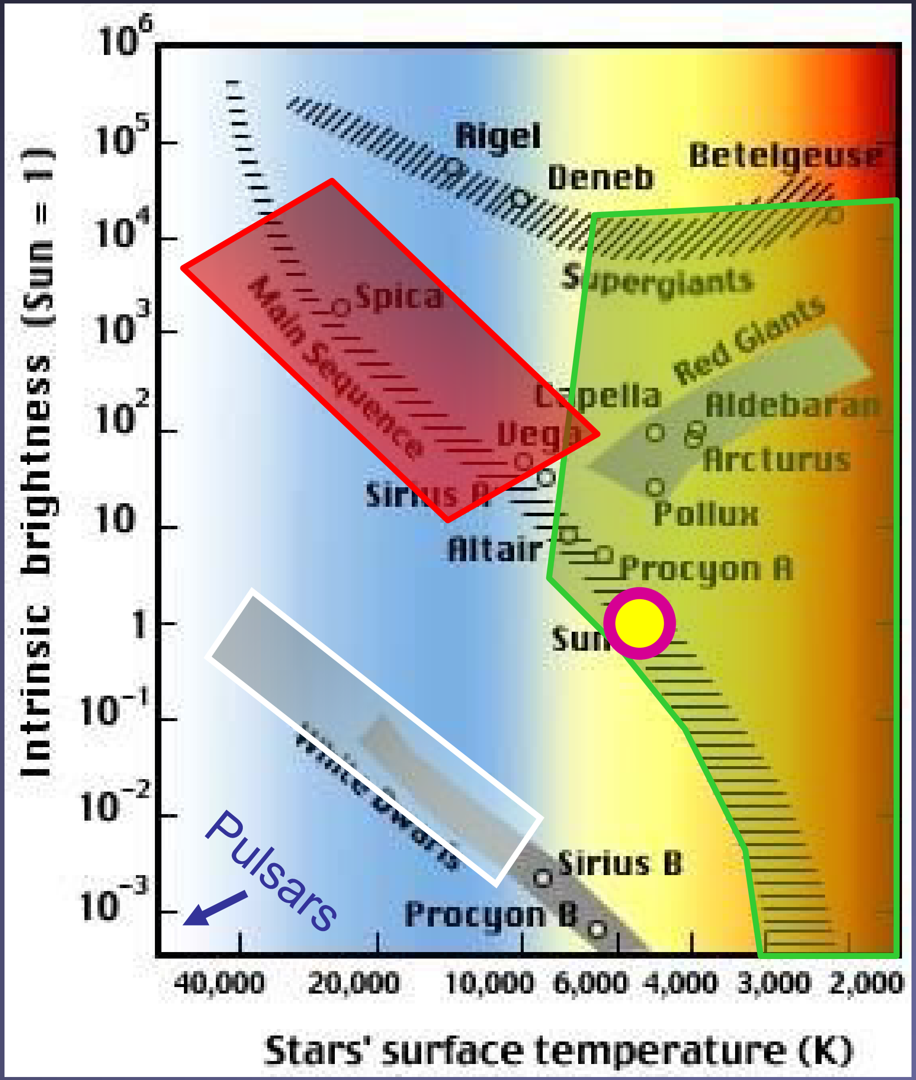
Activity in stellar envelopes caused by the magnetic field

Which stars have magnetic fields or show magnetic activity?

- Best studied star: Sun
- F, G, K, M, L stars (outer or full convection zones) show magnetic activity & have <B> fields of G-kG.
- Early type stars: Ap, Bp, (kG-100kG), Ae,Be (100G), O,B (100 G)
- White dwarfs have B ≈ kG-10^9 G, no activity
- Not on diagram: pulsars



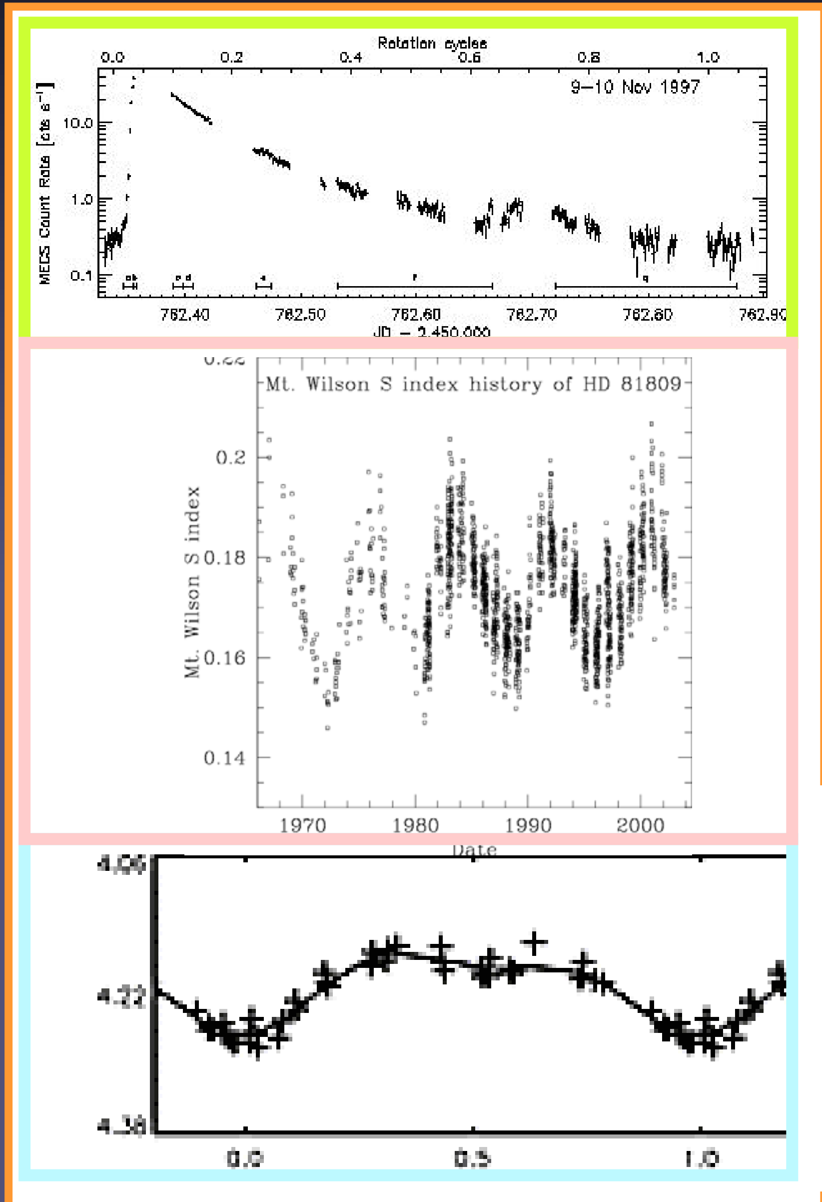
Stellar magnetic activity

- Magnetic activity: high energy radiation, e.g. X-rays, stellar wind, or stellar variability due to magnetic fields

- Stellar magnetic activity can be driven by:
  - interaction of magnetic field with convection in an outer convection zone (solar case) or in completely convective stars (dynamo driven fields). By far the most common
  - Modification of accretion of matter by magnetic fields (e.g. polars, i.e. AM Hercules systems) and/or interaction with an accretion disk as in classical T-Tauri stars
  - Interaction of magnetic field with turbulent wind in O, B stars

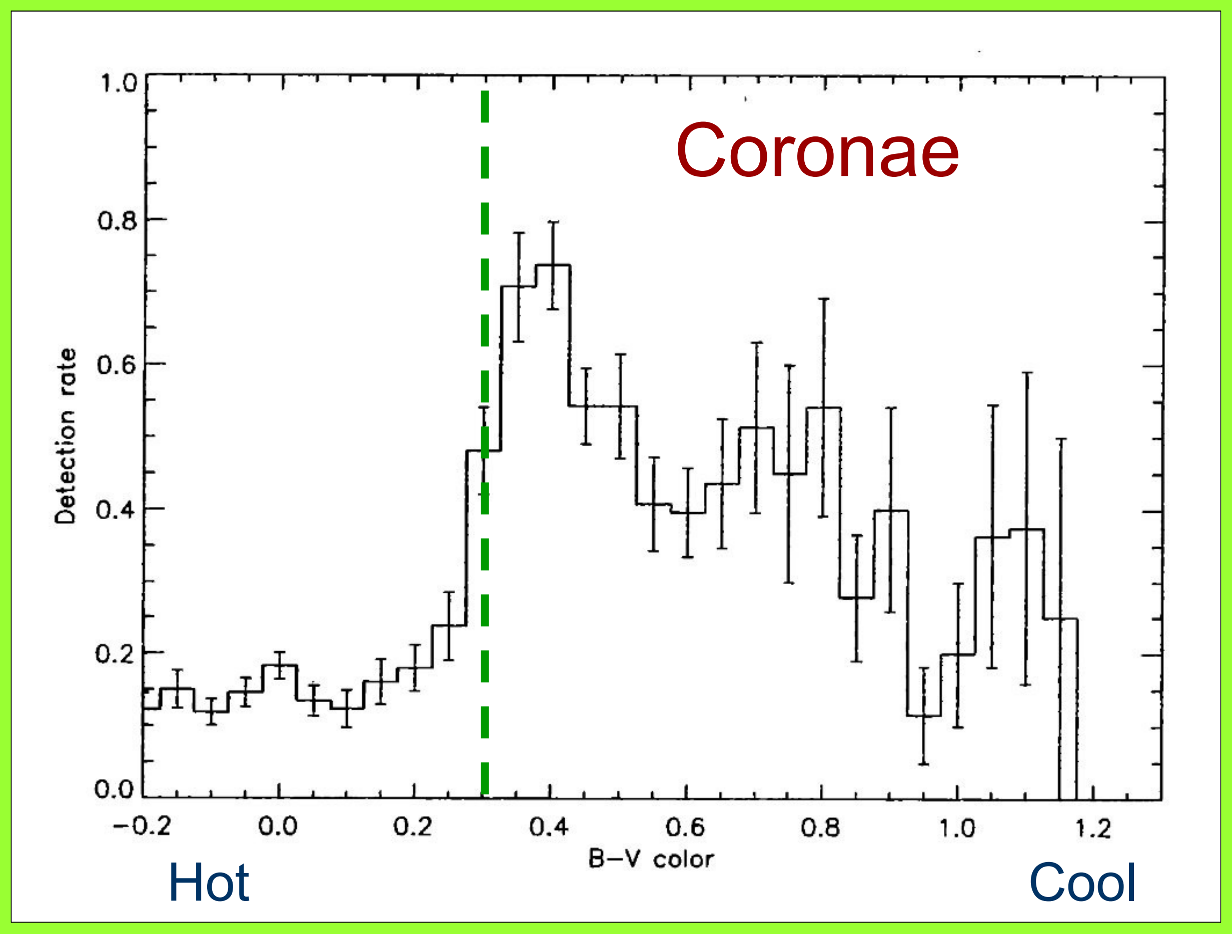
How is stellar magnetic activity measured ?

- X-ray emission
- Enhanced chromospheric emission and its variability
- Photospheric variability
- I'll concentrate mainly on cool stars, showing "solar-like" magnetic activity (although over a much larger range)

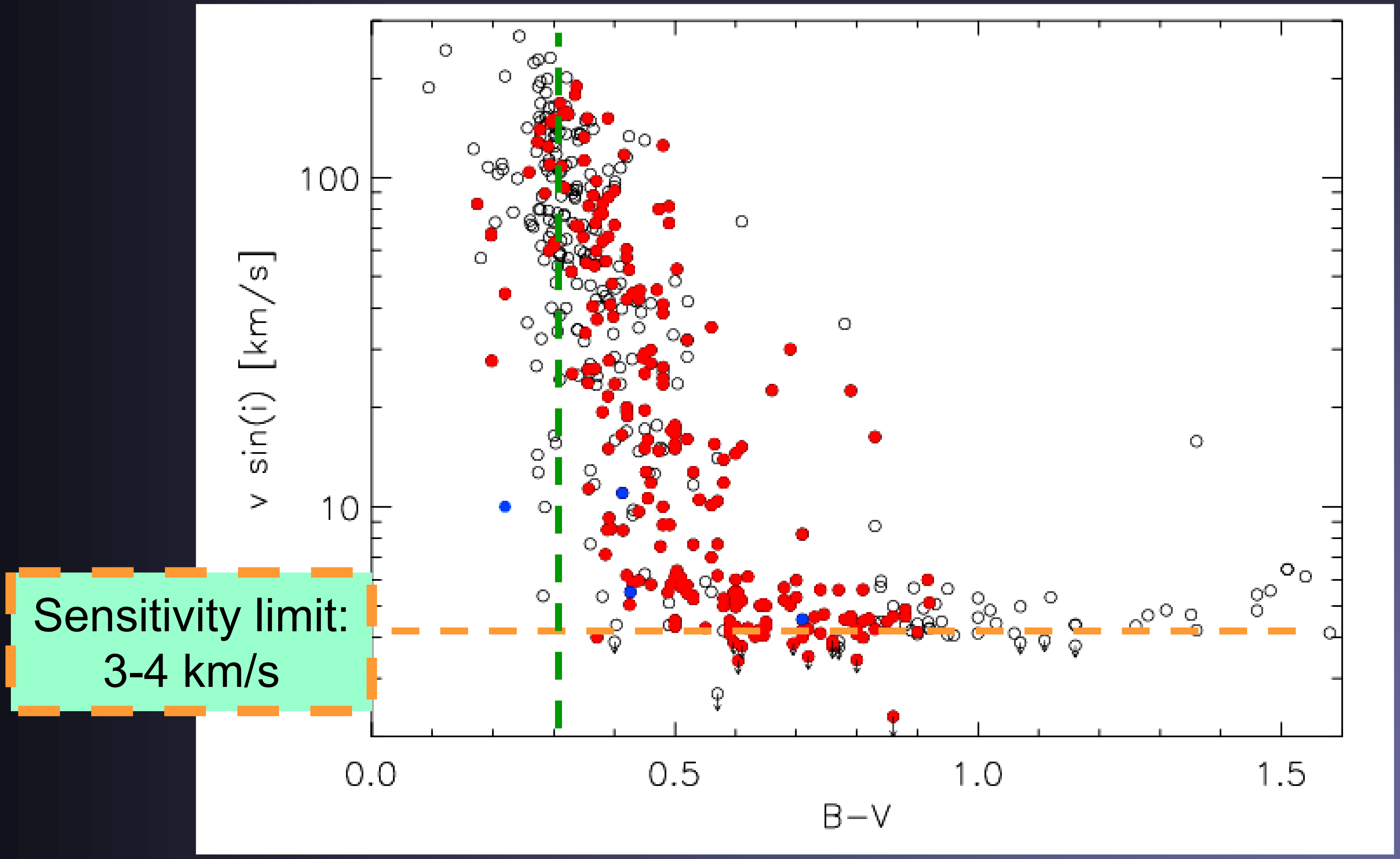


Which stars emit X-rays?

- Fraction of stars emitting X-rays vs. colour (i.e. temperature)
- Fraction increases at B-V=0.3
- Fraction decreases towards later types due to lower luminosity and sensitivity limit

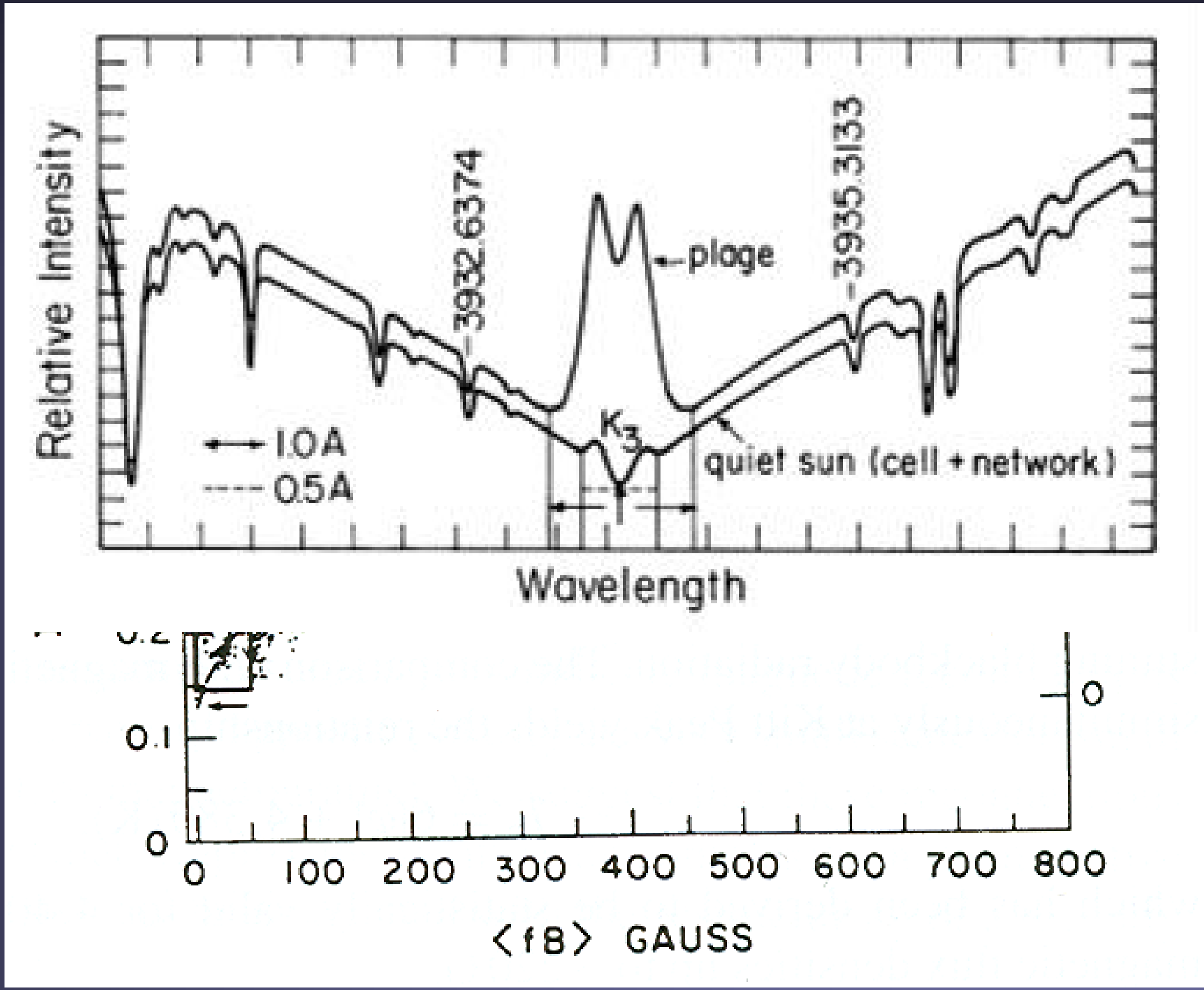


Rotational velocity vs. colour: evidence for rotational braking



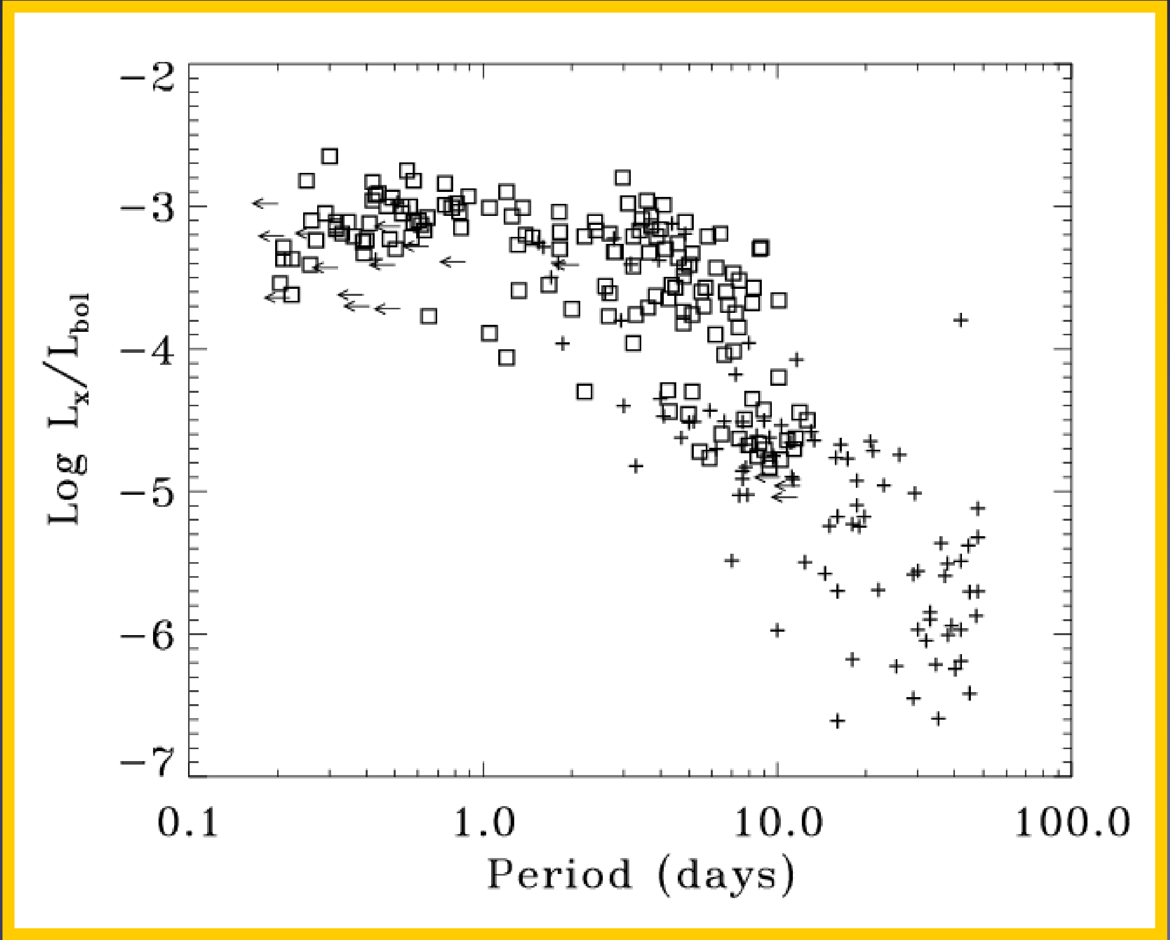
Ca II K as a magnetic activity indicator

- Ca II H and K: strongest lines in visible spectra of G and K stars
- $I_{core}/I_{wing} \sim \langle B\rangle^{0.6}$
- Ca lines are good tracers of stellar (chromospheric) magnetic activity
- Better S/N than X-rays. Can be observed from ground



Activity-rotation relationship

- Typical: Activity increases with decreasing rotation period
- Scatter is reduced if L_x/L_{bol} is plotted (instead of just L_x)
- Also typical: below a certain rotation period there is a saturation. I.e. activity does not increase anymore



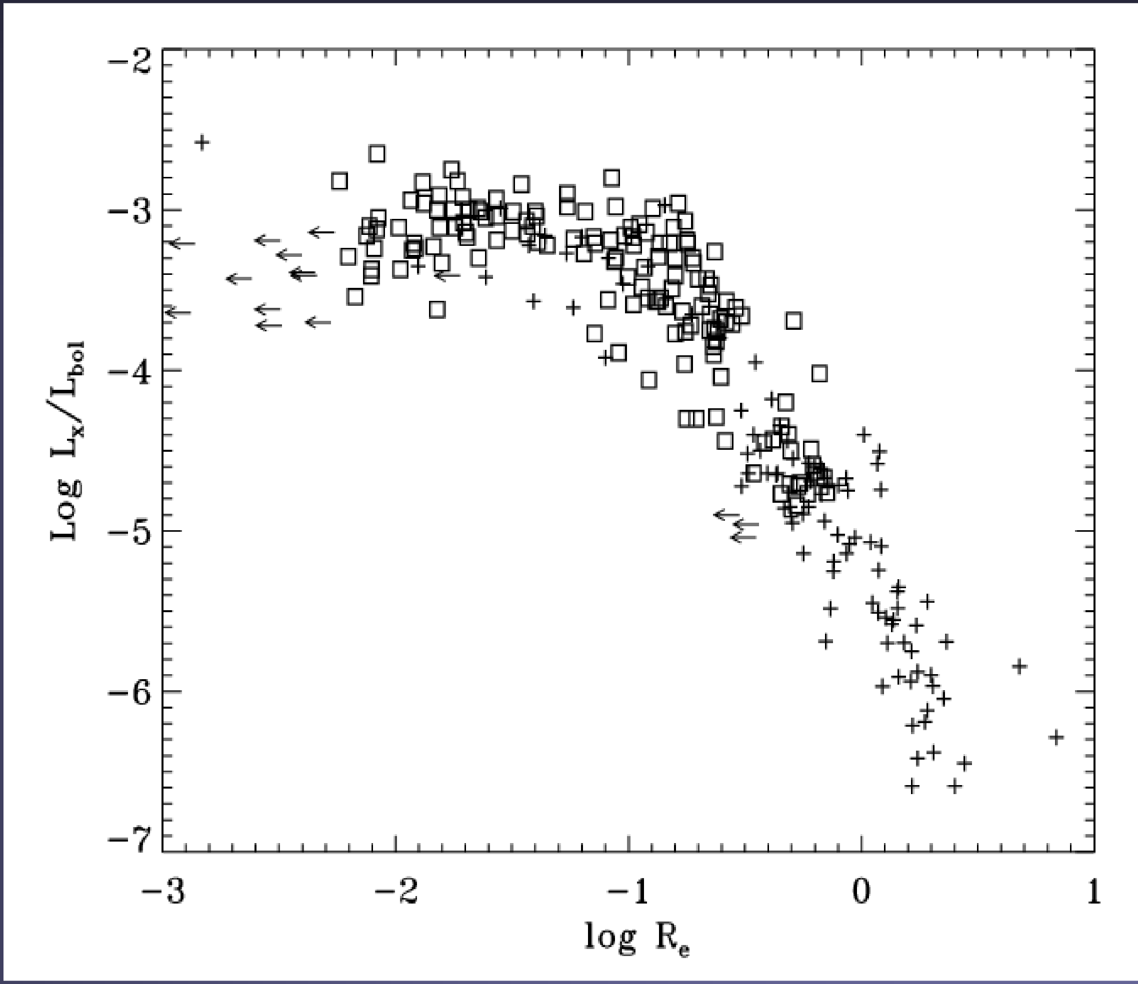
Pizzolato et al. 1993

Activity-rotation relationship

- Typical: scatter is further reduced if instead of rotation period the Rossby number is used.

$$Ro = \frac{v_c}{2H\Omega} \propto \frac{P_{\mathrm{rot}}}{\tau_{\mathrm{c}}}$$

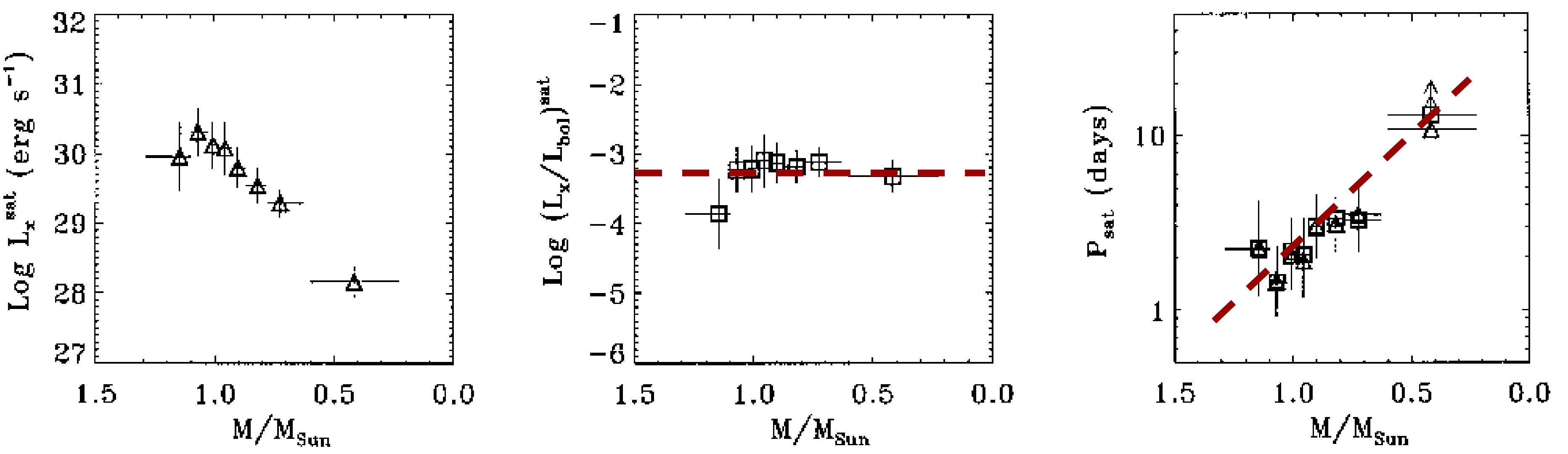
- Rossby number: ratio of rotation time-scale to convective timescale
- It removes (or at least reduces) the stellar mass dependence



Pizzolato et al. 1993

Activity-rotation relationship

- Level at which L_x saturates depends on mass
- Mass dependence is reduced for L_x/L_{bol}
- Period at which saturation takes place P_{sat} also depends on stellar mass

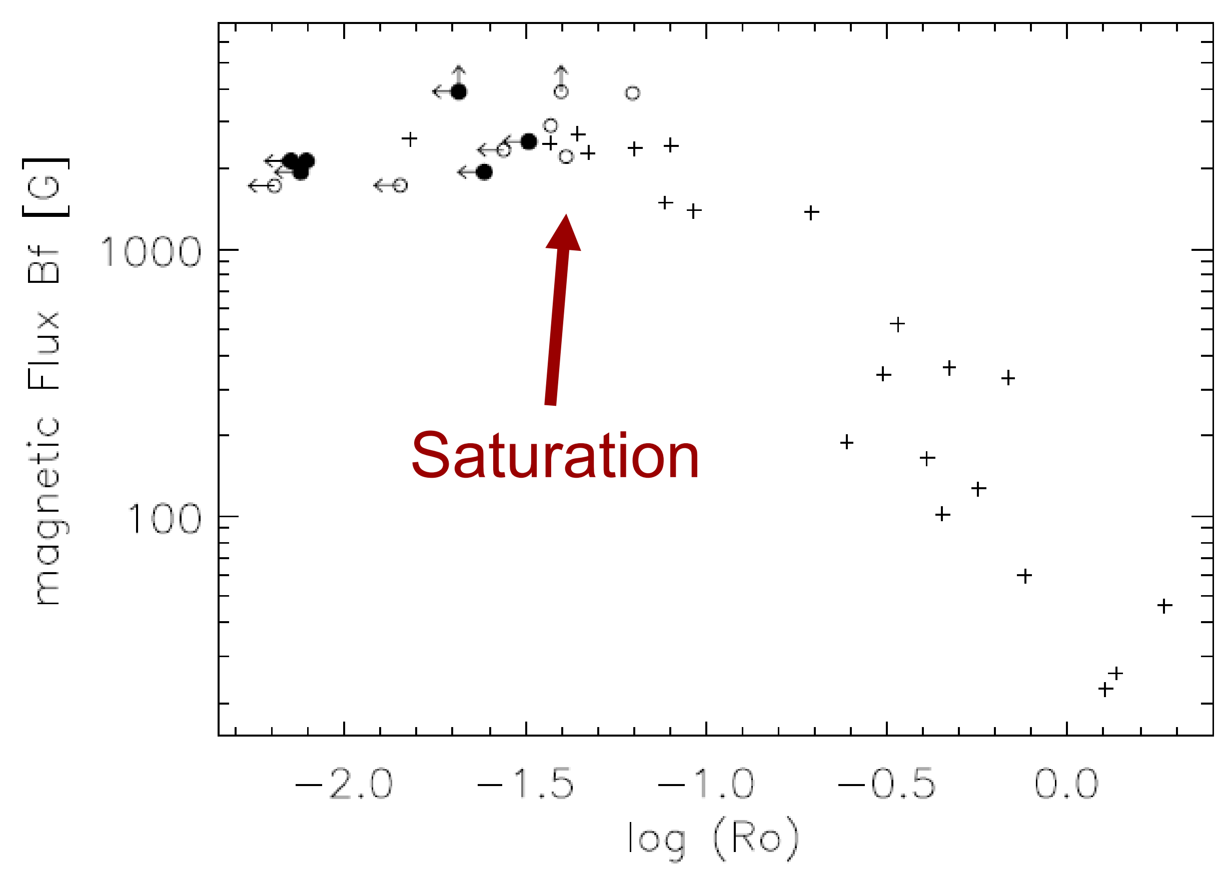


Pizzolato et al. 1993

Does the magnetic field saturate?

It really is the dynamo that saturates, not the heating!

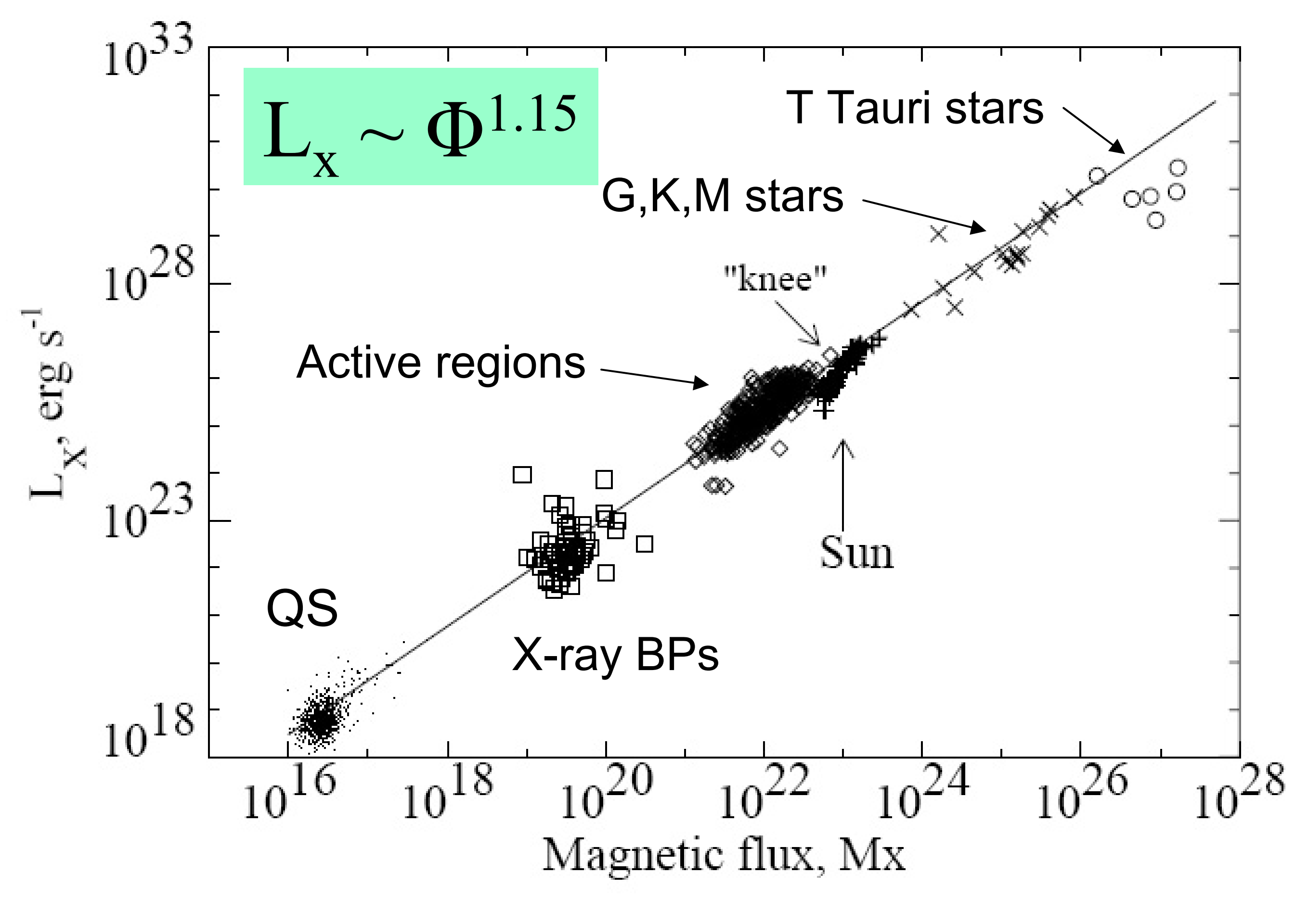
Data for G, K, M stars. Saturation in magnetic flux seen mainly for the most rapidly rotating M stars



Reiners & Basri 2009

Combined solar-stellar L_x-Φ relationship

Almost linear relationship over 12 orders of magnitude of flux



➔ universal (?) volumetric heating rate:

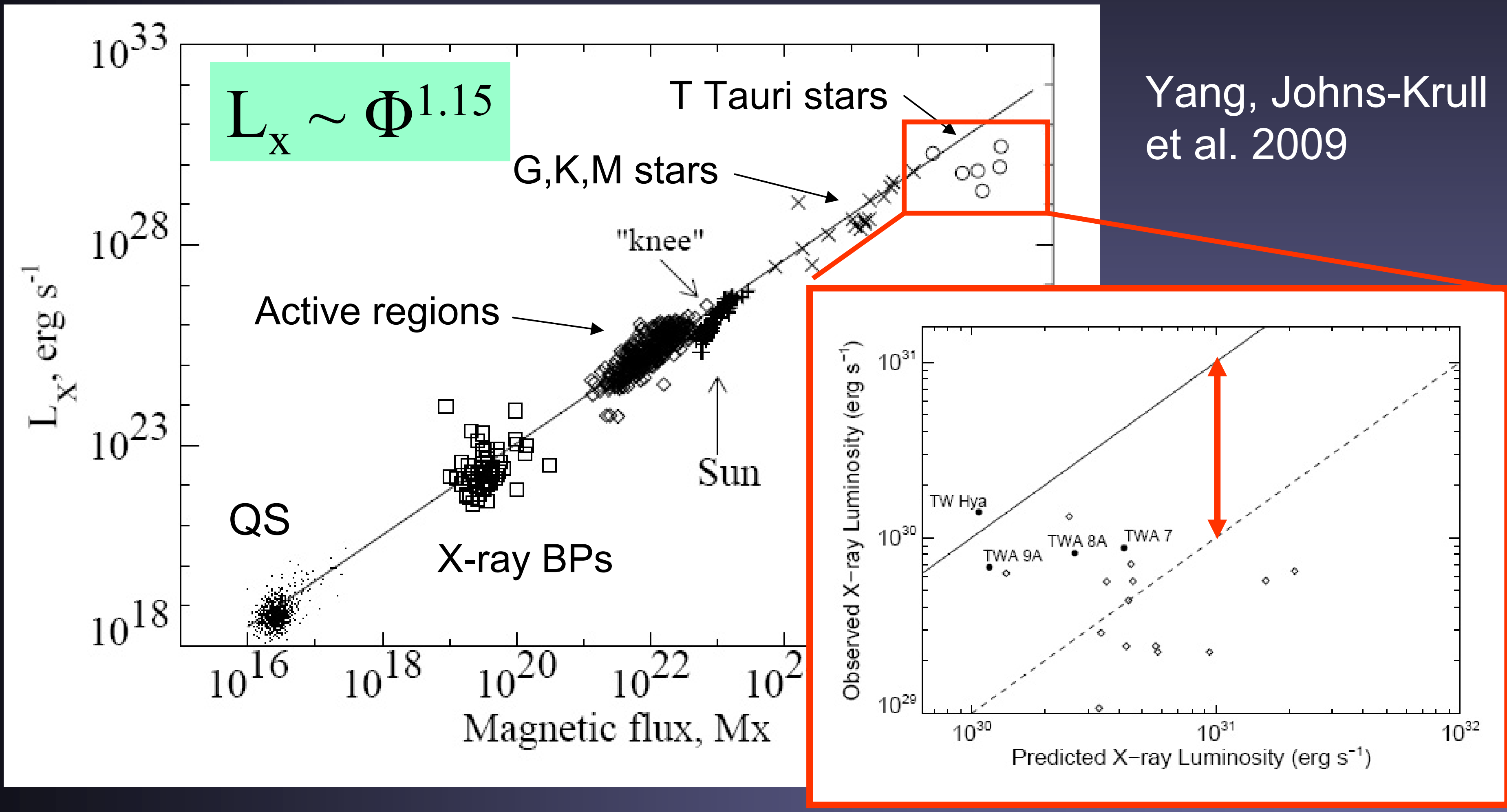
$Q \sim \underline{B}/L$

$\underline{B}$ = average field strength

L = length of field line between footpts

Pevtsov et al. 2003

L_x-Φ relationship: T Tauri stars

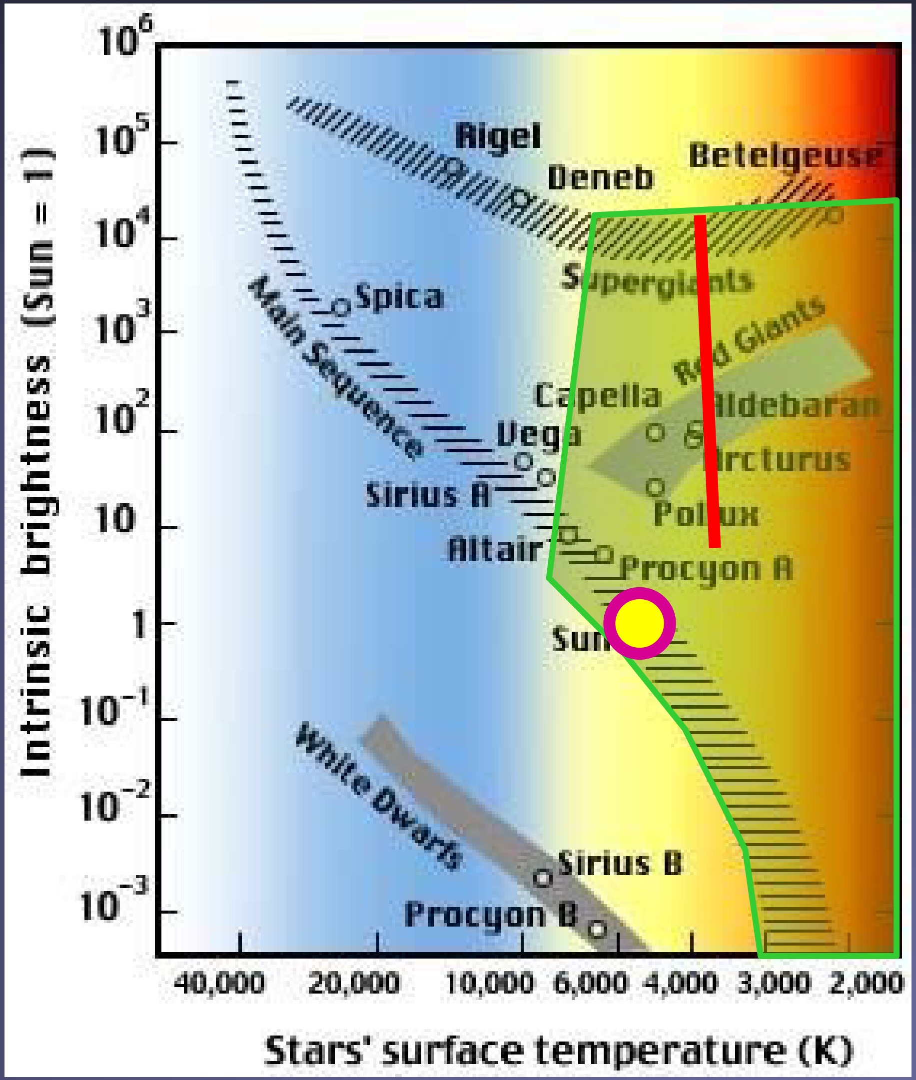


Yang, Johns-Krull et al. 2009

X-ray Coronal Dividing Line

- Giants hotter than the red line show strong X-ray emission and possess hot coronae
- Giants cooler than the red line show very little X-ray emission

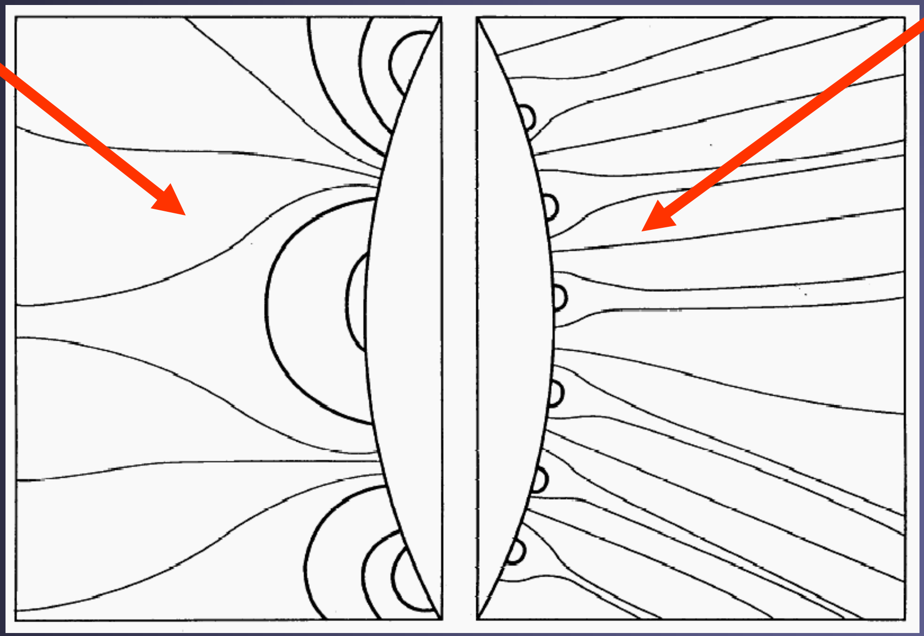
Haisch & Linsky; Haisch et al.



Magnetic topology across the X-ray Coronal Dividing Line

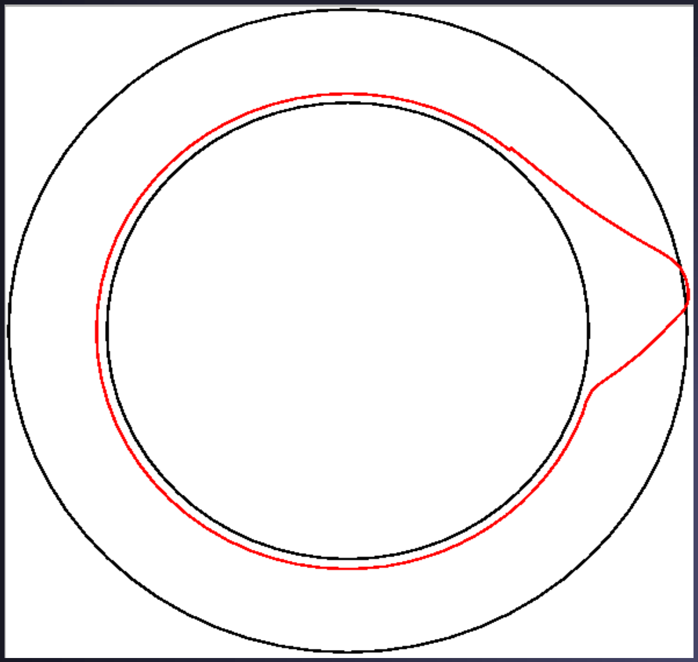
Leftward of the CDL:
- large-scale bipolar regions
- big coronal loops
- mostly closed field
- strong X-ray emission
- weak stellar wind

Rightward of the CDL:
- small-scale mixed polarity
- no large coronal loops
- mostly open field
- weak X-ray emission
- strong stellar wind

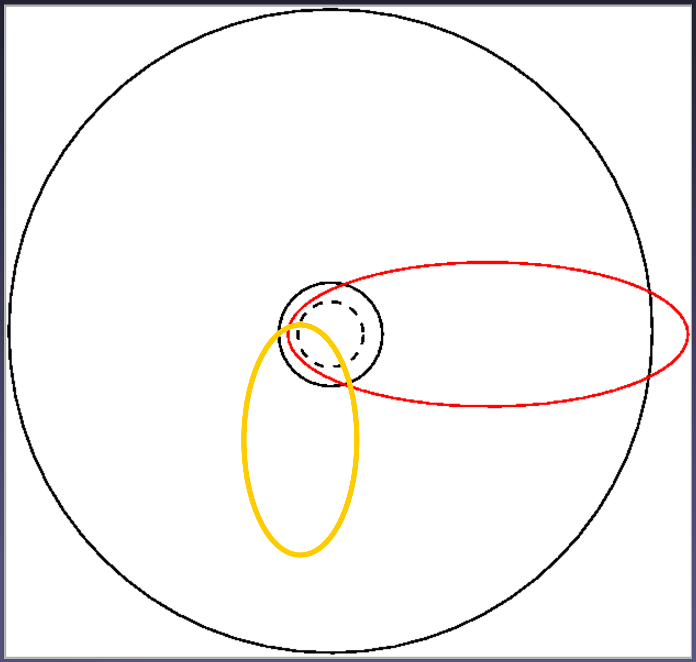


Rosner et al. (1995)

Eruption vs. trapping: buoyancy vs. curvature



Main-sequence star



Giant

Sufficiently small initial radius:

➔ curvature force increases more rapidly than buoyancy force

➔ new equilibrium within the convection zone

Trapping for $R_{tube} / R_{star} \lesssim 0.2$

Magnetic topology across the X-ray Coronal Dividing Line

- **Leftward of the CDL:**
  - → large-scale bipolar regions
  - → big coronal loops
  - → mostly closed field
  - → strong X-ray emission
  - → weak stellar wind
- **Rightward of the CDL:**
  - → small-scale mixed polarity
  - → no large coronal loops
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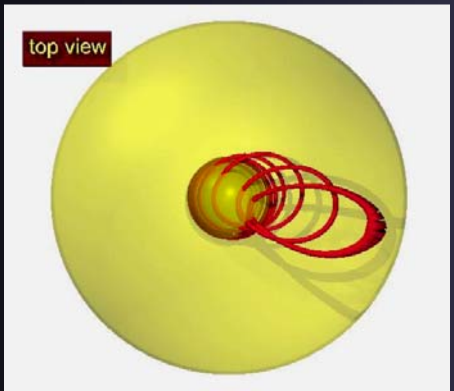
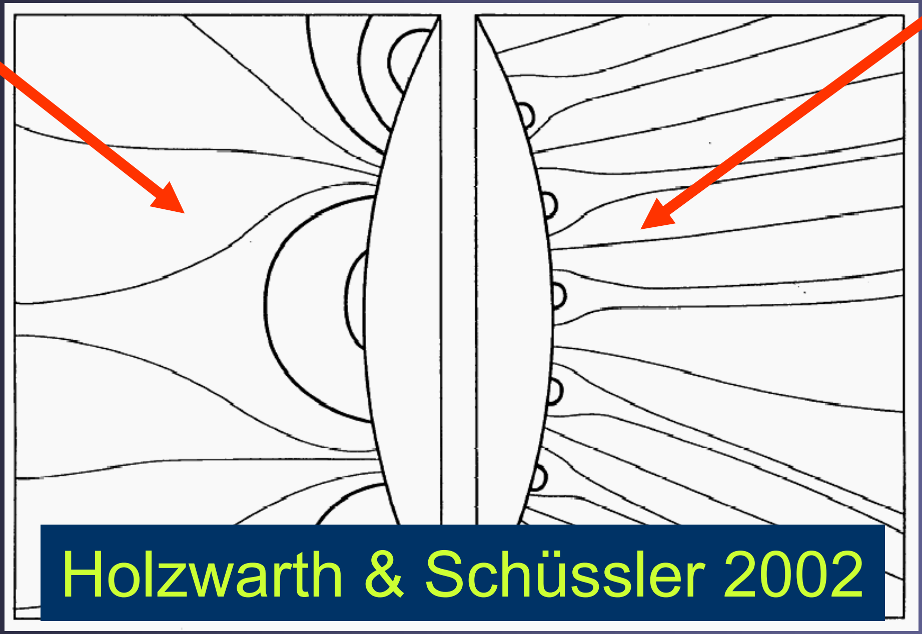
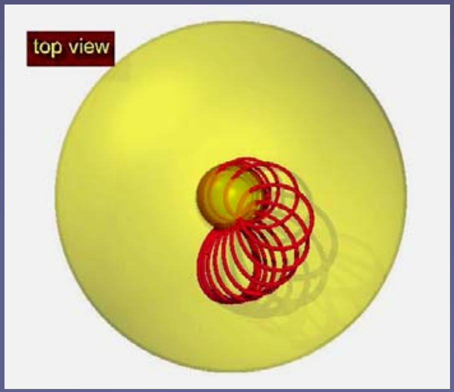
  - → weak X-ray emission
  - → strong stellar wind





Holzwarth & Schüssler 2002

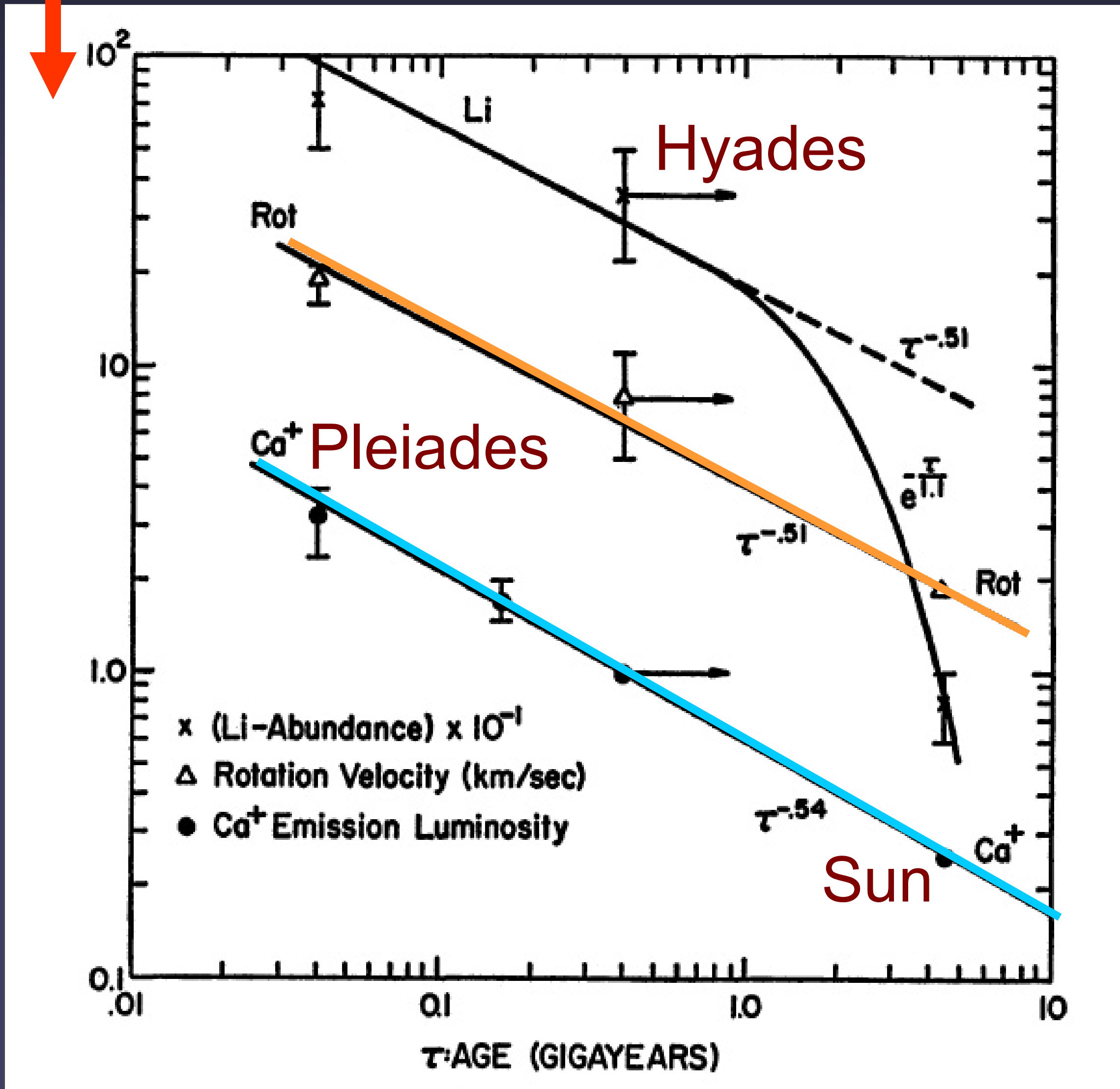


Rosner et al. (1995)

Spindown of cool stars

Spinup due to contraction

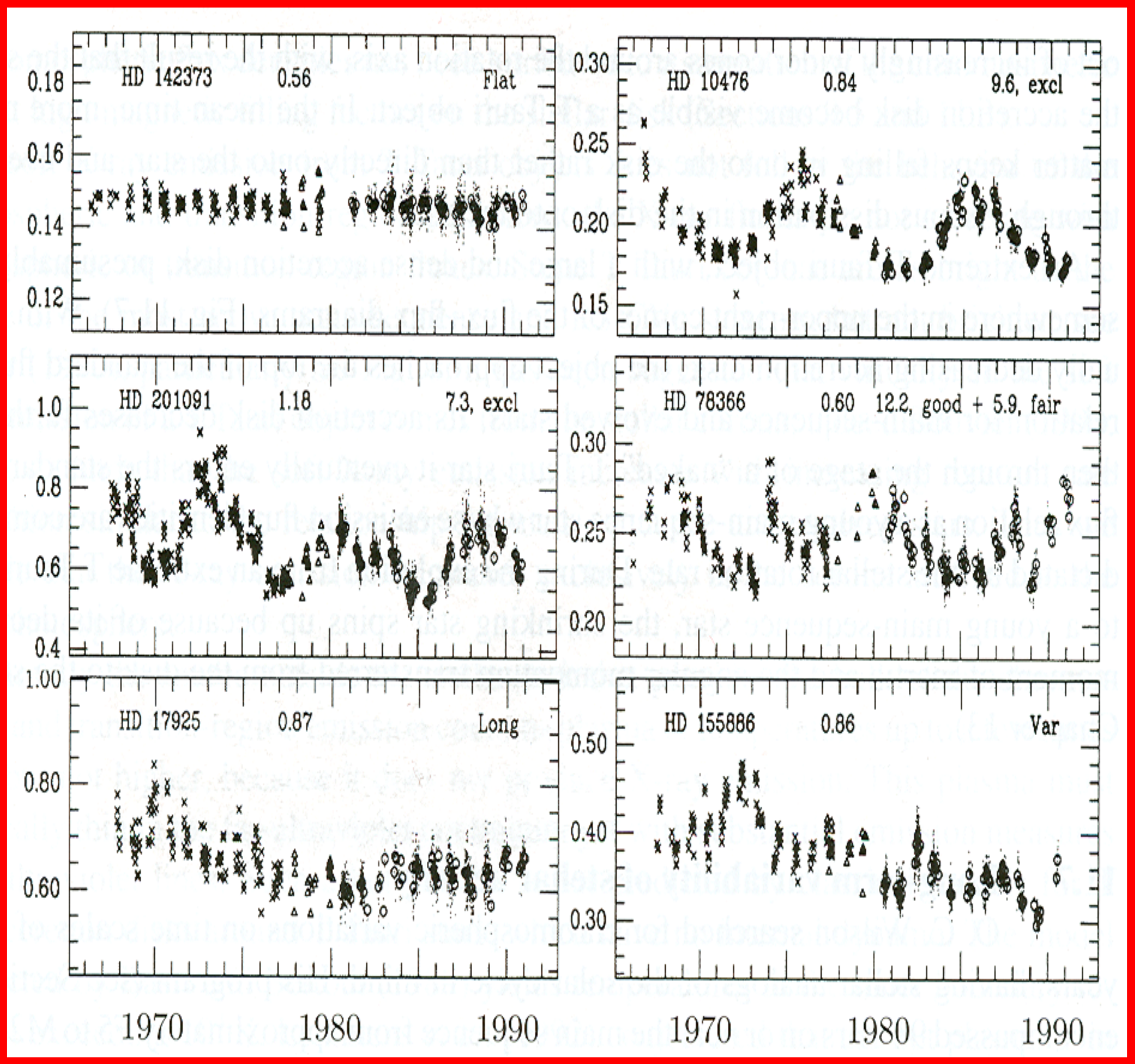
- Rotation rate evolves with stellar age on main sequence: $\Omega \sim t^{-1/2}$
- Ca II H+K flux (i.e. chromospheric activity) also decreases with $\Omega \sim t^{-1/2}$



Skumanich 1972

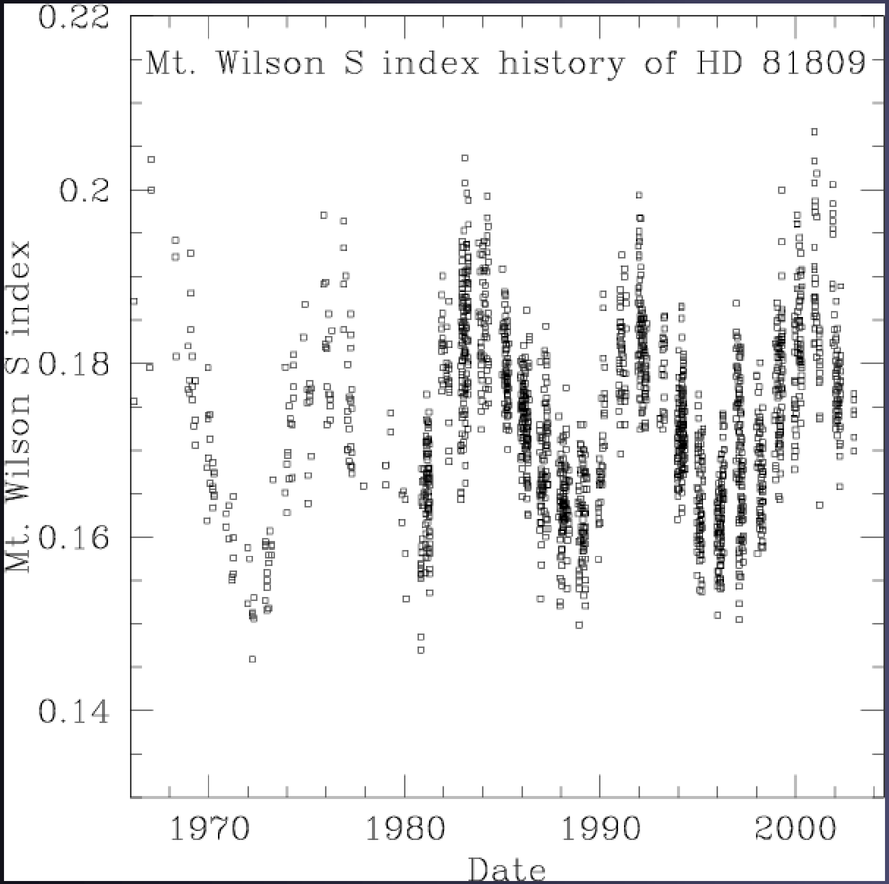
Stellar activity cycles

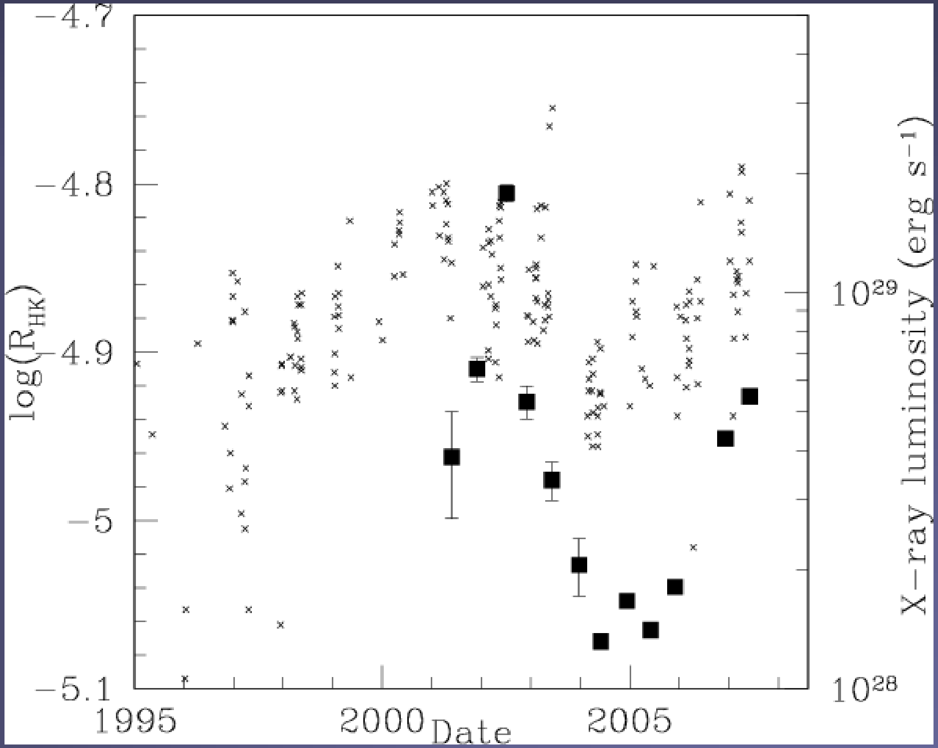
- Measurements of Ca II H and K flux over nearly 3 decades from Mt Wilson survey (started by Olin Wilson)
- Stars at different activity levels are seen. Some clearly display cycles



Activity cycles in chromosphere & corona

- Chromospheric activity cycle from Mt Wilson & Lowell Obs. (extension & continuation of Mt Wilson program)
- XMM/Newton shows parallel X-ray cycle

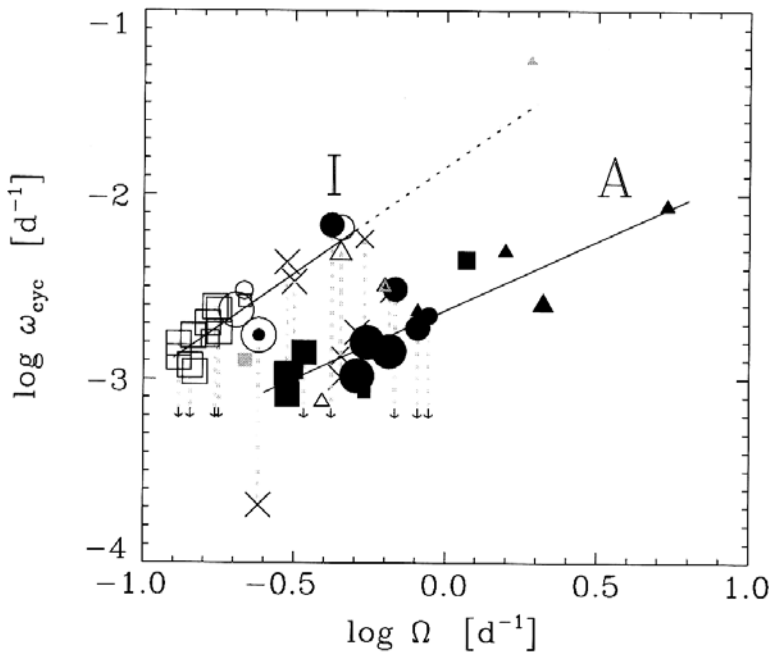


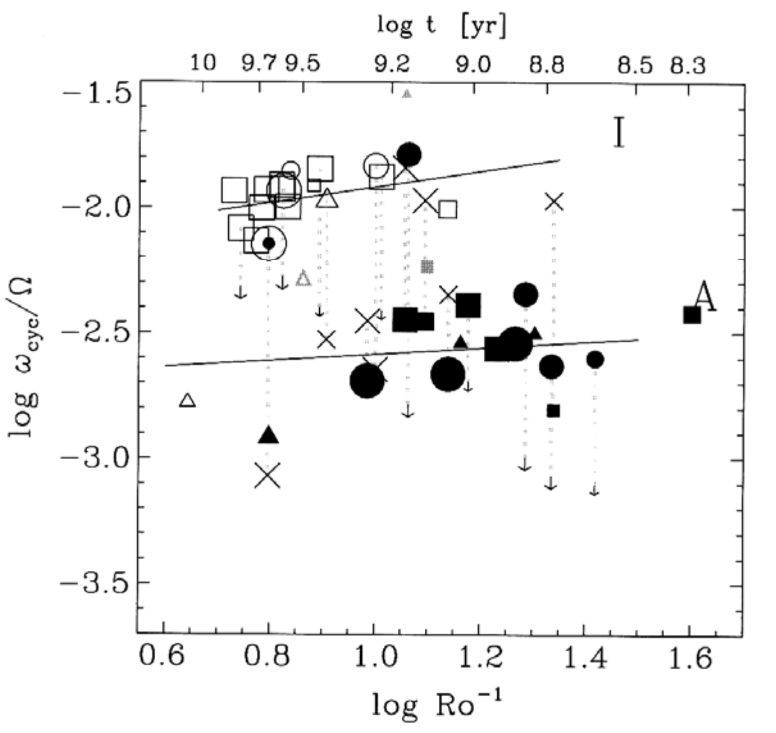


Cycle period vs. rotation period

- Cycle frequency ω_{cyc} scales with rotation rate Ω
- Two branches: inactive stars: I, active stars: A
- Active stars have shorter cycles (for given Ω)
- $\omega_{cyc} \sim \Omega^{1.15}$ for I stars
- $\omega_{cyc} \sim \Omega^{0.8}$ for A stars

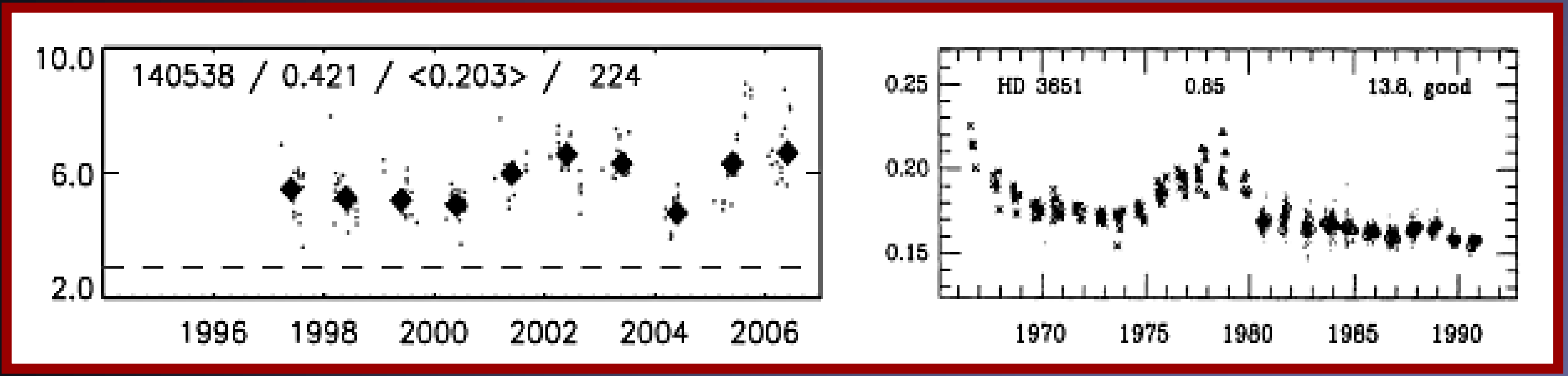
Saar (2002)



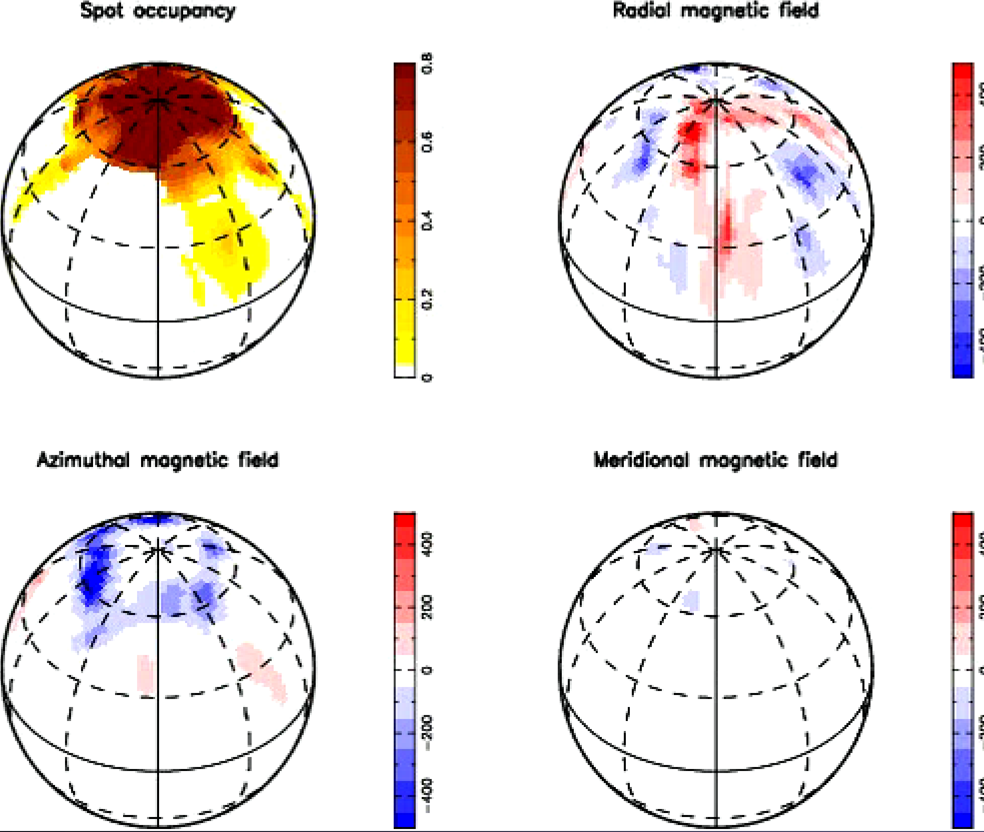


Stars leaving or entering a Grand Minimum?

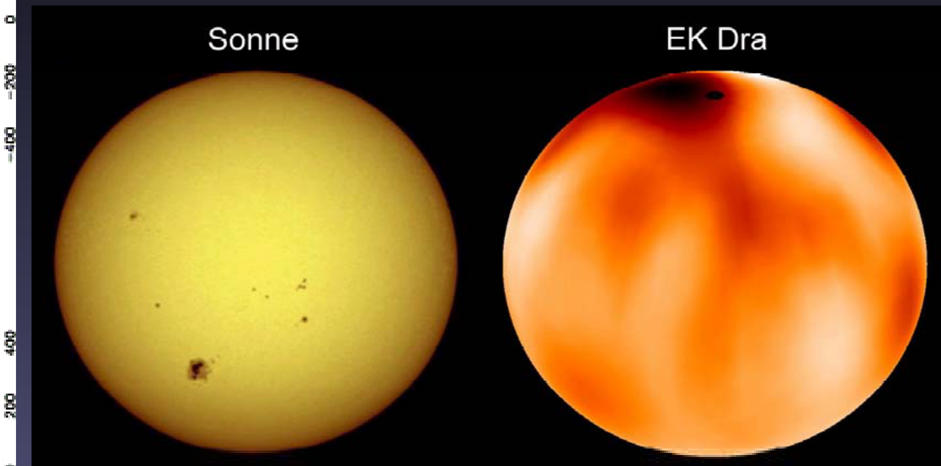
- Some stars are seen to move into or out of a flat low-activity state → Interpreted as entering or leaving a Grand Minimum
- HD 3651: over 6 years in low activity state: GM candidate
- HD 140538: spent 2-3 years in low activity state: if that is a Grand Min, then Sun is now also in a Grand Min. since 2006

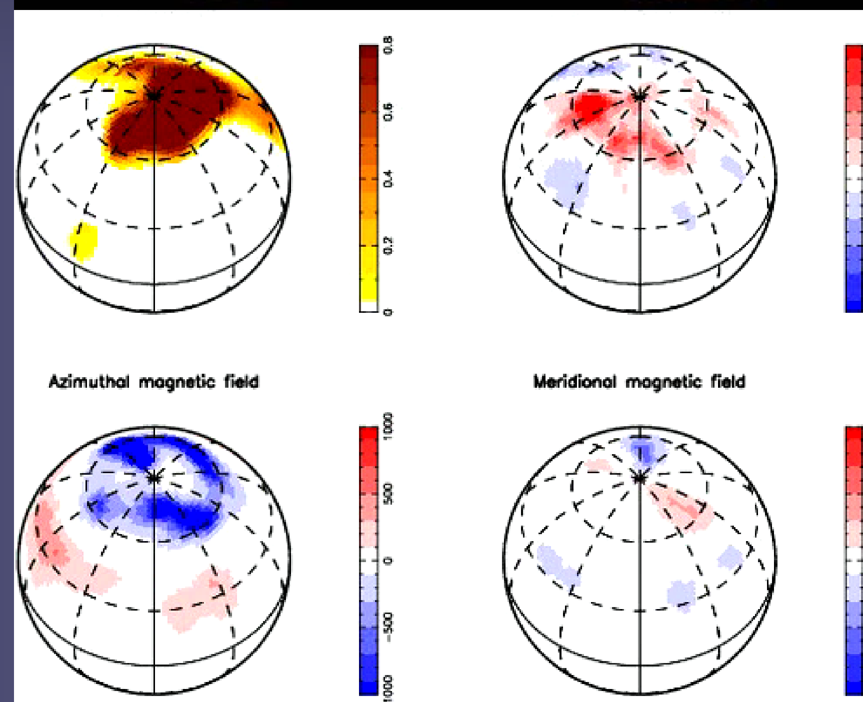


Baliunas et al. 1995, Hall et al. 2007



Sunspots - starspots

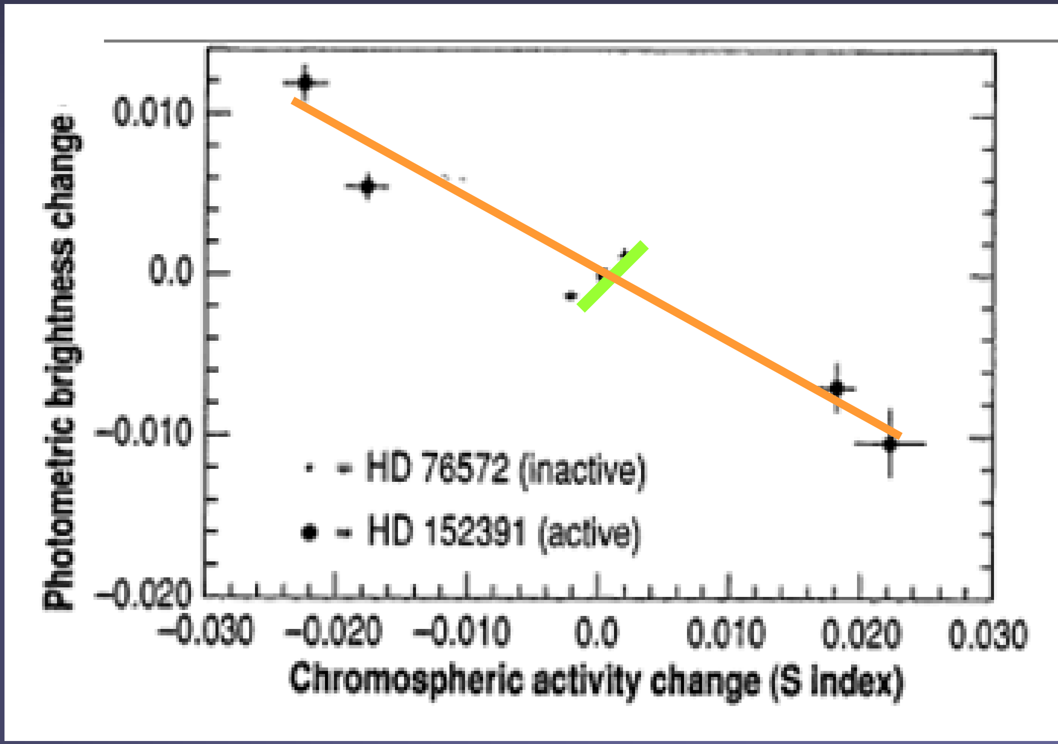




- Active binary stars, slightly evolved
- Display large spot coverage (10% or more of visible hemisphere)

Ratio of faculae to plage in active to inactive stars

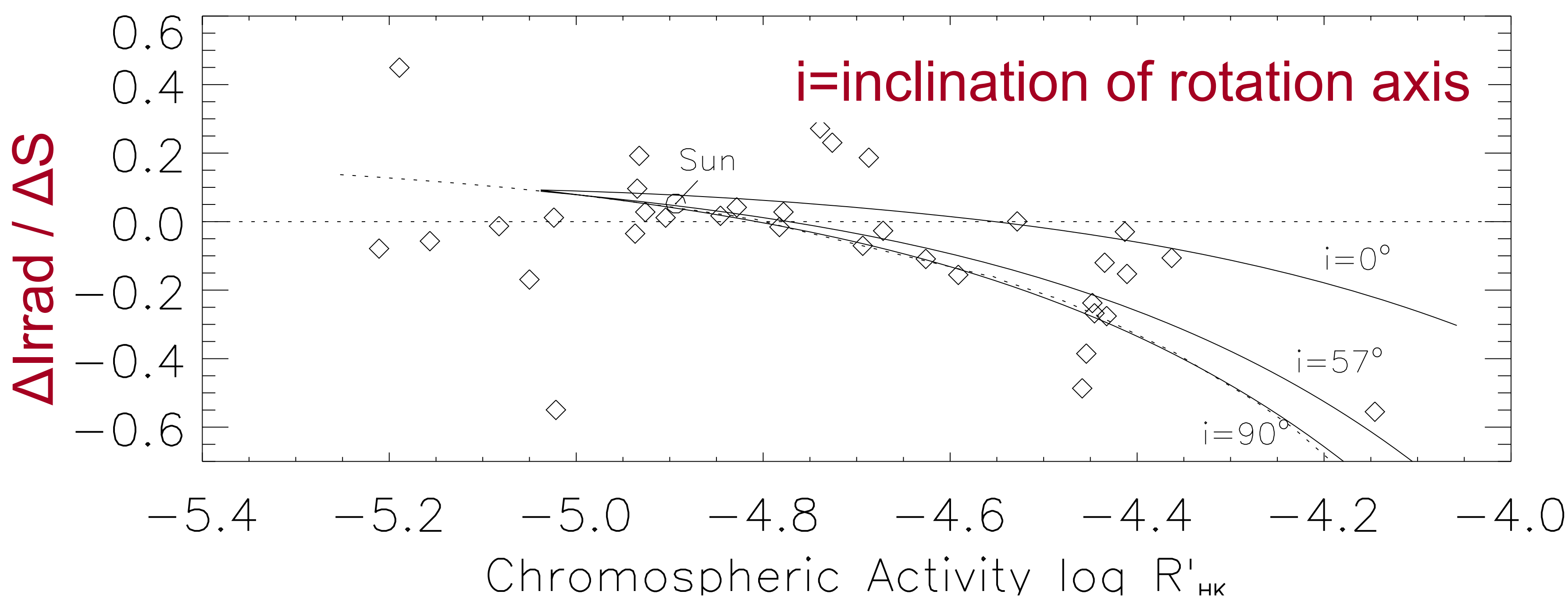
- inactive star displays behaviour similar to Sun: at cycle phase with higher activity (chromospheric index) star is brighter
- active star displays opposite behaviour: star is darker during more active phase
- Ratio of faculae (plage) to spots chages with increasing activity



Radick et al. 1989

Extrapolation to active stars

- results of Lockwood et al. (1992); Radick et al. (1998, 2007): more active stars dark at high activity
- Extrapolation from Sun (Knaack et al. in prep.) roughly reproduces ➔Strengthens "solar paradigm" for stellar activity



Is the Sun a sun-like star?

- Consider variability vs. activity
- Sun lies slighly (<1σ) above the relation for chromospheric variability
- Sun lies 2σ below the relation for photospheric variability