↦ new spots show different rotation from old spots
- Torsional oscillations => Differential rotation not constant, changes during the solar cycle
  - See e.g., Covas, E. et al., 2001, A&A 371, 718



Internal solar rotation profile from helioseismology (Howe et al. 2000).

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI