The Various Variations of Cool Stars

Variations of Solar-like Dwarfs (luminosity class V) on a Veritably Vertiginous Variety of Timescales

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(with special thanks to the organizers, Afrin®, Sudafed® for making this talk possible)

Variability in Cool Dwarfs

Present on many temporal and spatial scales

Of fundamental importance for characterizing/ understanding MHD flows, dynamos, energetics, etc…. everything interesting!

Phenomena/Timescales:

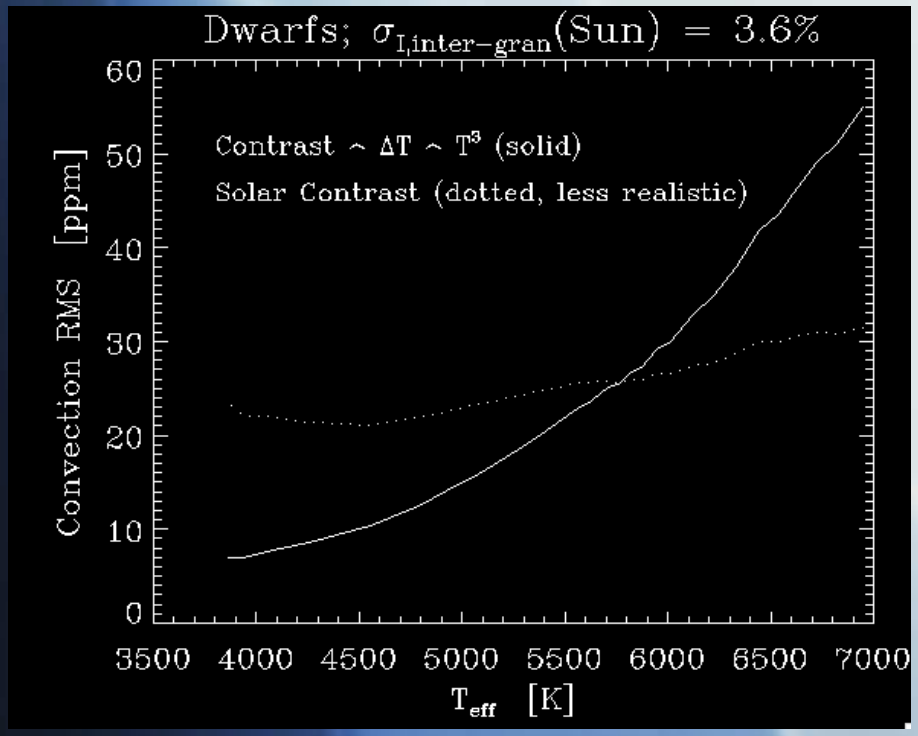
- Convection [mins]
- Flares [mins-hours]
- Rotation [hours-weeks]
- Differential rotation [weeks-months]
- Active Region growth/decay [weeks-months]
- Active Longitude switching (“flip-flops”) [years]
- Activity cycles [years-decades]
- Long-term maxima/minima (eg, Maunder min.) [centuries]

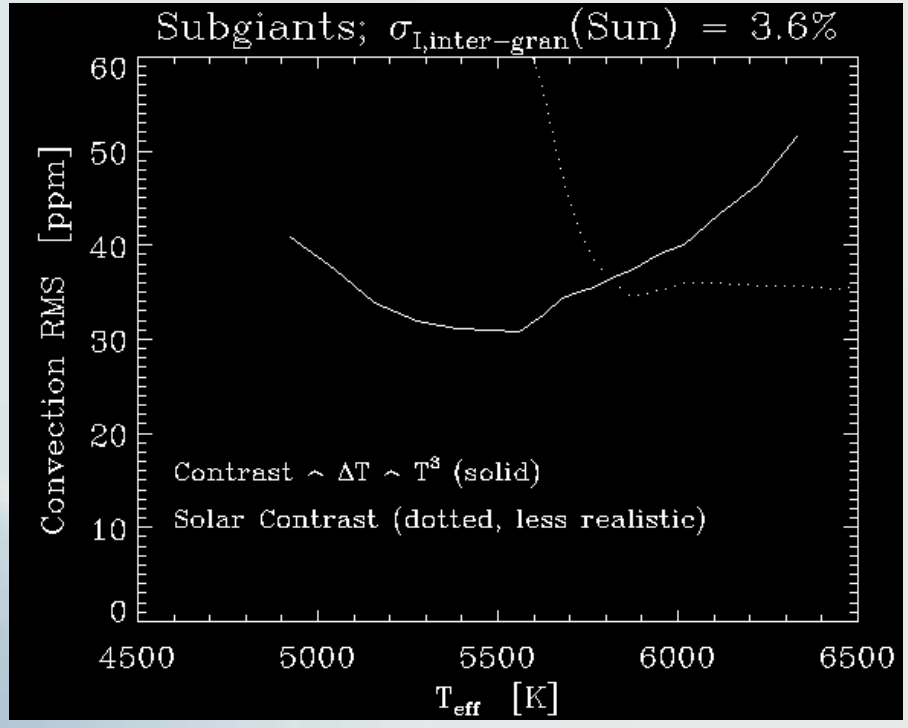
Convection

(Limited) info from models, line bisectors

- Assume cell size scales as pressure scale height: $d \sim (H_P / H_{P,Sun}) d_{Sun}$
- Assume intensity RMS goes as

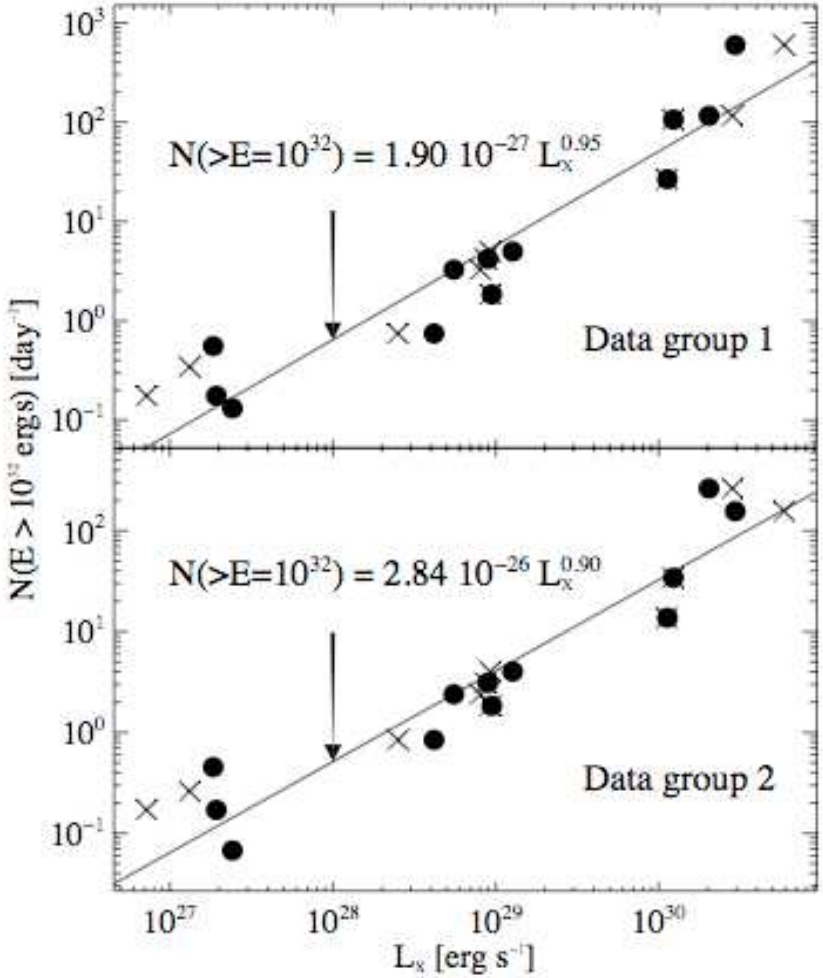
  $\sigma_{I,cell} \sim (\Delta F/\Delta F_{Sun})\, \sigma_{I,cell,Sun} \sim (T_{eff}/T_{eff,Sun})^3\, \sigma_{I,cell,Sun}$ (here, used $\sigma_{I,cell,Sun} = 3.6\%$)
- Number of cells $N \sim (R_*/d)^2$
- Expected stellar RMS intensity is then $\sigma_I \sim N^{1/2}\, \sigma_{I,cell}$
- Noise floor for Kepler/Corot-type planet transit/helioseismology missions





Flares

Best data for GK stars probably from X-ray monitoring (optical data only sees brightest flares on faintest stars)

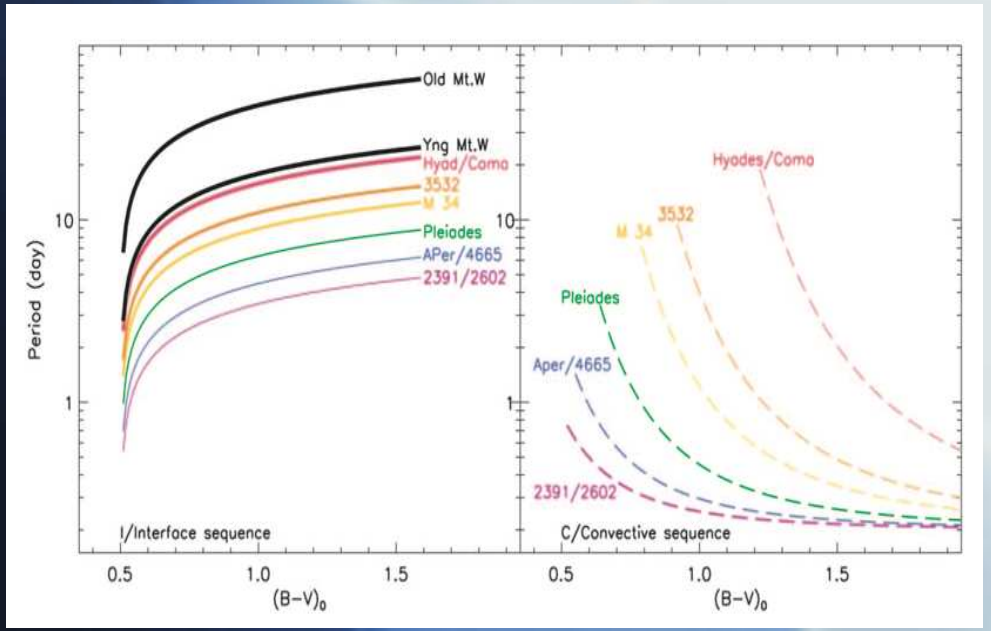


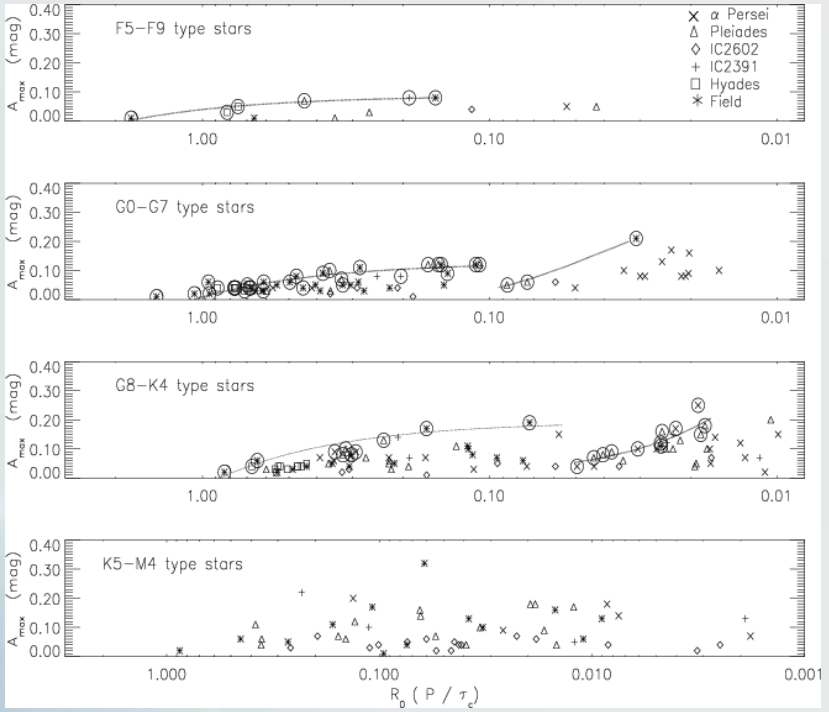
- $N(E>10^{32}\ \text{ergs}) \sim L_X^{0.9}$ (Audard et al 2000) ~ an X1 flare
- $dN/dE \sim E_{tot}^{(1-\alpha)}$; $\alpha_{Sun} \sim 1.6$, $\alpha_{youngSun} \sim 2.2$ (Audard et al 2000)
- $L_X \sim t^{-0.6}$ (Güdel etal 1998); $\alpha \sim L_X^{0.2}$ (fit to Audard et al 2000)
- Can use to extrapolate to other E ranges, estimate number of X-ray, white light flares for Sun at any age.

Rotation

Data: photometry (spot+plage), activity diagnostic (Ca II, Xray), line profile shape, Doppler imaging

- Rotation spans 0.2 - 50^{+} d in single dwarfs
- $P_{rot} \sim f(M)t^{0.55}$ (Skumanich 1972; Barnes 2003, "I" branch = interface dynamos?)
- $P_{rot} \sim \exp(-g(M,t)t)$ (Barnes 2003, "C" branch = convective dynamos?)
- Maximum amplitude $A_{pho}(max) \sim a - b(P_{rot}/\tau)$ (Messina etal 2001)
  (spread below this due to sini, distribution of spots); increases for lower mass

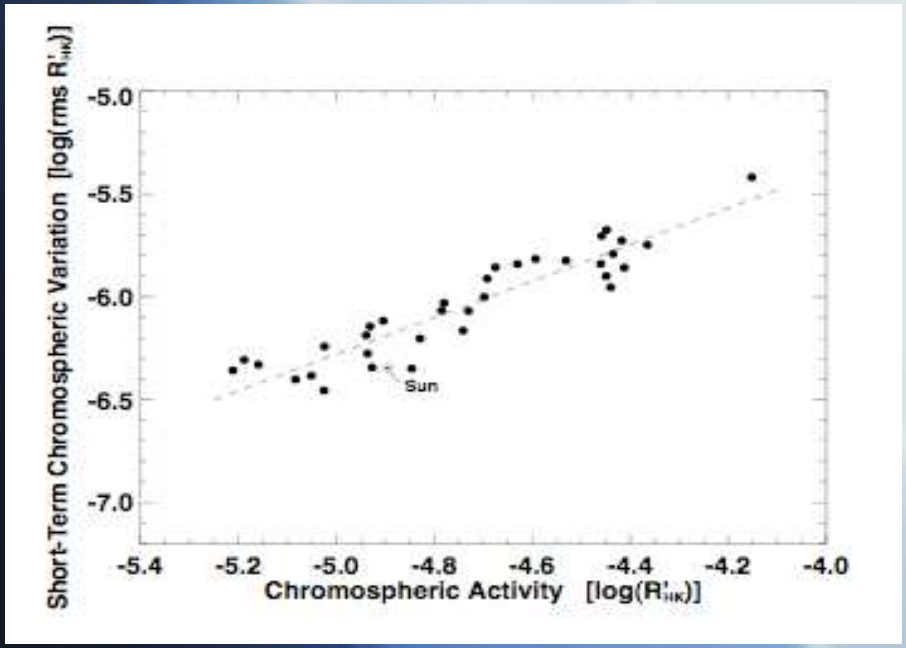


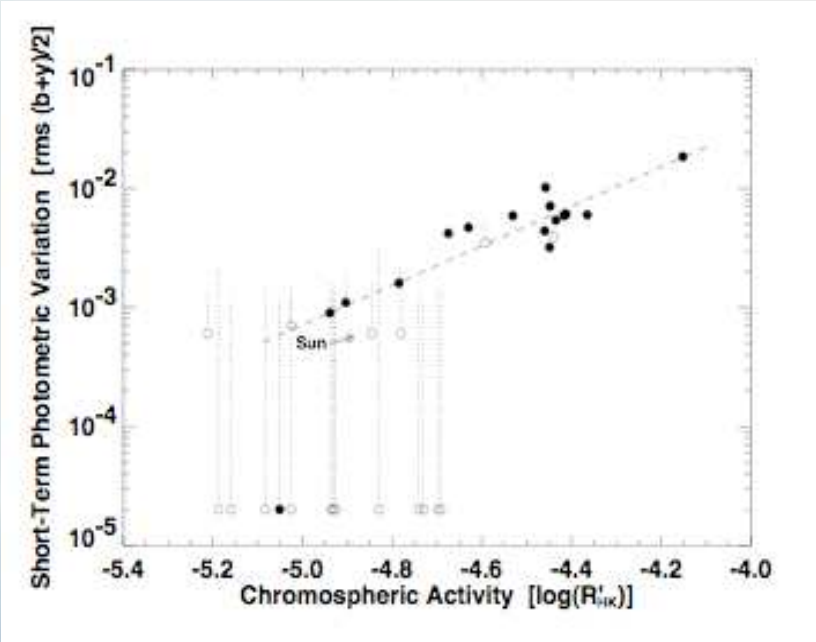


Rotation II. RMS variation

Data: intra-seasonal HK,photometric RMS (includes differential rotation, AR growth/decay)

- σ_{HK}(short-term) ~ $(F'_{HK}/F_{bol})^{0.88}$ (using Radick ea 1998)
- σ_{pho}(short-term) ~ $(F'_{HK}/F_{bol})^{1.62}$ (using Radick ea 1998)
- So σ_{pho} (short-term) ~ σ_{HK}(short-term)$^{1.84}$



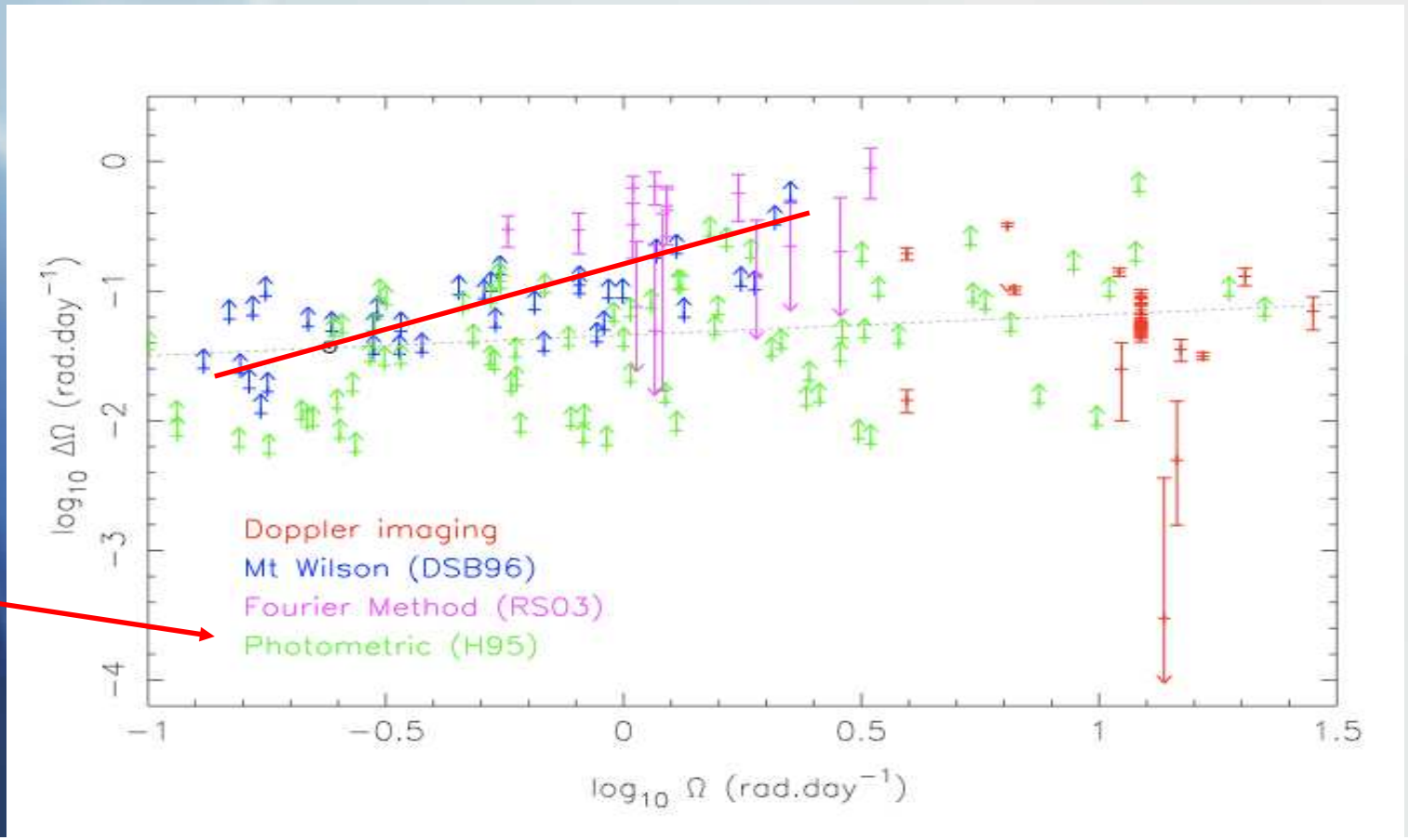


Differential Rotation

Data: focus on single dwarfs, similar kinds of data, get ΔP_{rot}

- Barnes et al 2005 found $\Delta\Omega \sim \Omega^{0.1}$ (!), but included evolved stars & binaries (Hall 1995)
- $\Delta\Omega \sim \Omega^{0.7}$, $\Delta P_{rot} \sim P_{rot}^{1.3}$ (Donahue ea 1996) ($P_{rot} > 3$d) [other dwarf data consistent]
- $\Delta\Omega$ saturation, decline for $P_{rot} < 3$ d? (Barnes etal 2005, reinterpreted)
- T_{eff}, Mass dependence for high Ω (Barnes etal 2005)

Many evolved stars & binaries



Active Region Growth/Decay

Data: Ca II HK, photometry

Analyze: spot lifetimes, pooled HK variance ($\int\sigma_{HK}^2$)

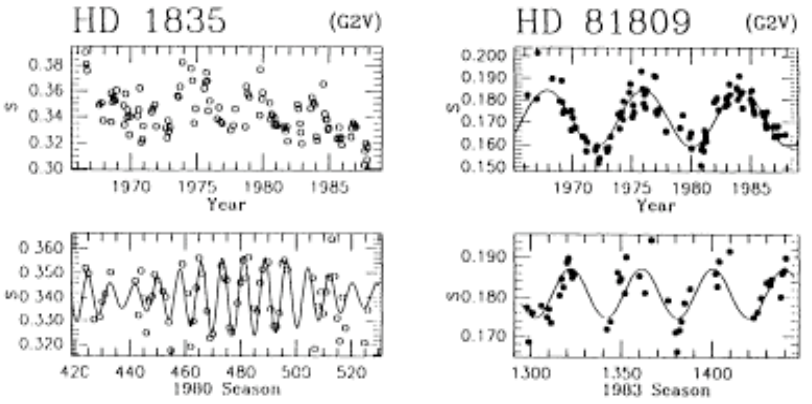
active P_{rot}~8d inactive P_{rot}~20d

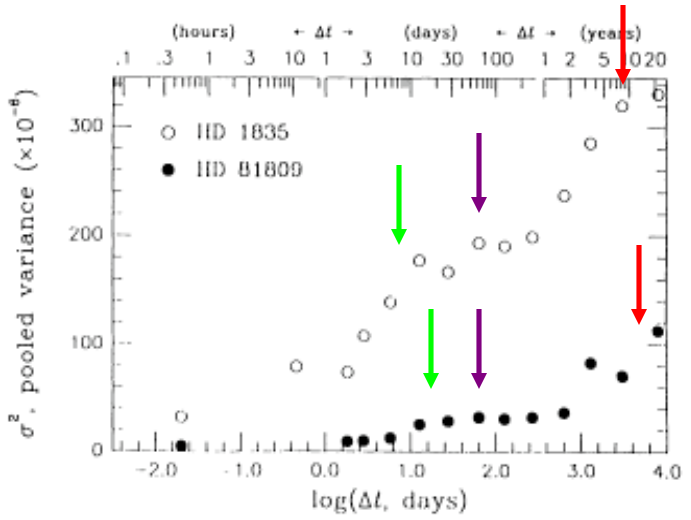
Long-term

Jumps in $\int\sigma_{HK}^2$ at significant new phenomena:
rotation,
ARGD,
cycles

Rotation

ARGD





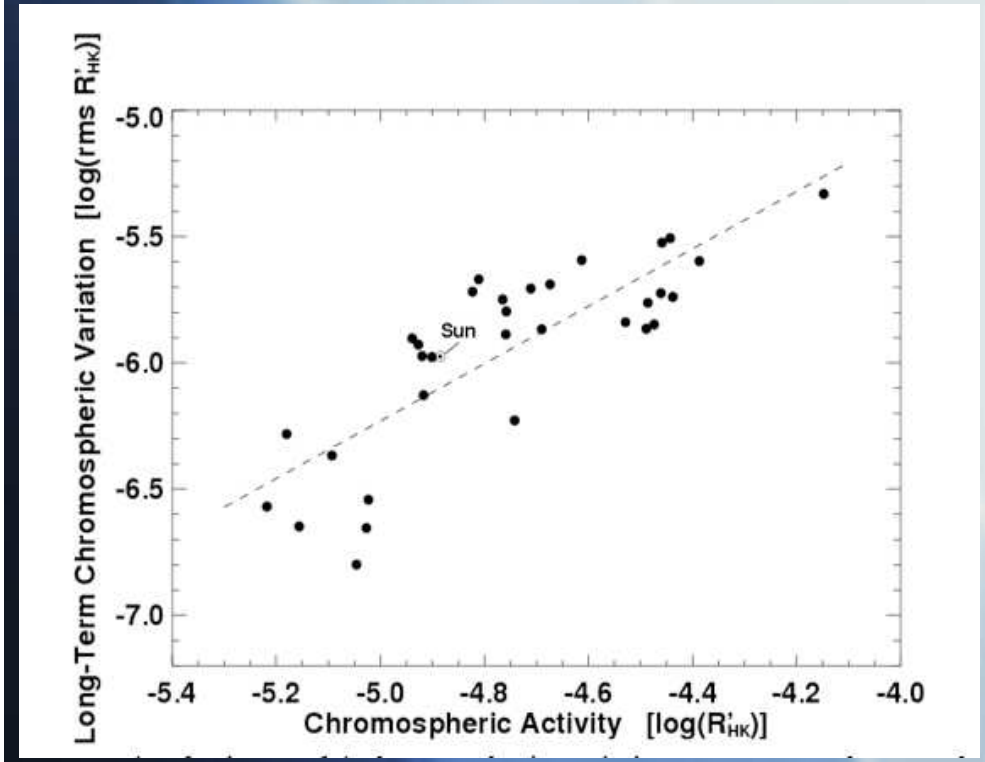
Pooled variance $\int\sigma_{HK}^2$

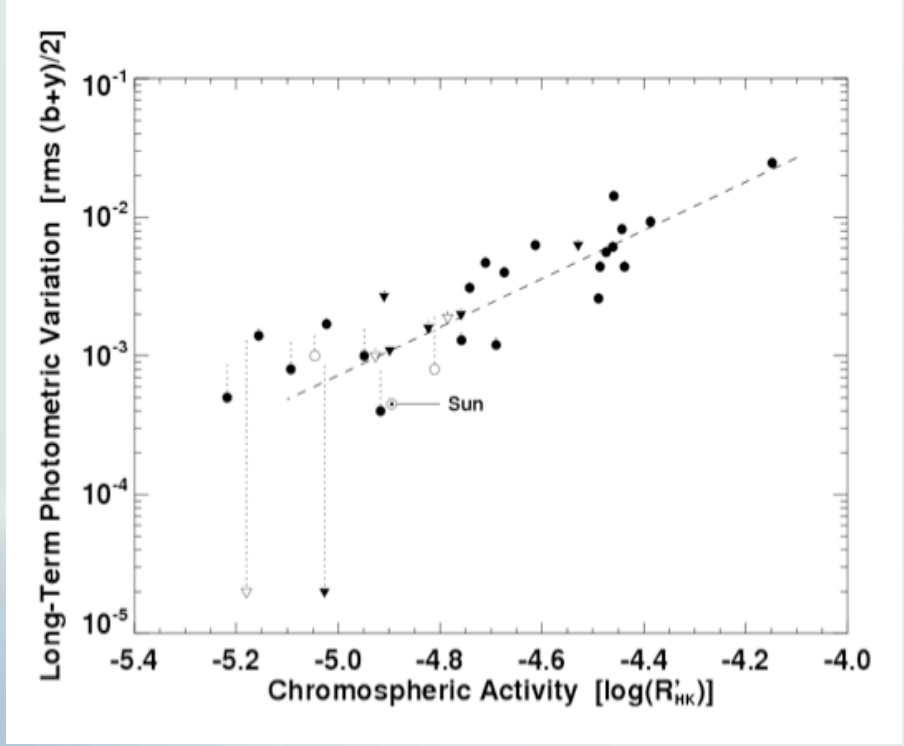
Dobson et al 1990

Magnetic Cycles. RMS variation

Data: seasonally averaged HK,photometric RMS (includes active longitude flip-flops, some AR growth/decay)

- $\sigma_{HK}(\text{long-term}) \sim (F'_{HK}/F_{bol})^{1.15}$ (using Lockwood ea 2007)
- $\sigma_{pho}(\text{long-term}) \sim (F'_{HK}/F_{bol})^{1.85}$ (using Lockwood ea 2007)
- So $\sigma_{pho}(\text{long-term}) \sim \sigma_{HK}(\text{long-term})^{1.61}$
- And: $\sigma_{pho}(\text{long-term}) \sim \sigma_{pho}(\text{short-term})^{1.14}$; $\sigma_{HK}(\text{long-term}) \sim \sigma_{HK}(\text{short-term})^{1.31}$





Magnetic Cycles II. Cycle Period

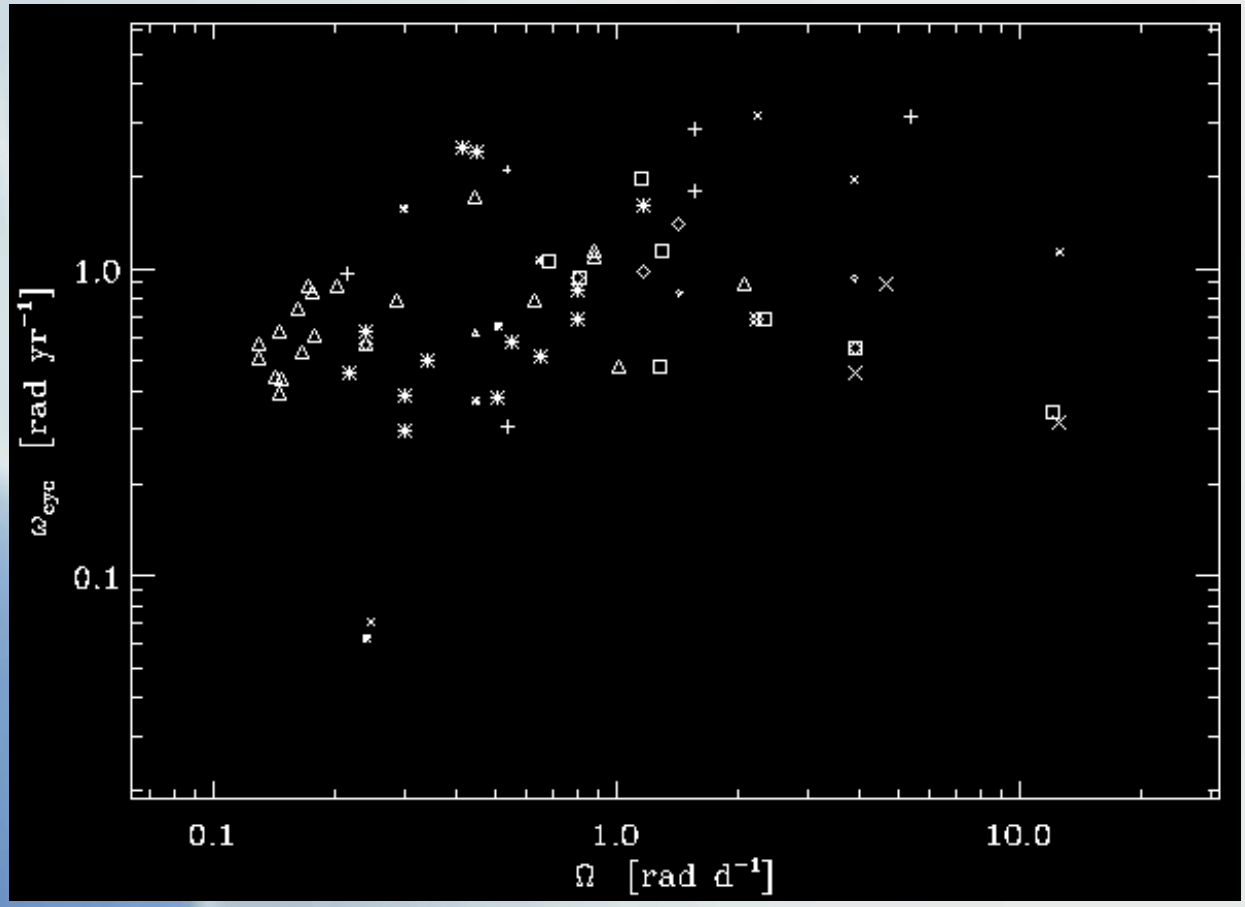
(Work in progress….)

Backtrack from Saar & Brandenburg (1999), take only single dwarfs

Update data from with Frick et al (2004), Messina & Guinan (2001), plus….

Nothing obvious at first….

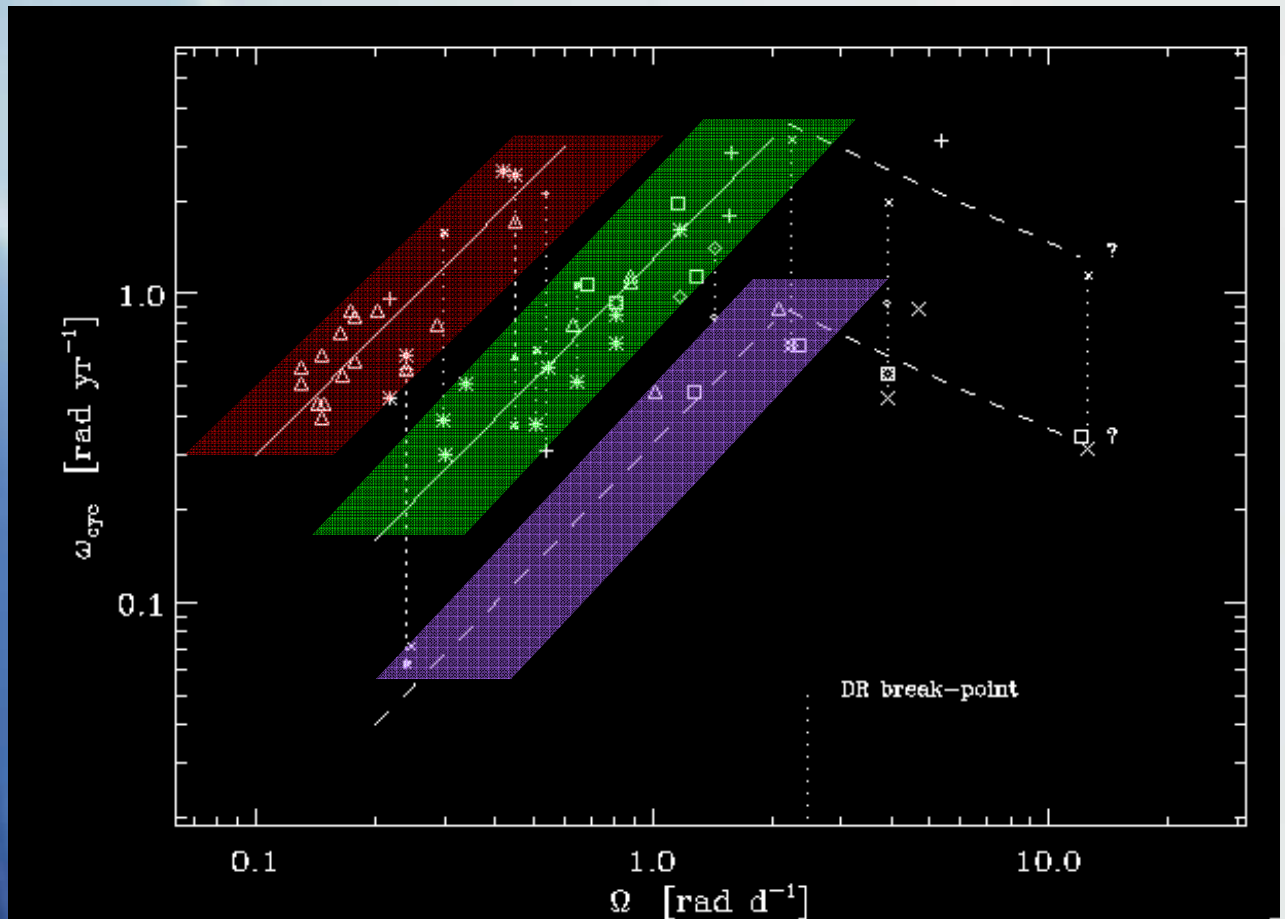
- $\omega_{cyc} \sim \Omega^{0.0}$?
- But consider where secondary P_{cyc} (smaller symbols) lie



Magnetic Cycles II. Cycle Period

Consider P_{cyc}(2nd) (connected to main Pcyc by vertical dotted)…

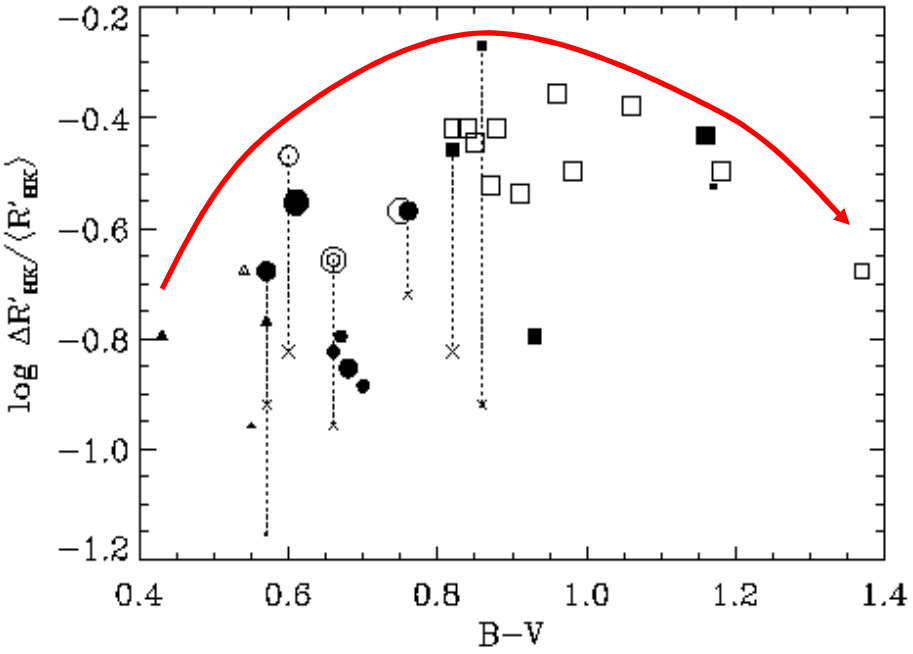
- 2 or 3(?) bands, separated by factors of 4, each with $\omega_{cyc} \sim \Omega^{1.3}$
- Possible break at $\Omega \sim 10$ x solar - the same point where $\Delta\Omega$ slope changes….
- Multimode dynamo, with change in behaviour with $\Delta\Omega$ at high Ω?

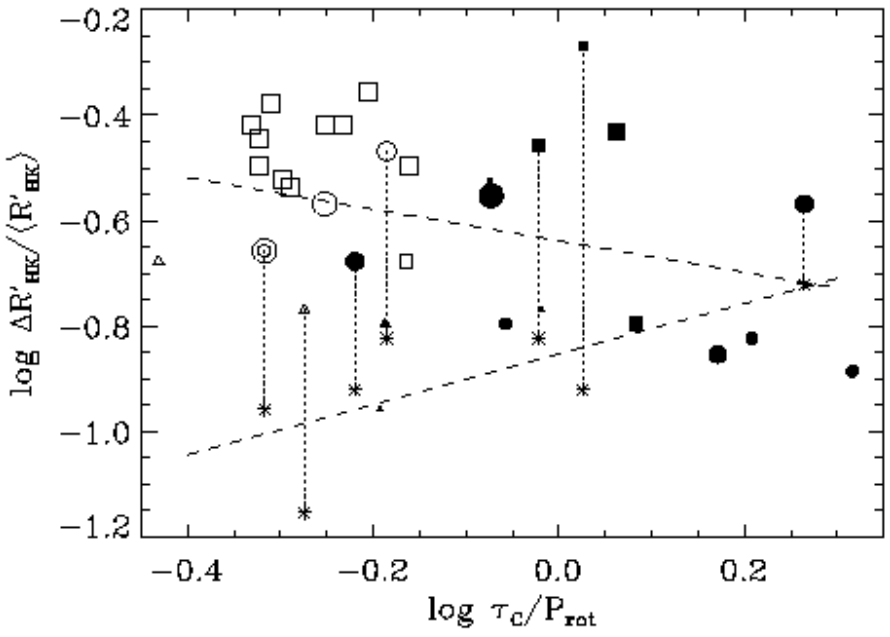


Magnetic Cycles III. Amplitudes

- Ca II HK = plage/network data: Max A_{cyc} increases with B-V to peak in mid K (Saar & Brandenburg 2002)

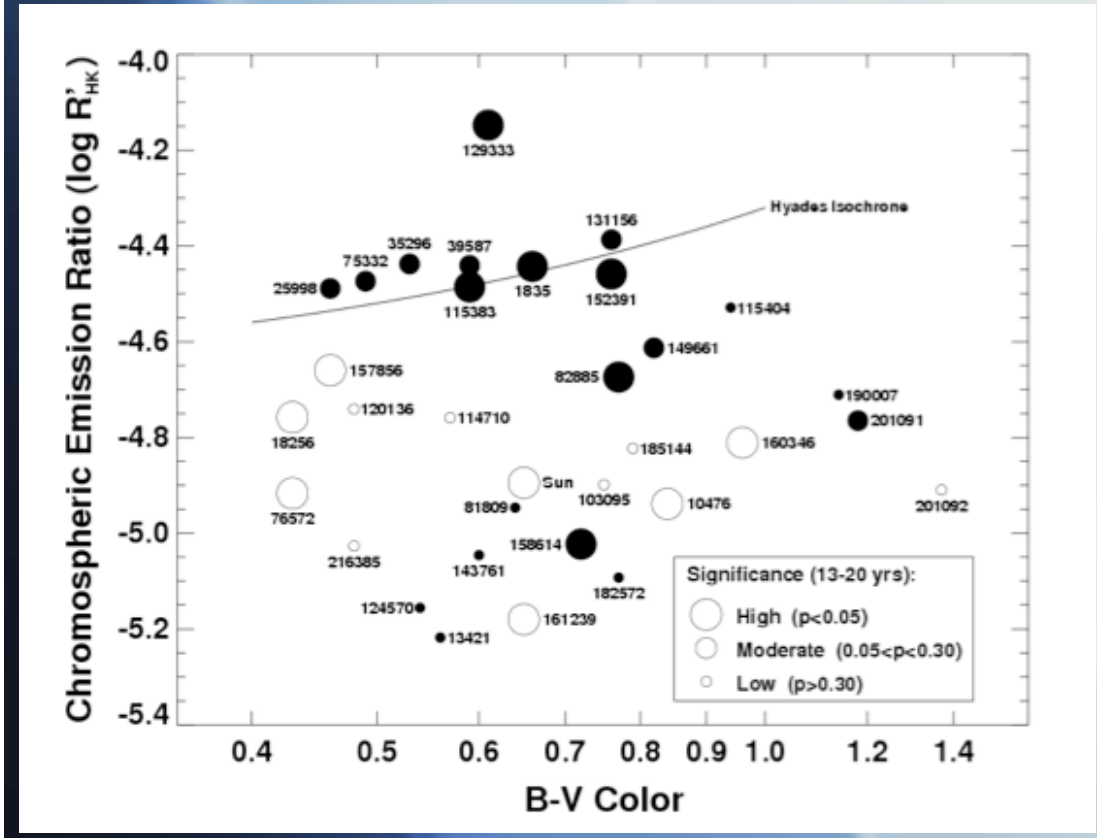
  (recall A_{cyc}(spot) kept increasing at low masses)
- A_{cyc} decreases with Ro^{-1}; A_{cyc}(2nd) increases with Ro^{-1} - sign of multimode dynamo? (Moss ea 2008)

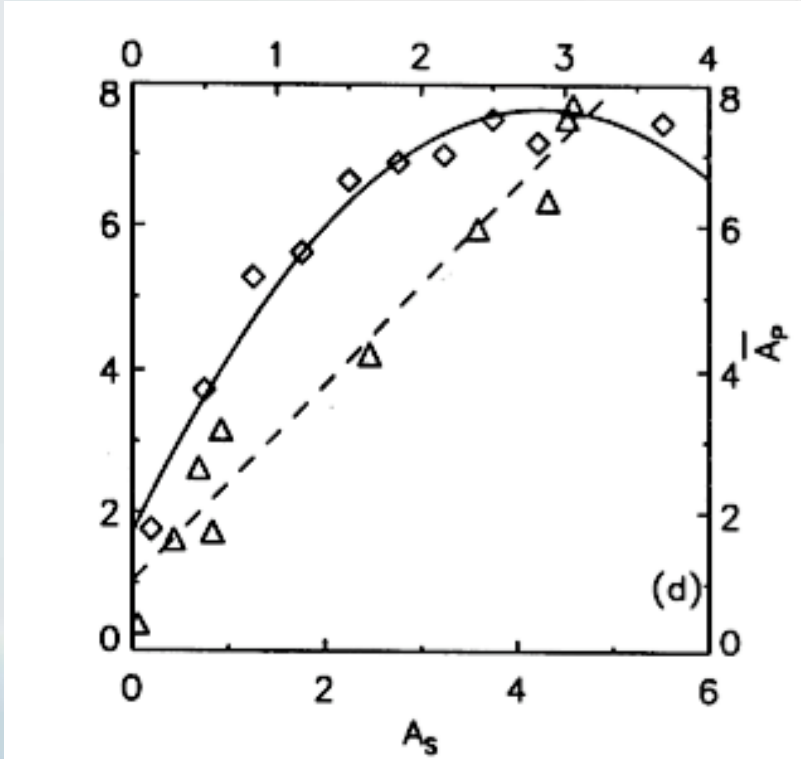




Magnetic Cycles IV. Bright or Dark?

- Look at the sign of the A_{HK} - A_{pho} relation (Radick ea 1998, Lockwood ea 2007)
- Positive for low R'_{HK} stars (vis Sun) - more activity = brighter ⇒ plage/network dom.
- Negative in high R'_{HK} stars - more activity = fainter ⇒ spot dominated
  (Exceptions are either evolved, or low significance)
- Correlation sign change seen in Sun in most active cycles too! (Foukal 1997)





Long-term variations: minima

The Sun clearly has magnetic Grand minima (and maxima) but their existence in other cool stars has been questioned recently (Wright 2004).

Wright found few low activity (log R'_{HK} <-5.1) stars within ΔM_v = 1 of the Main sequence (log M/H= 0).

He concluded that truly solar-like stars in Maunder-like minima are rare.

Is the Sun an oddball for having magnetic minima?

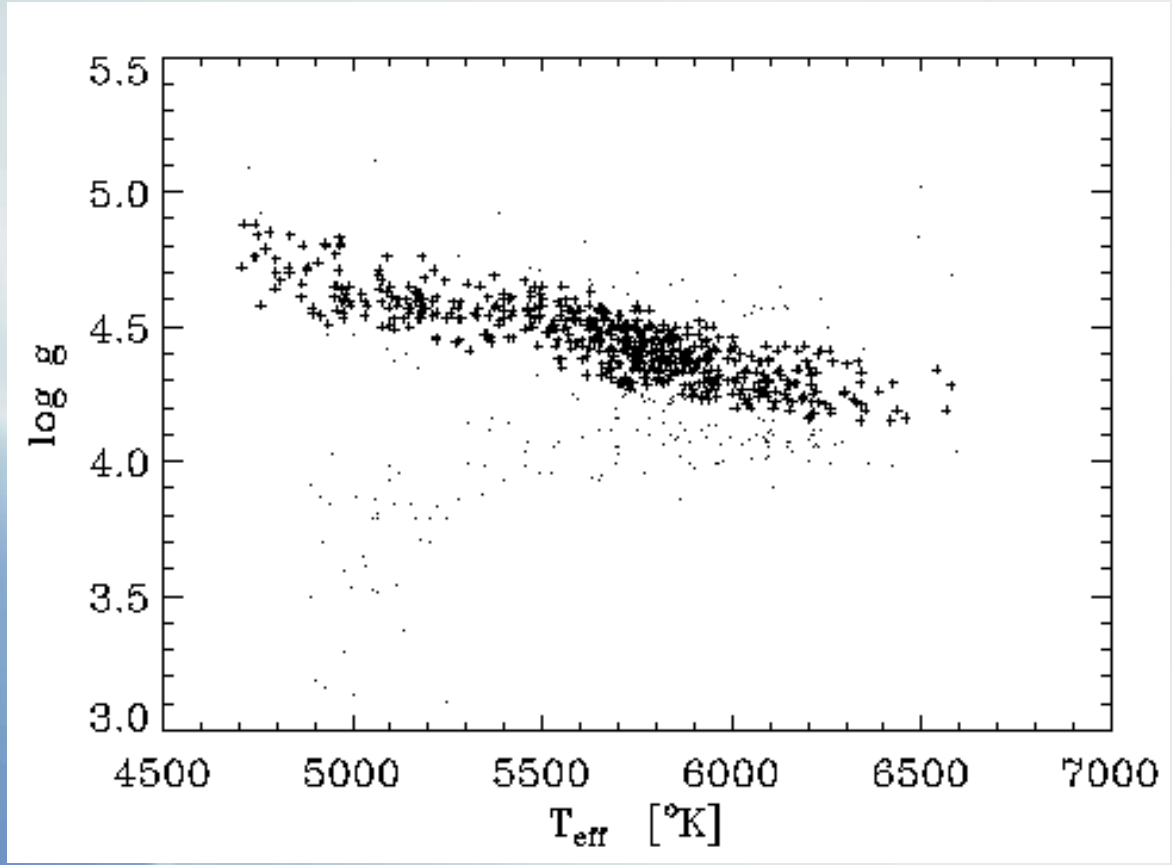
Important for Climate, dynamos, Sun-in-time evolution

Answer: yes and no….

Are Maunder-like minima rare?

Problem: Wright's use of ΔM_V confuses evolution and metallicity (M/H) differences. Cleanly separate dwarfs by using spectroscopically determined T_{eff} and log *g* values (Valenti & Fischer 2005).

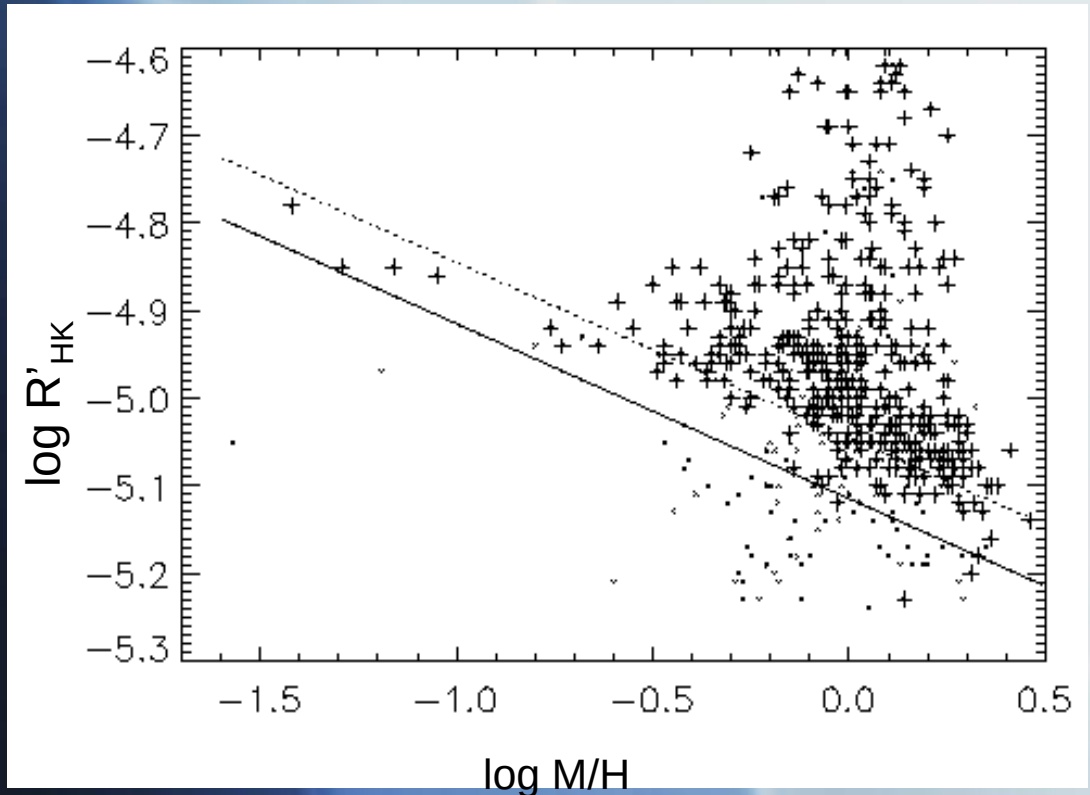
When you do this, dwarfs may be separated independent of their M/H.



Are Maunder-like minima rare? II

Do this and minimum activity (R'_{HK}) in dwarfs is (apparently) a strongly *decreasing* function of metallicity M/H!

Trend should be flat or even reversed ($S_{HK}=C_{core}/C_{cont}$; C_{core} ~ same, C_{cont} ⇑ at low M/H)



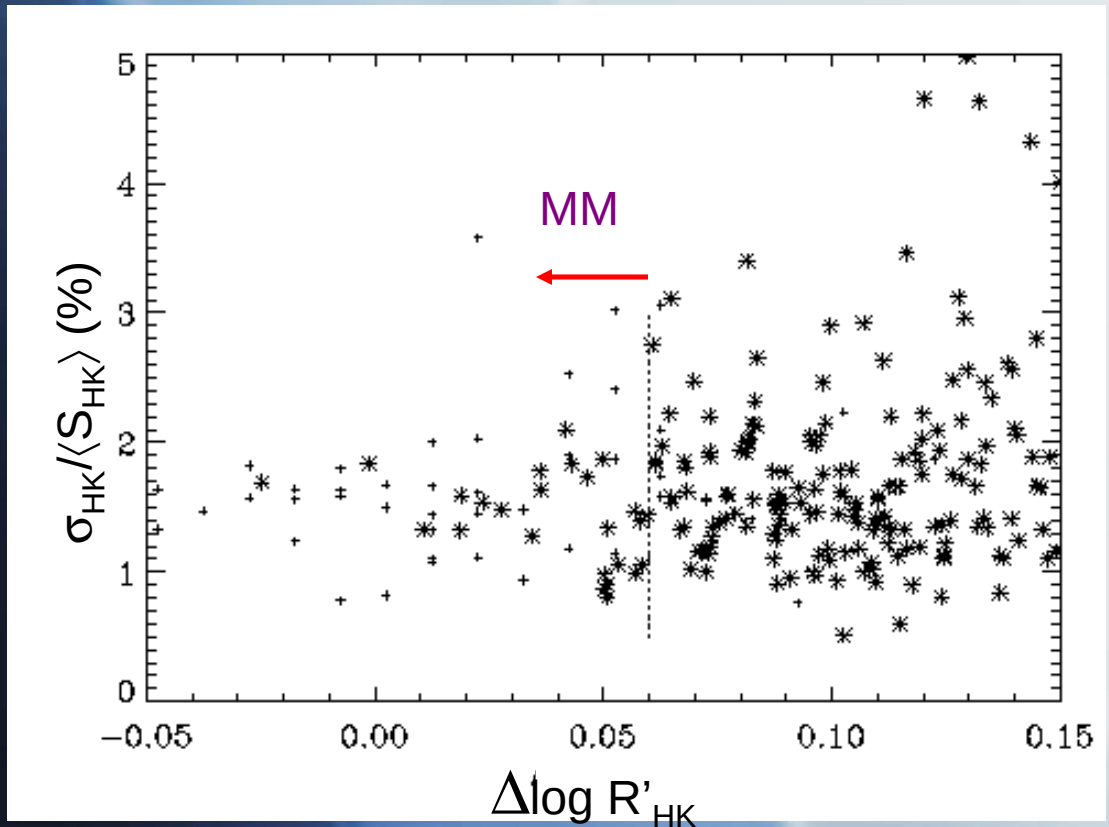
- Likely there is an HK calibration problem
- Flat log R'_{HK}<-5.1 MM level inappropriate
- Instead, look for MM stars near bottom dwarf R'_{HK} boundary

+ = dwarf, x = evolved

Are Maunder-like minima rare? III

Dwarfs within $\Delta \log R'_{HK} \leq 0.06$ (~+15%) of R'_{HK}(M/H) boundary show minimal variability ($\sigma_{HK}/\langle S_{HK} \rangle \leq 2\%$).

These are our new Maunder minimum star candidates.



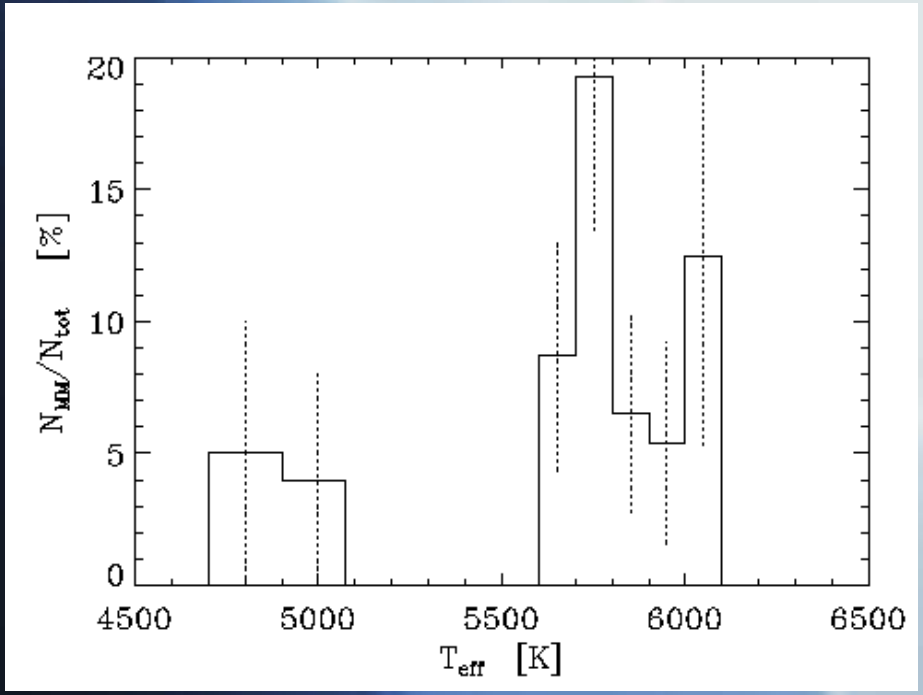
- MM candidates:
  $\langle T_{eff} \rangle = 5730 \pm 271$ K
  $\langle [M/H] \rangle = -0.015 \pm 0.400$
  6.1% of sample dwarfs
- Sample:
  $\langle T_{eff} \rangle = 5610 \pm 379$ K
  $\langle [M/H] \rangle = -0.015 \pm 0.228$
- ∴ MMs have narrower T_{eff} but wider M/H distribution

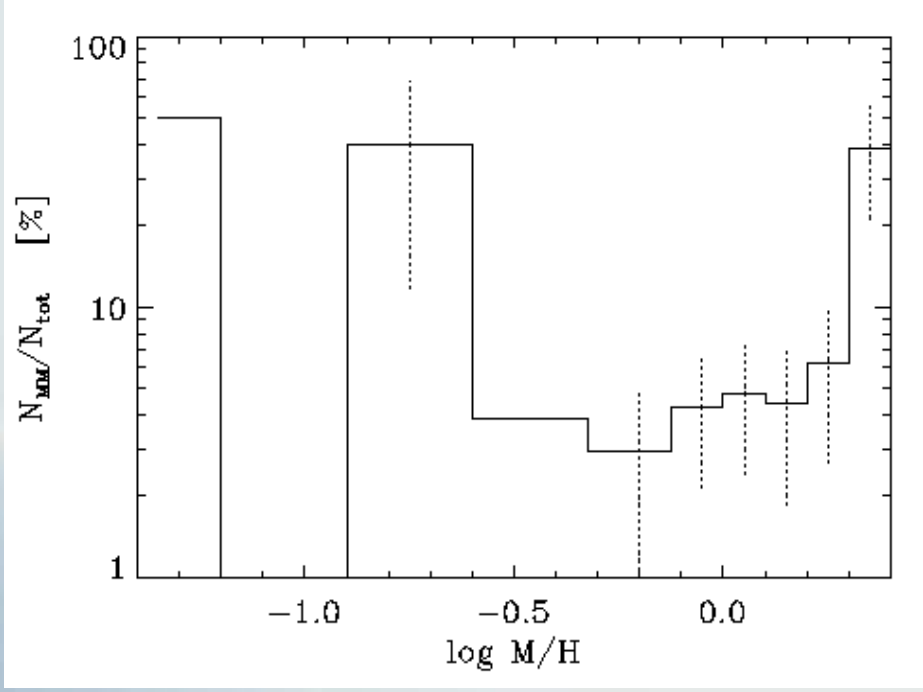
*= dwarf; += evolved

Are Maunder-like minima rare? IV

Answer(?): No, ~8% of G dwarfs in sample are MM candidates. But only ~1% of K dwarfs and ~3% of F dwarfs (all F8-9) are candidates.

- Consistent with number of "flat activity" stars in solar-age M67 (Giampapa et al 2006) if binaries excluded.
- No MM candidates in T_{eff} gap 5100-5600 K (~K1 to G5), few cooler.
- MM candidates more frequent in low and high metallicities.

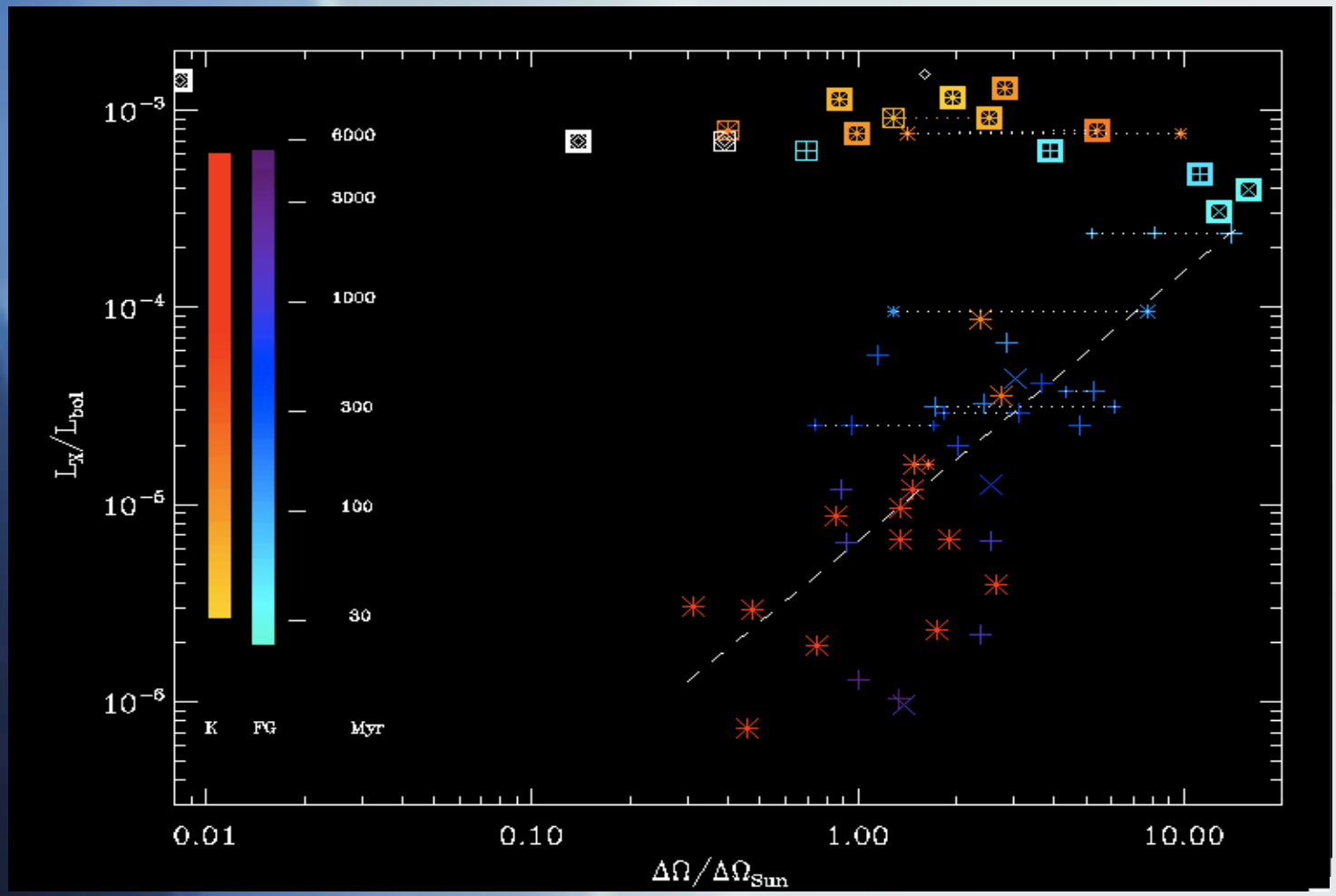




About the new Maunder-like candidates

- Mostly G5-F9 stars. All metallicities, but low and high M/H favored.
- About 8% of G dwarfs in Wright et al (2004) sample with σ_{HK} are candidates. Sample is biased to low activity, tho!
- This is consistent with number of "flat activity" stars in solar-age M67 (Giampapa et al 2006) if binaries/outliers excluded.
- None of the MM candidates in the Wright et al sample has been detected in X-rays to date.
- Statistics are meager, but MM candidates in the Wilson cycle sample are consistent with being drawn from the same Ro^{-1} (~dynamo number) distribution of non-candidate dwarfs, ***if*** non-MMs are restricted to ages > 2 Gyr. $\Rightarrow$ MM candidates are rotationally indistinguishable from older (>2 Gyr), variable dwarfs. They are capable of cycles, but don't have them now.
- Sun is not odd. Possibly all older early-mid G stars have some Maunder-like episodes. Young Sun did not.

SDR vs. L_x/L_{bol} (proxy for B, dynamo)



Key:

X=F

+=G

☯=K

◆=M

box=DI

large=HK

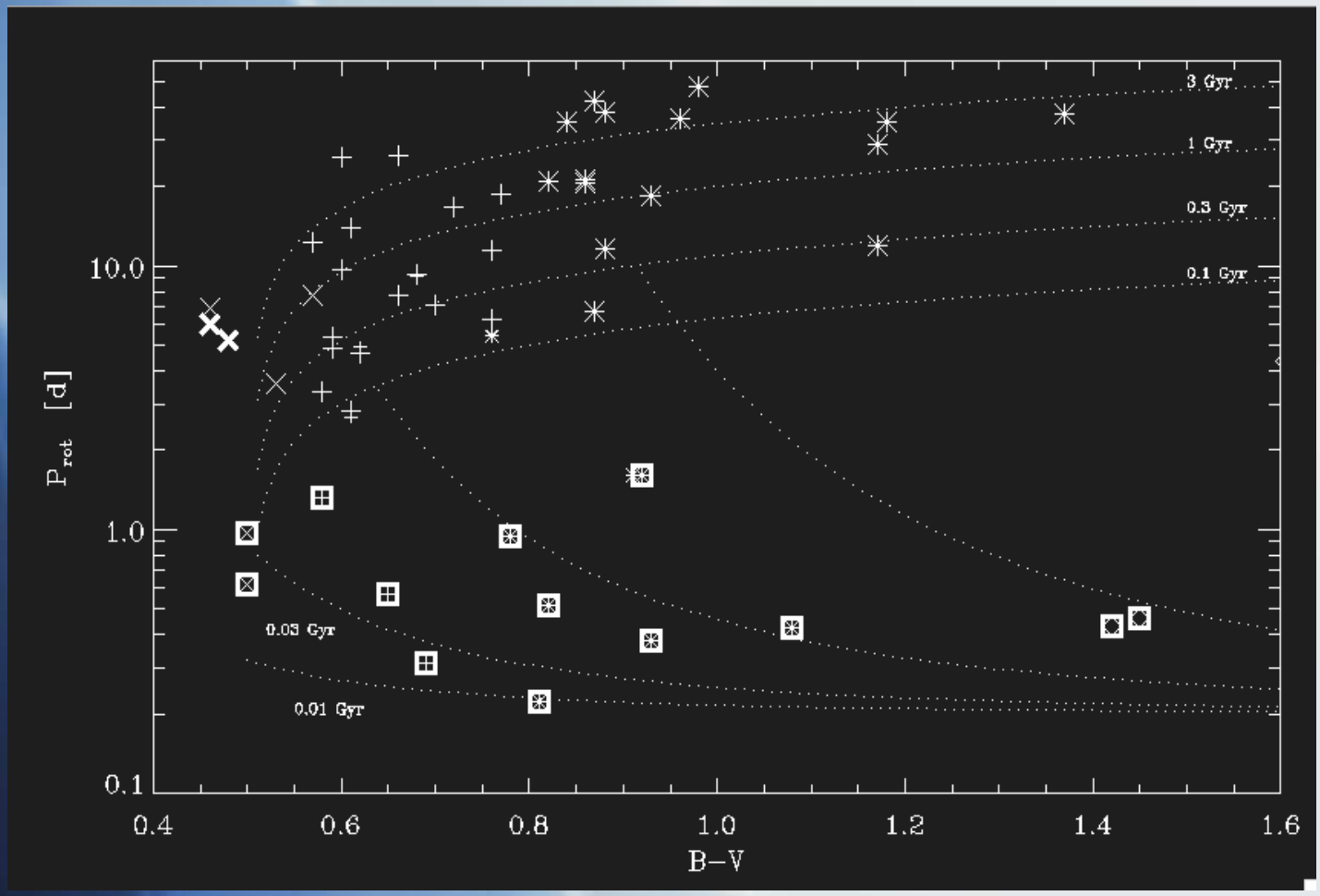
small=phot.

$L_x/L_{bol} \sim \Delta\Omega^{1.36}$ σ =0.48 dex for $L_x/L_{bol} < 6\times10^{-4}$ ($\Omega < 10$ d^{-1})

$L_x/L_{bol} \sim 10^{-3}$ (for $\Omega > 10$ d^{-1}), saturation - for **all** $\Delta\Omega$!

⌫ L_x/L_{bol} a maximum **regardless** of $\Delta\Omega$!

Check color - P_{rot} diagram



Key:

X=F

+=G

☯=K

◆=M

box=DI

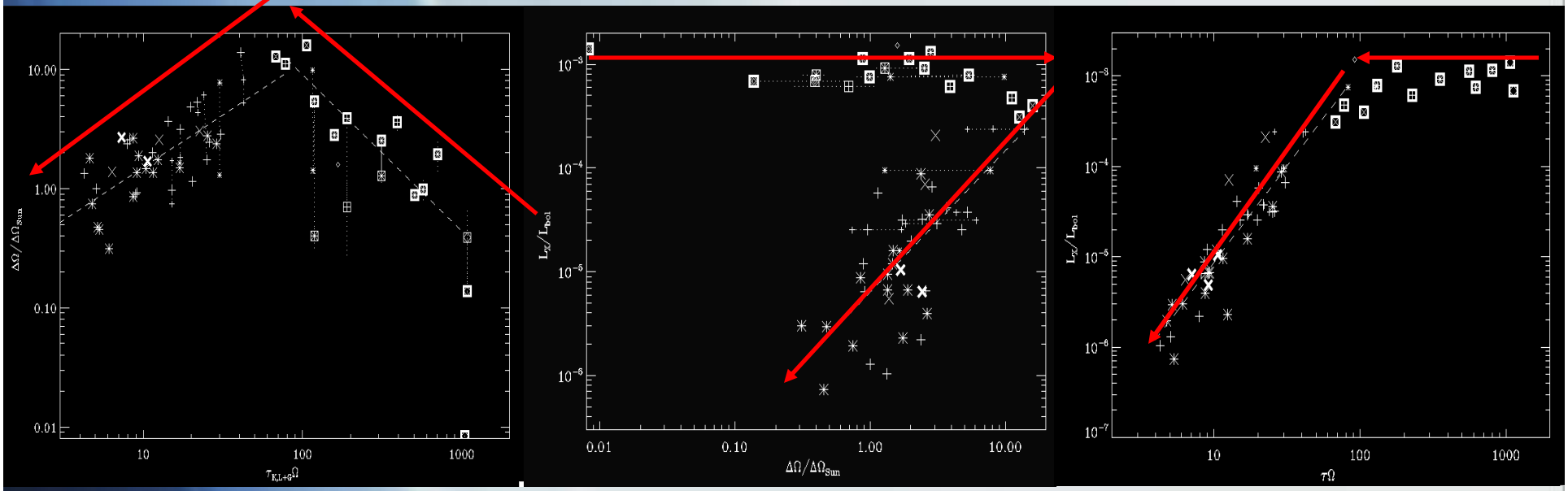
bold=FTLP

large=HK

Stars with increasing/decreasing shear neatly divide into Sydney's I (interface dynamo?)/C (convective dynamo?) branches.

The Evolution of SDR (combined view)

Arrow of time:



$\Delta\Omega$ - Ro

L_x/L_{bol} (B) - $\Delta\Omega$

L_x/L_{bol} - Ro

$\Delta\Omega$ increases to a maximum as Ω declines, then decreases.

L_x/L_{bol} is steady during the initial $\Delta\Omega$ increase, but decays once $\Delta\Omega$ begins to decrease.

Initially: $\Delta\Omega \sim Ro^{+1.3}$ while $L_x/L_{bol} \sim 10^{-3}$ (saturated activity)

Then $\Delta\Omega \sim Ro^{-0.9}$ after $Ro^{-1} \sim 80$ or $\Omega < 10\ d^{-1}$

Summary: Two SDR regimes!

- $\Delta\Omega$ increases with Ω at low Ω (standard rotation-activity, Sydney's I branch - solar-like tachocline/interface dynamo, local τ_c best)
- $\Delta\Omega$ decreases with Ω at high Ω (saturated activity, shear dynamo ineffective, Sydney's C branch - so… convective/turbulent dynamo?, global τ_c best)

Evolutionary scenario: starting with low $\Delta\Omega$ and high Ω and a convective dynamo, stars spin down gradually increasing $\Delta\Omega$ at CZ/radiative zone interface until $\Delta\Omega$ is large enough to "take over" (at ~60 Myr in G stars, ~120 Myr in early K, ~ 1 Gyr late M). Thereafter, more efficient tachocline dynamo is dominant, and spindown increases; magnetic activity steadily decreases.

Some implications

Convective dynamo in rapidly rotating stars could explain:

- Low latitude spots (should be high latitude/polar if arising from tachocline dynamo)
- Strong dynamo action in tachocline-less 3D models (Brown et al. 2007)
- Reduced activity changes with Ω on saturation branch
- Reduced spindown rate in younger stars
- Gradual convective ⩓ tachocline/ transition could explain lack of activity break in M stars