Nuclear burning stars

Stellar X-ray Astronomy

- Hot (millions degrees) coronae made of plasma emit mostly in soft X-rays (but only $1/10^6$ of the entire solar energy budget is emitted in X-rays)
- Possibilities of detections of other stars were expected to be low
- Since *Einstein*, large advances and discoveries in the field of X-ray stellar astronomy

➔A sizable number of stars (depending on their spectral type) are emitting X-rays, although via non-accreting mechanisms

- Drawback: stellar coronae not spatially resolved ➔ information inferred in eclipsing binaries where size information can be estimated from light curve analysis. Best-case scenario when one star is X-ray emitting and the other is X-ray dark

A few numbers: L_X ("quiet" Sun)≈ a few $\times 10^{27}$ erg/s, $\approx 10^{-7}$ optical luminosity
thermal spectrum + lines, 10^{10} times fainter than Sco X-1

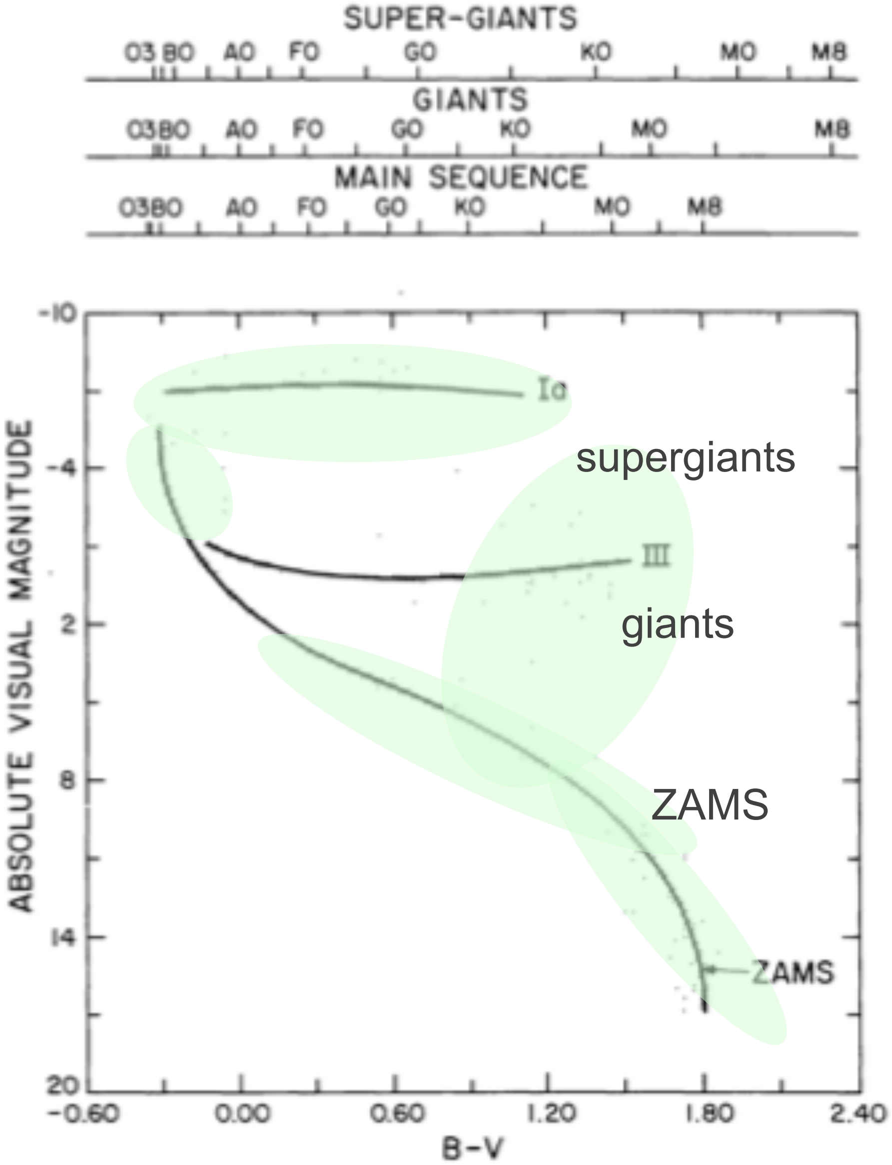
Summary

- F to mid-M stars
- A and late-B stars
- Very low-mass (VLM) stars + brown dwarfs (BDs)
- Pre main-sequence stars
- O, B stars

Stellar X-ray variability

- Flares are a very common type of variability in stars (minutes-days)
- Indications that they are related to magnetic reconnection: magnetic fields conveys energy into the corona where it is liberated
- Flares are restricted to magnetic stars, hence they are associated to stars harbouring a dynamo (cool stars) – rare in F, G stars, common in M dwarfs
- X-ray flare luminosity up to 10^{37} erg/s (at most 10^{32} erg/s in the Sun), up to 100 keV (Algol)

What kind of stars are X-ray emitters?. I

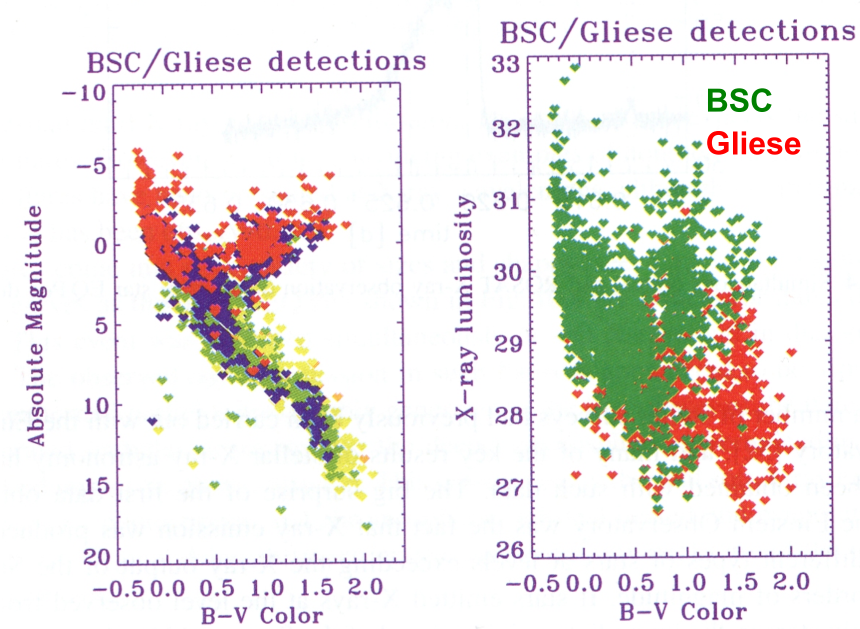


Einstein results (overlays) – Rosner et al. (1985)

What kind of stars are X-ray emitters?. II

• Many different types of stars are X-ray emitters (some exceeding the solar level by several orders of magnitude).

• RASS (ROSAT All Sky Survey): $F_{x,lim} \approx 2\times10^{-13}$ erg/cm^2/s ➔ solar-like X-ray emission ($Lx \approx 2\times10^{27}$ erg/s) only for stars within 10 pc



BSC: Bright Star Catalog (down to V=6.5, ≈10000)
Gliese: volume-limited cat. (d<25 pc from the Sun, ≈3200)

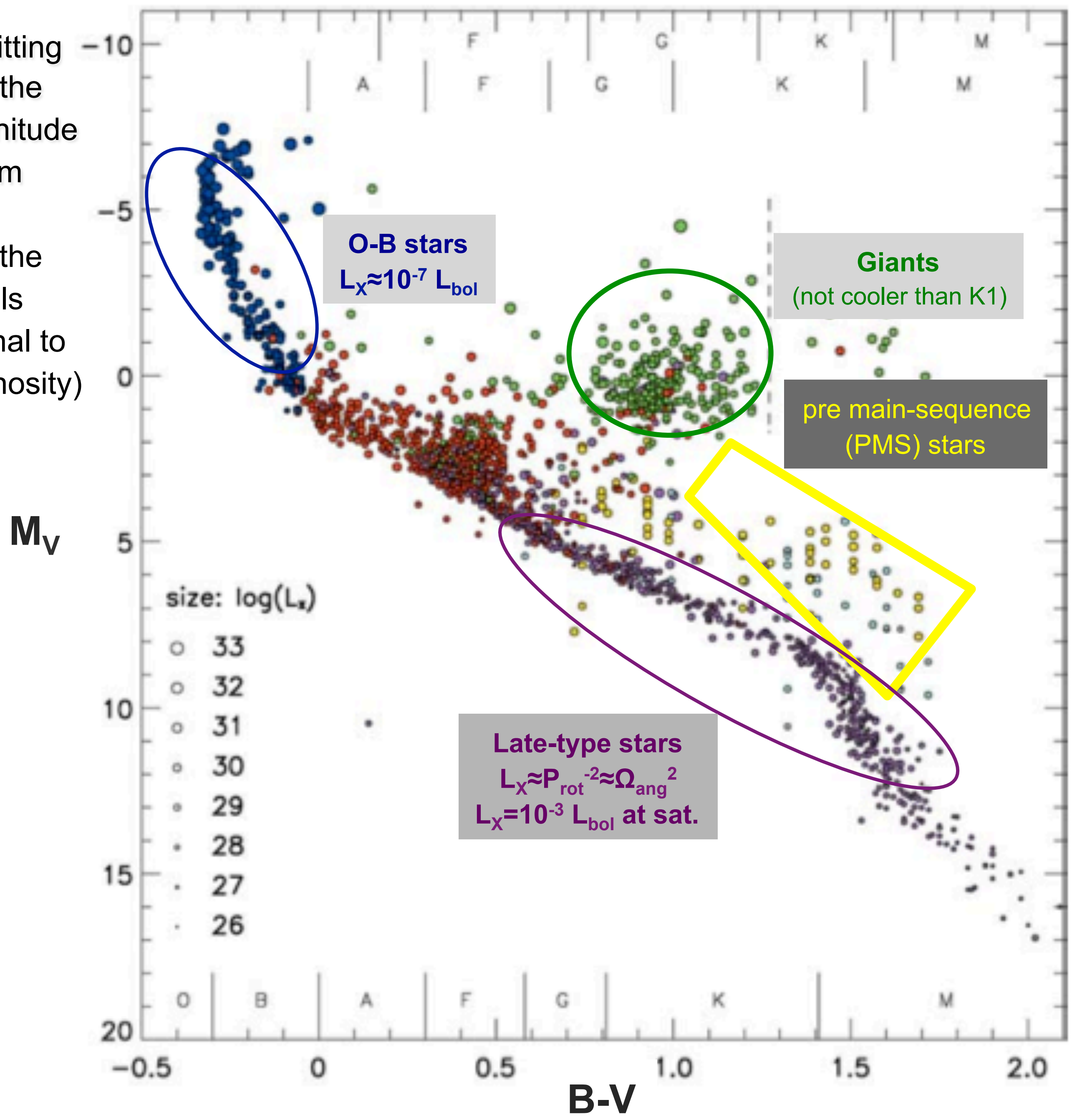
Color-coding (*left panel*)
yellow: $Lx<10^{28}$ erg/s
green: $Lx=[10^{28}-10^{29}]$ erg/s
blue: $Lx=[10^{29}-10^{30}]$ erg/s
red: $Lx>10^{30}$ erg/s

➔ huge spread in X-ray luminosities RASS

➔ large spread also expected in L_x/L_{bol}

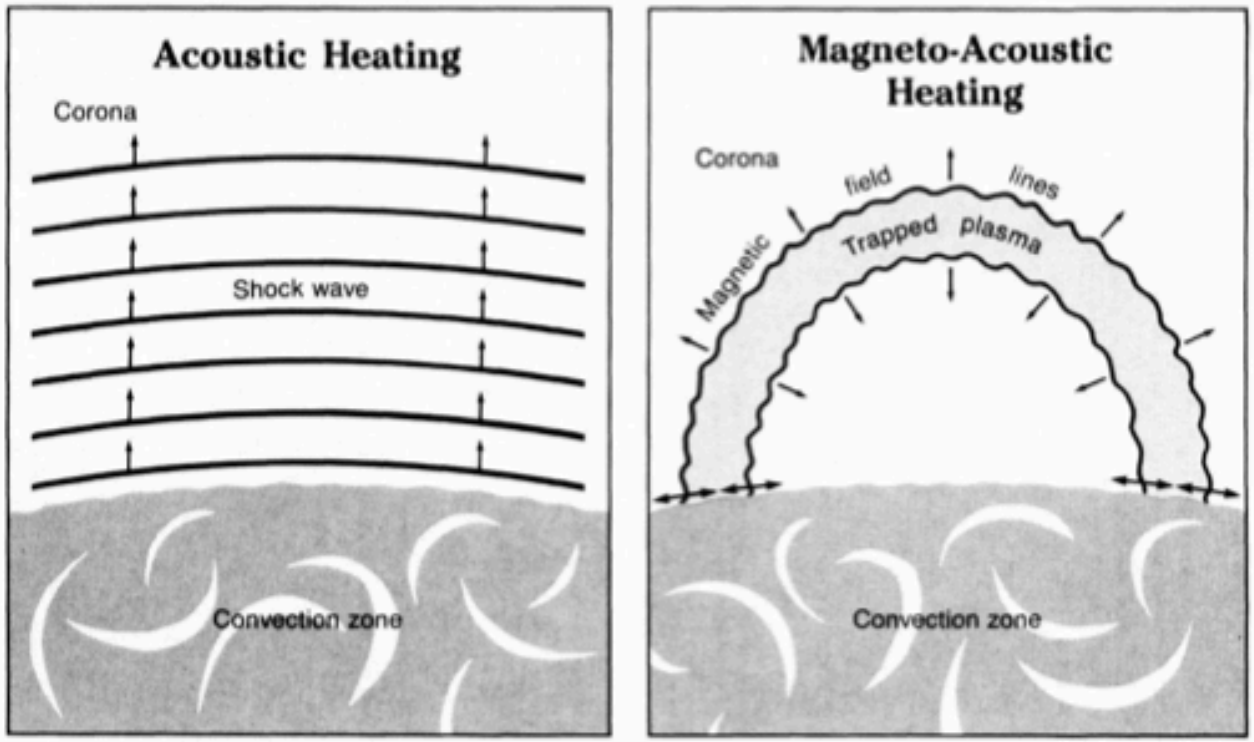
X-ray emitting stars in the color-magnitude diagram

(size of the symbols proportional to X-ray luminosity)



Guedel 2004

Heating the corona



Acoustic heating: acoustic waves penetrate into corona. ruled out due to dependency of L_X on rotational speed.

Magneto acoustic heating: Heating by waves and/or particles induced from magnetic fields at the bottom of the corona (magnetic reconnection?).

X-ray activity is connected to magnetic fields!

Coronal plasma confined in the magnetic field loops. Rotation becomes lower with age because of emission by **a magnetized coronal wind** (hence, mass loss). **Slow rotation may suppress field generation.** Low gravity and/or strong winds may prevent the heating and confinement of the plasma

X-ray luminosity vs. Period relation: preamble (I)

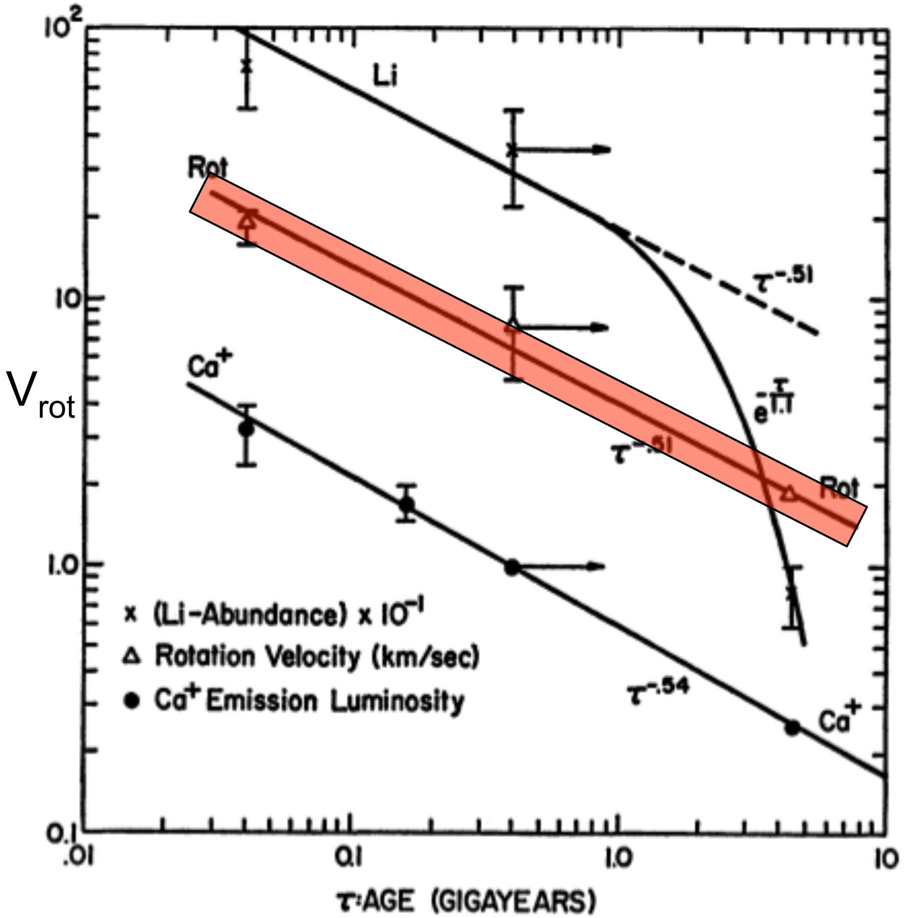
The magnetic dynamo operates in a highly convective fluid (plasma) subject to convective and rotational motions whose characteristic time scales are the *convective turnover time* (period of circulation within a convective cell) and the stellar rotational period

$$R_0 = P_{rot}/\tau_{conv}$$

Rossby number=ratio between the measured rotation period and the convective turnover time.
Good indicator of the efficiency of the dynamo mechanism in the generation and amplification of the stellar magnetic fields
➔ **level of stellar magnetic activity**
Often replaced by the rotational period of the stars (see the original results from Pallavicini et al. 1981), since τ_{conv} is empirically determined

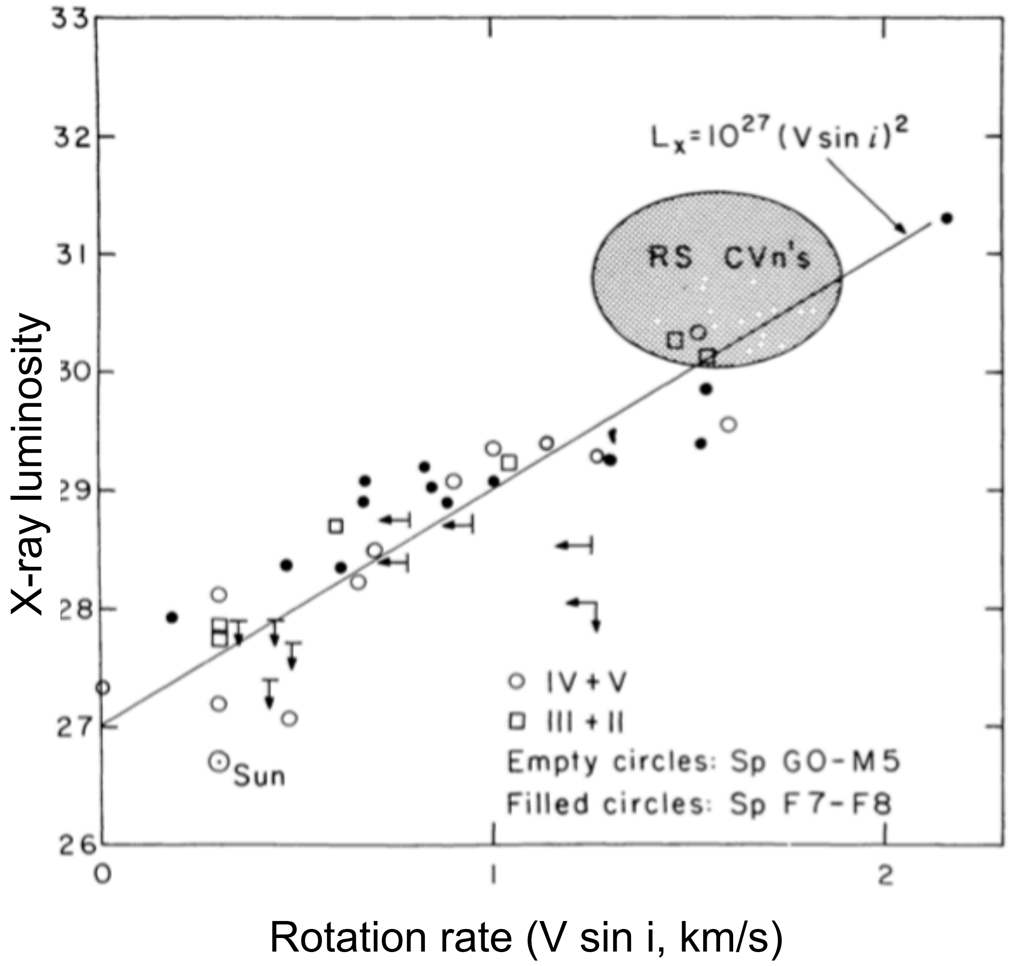
Differential rotation at the diffusive/convection zone boundary drives the dynamo which produces the magnetic fields in “convection” stars. Convection carries the field to the surface, where it erupts in closed loop structures in which the coronal plasma is heated and confined.
At increasing stellar age, rotation is slowed by emission of a magnetized coronal wind. Young stars rotate faster, hence produce more X-rays. **Magnetic fields transport angular momentum, hence control the spin rate of the star. MAGNETIC CORONAL HEATING.**
As the star becomes a giant, rotation slows down and coronal emission may disappear: slow rotation may suppress field generation or the low gravity and/or the strong cool wind may prevent the heating and confinement of the plasma at the surface.

X-ray luminosity vs. Period relation: preamble (II)



Rotation velocity decreases with time
(Skumanich 1972)

X-ray luminosity vs. Period relation: preamble (III)



Fast rotation → more X-rays

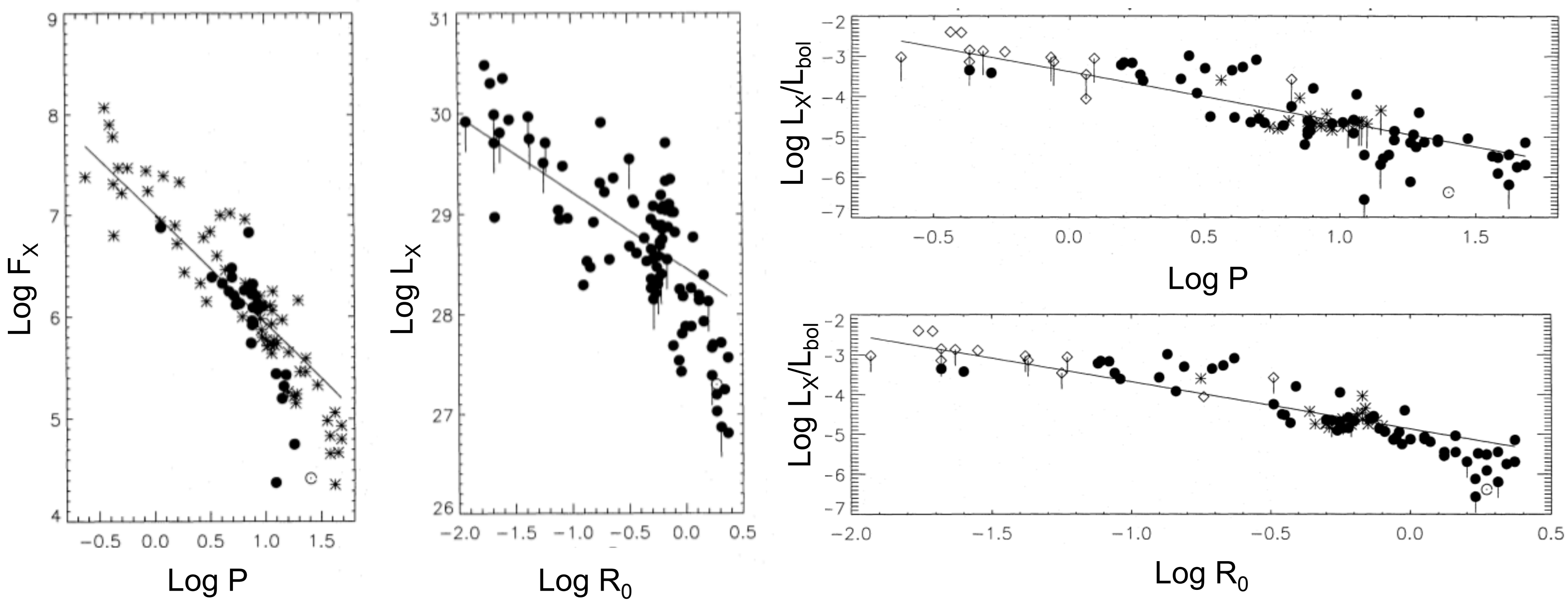
Stars which rotate faster have higher X-ray luminosity

Einstein and EXOSAT data

Stars of different spectral types

(Rosner et al. 1985)

X-ray luminosity vs. Period relation: preamble (IV)

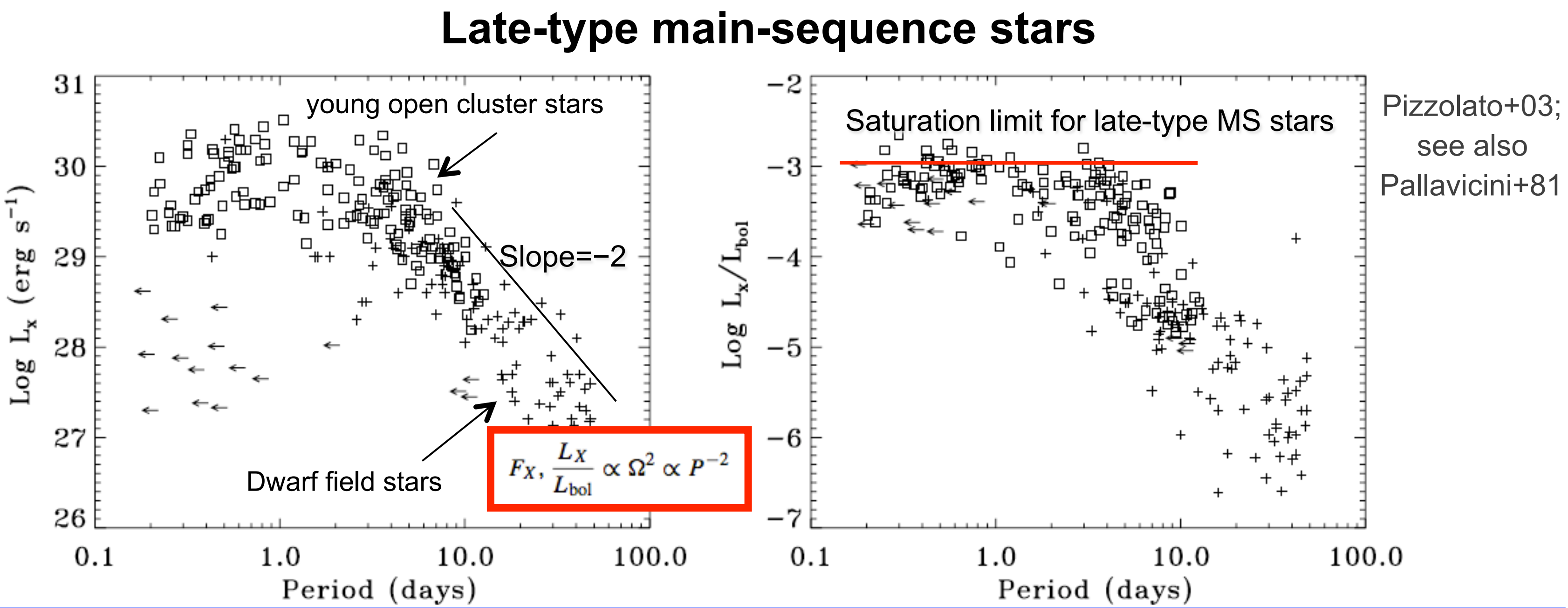


- Magnetic activity depends on stellar rotation
- L_X related to magnetic fields
- L_X decreases with rotational period

L_X/L_{bol} (sort of *coronal efficiency*) prop. to $1/R_0^2$

Hempelmann et al. (1995)

X-ray luminosity vs. Period relation



- P<3−5 days: $L_X/L_{bol} \approx 10^{-3}$ ("saturation limit", coronal stripping?): no obvious dependence on the rotation rate
- P>3−5 days: Lx/L_{bol} decreases for increasing periods

✓ Strength of magnetic fields ➔ X-ray emission because of the dynamo process

✓ Stellar rotation is thought to be braked by magnetically threaded winds and mass loss

➔ young stars in clusters rotate faster than field (old) stars

Conclusion: magnetic activity "regulated" by rotation: **faster rotation, more X-rays**

✓ Long-term periodicity studies of stellar coronae needed also to understand the scatter

✓ Sun: L_X varies by 1-2 orders of mag during a cycle, while P_{rot} does not

Rotation-activity law

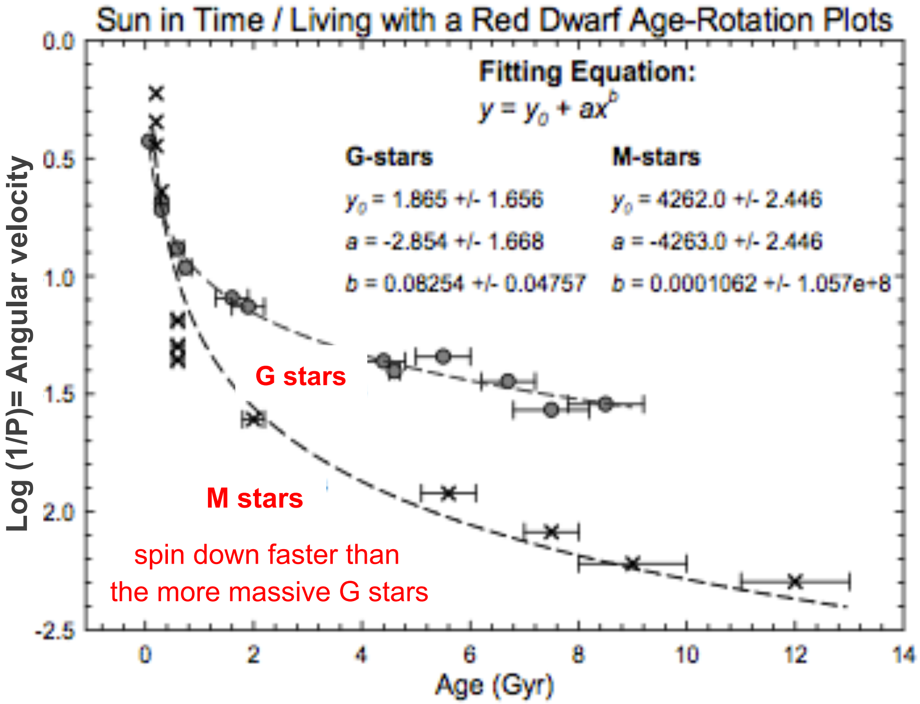
Stellar rotation and magnetic activity operate in a feedback loop; as a single low-mass MS star ages, it sheds a **magnetized wind**, thus **spinning down** due to angular momentum transport away from the star. This, in turn, weakens the internal dynamo and thus reduces magnetic activity (e.g., Skumanich 1972). This negative feedback loop tends to converge toward a definitive rotation period P that depends only on mass and age once the star has evolved for a few 100 Myr (e.g., Soderblom et al. 1993). It is thus most likely **rotation**, and only indirectly **age**, that determines the level of **magnetic activity** [*from Guedel et al. 2004*]

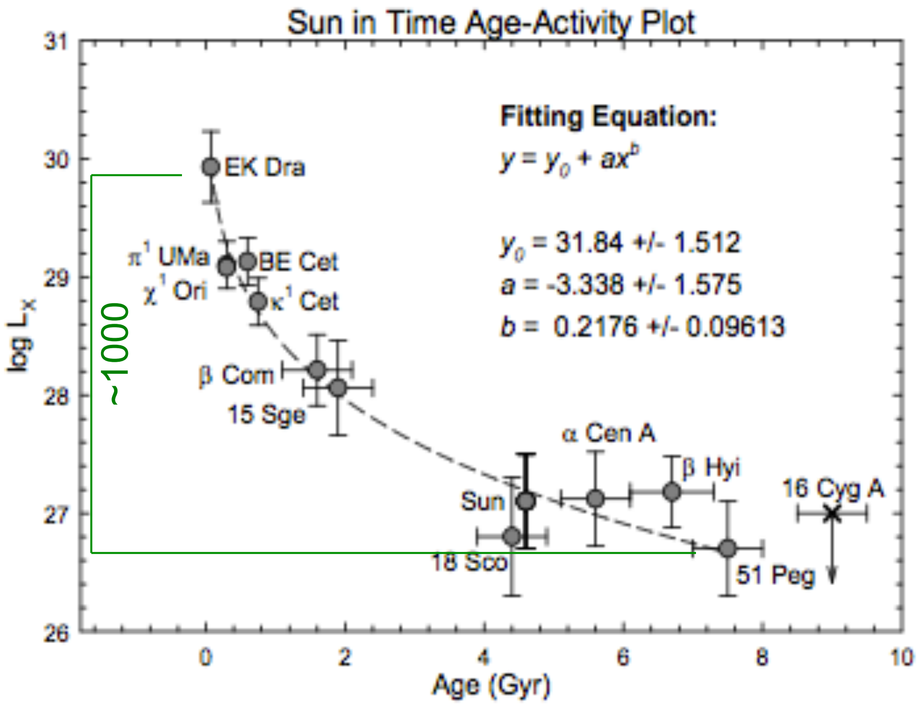
Young age: magnetized wind → Angular momentum transported away from the star

↓

Final P depending only on mass and age ← Weaker dynamo mechanism, lower magn. activity

Guinan & Engle 2009





Aged star have lower X-ray luminosity

✓ M stars: rapid magnetic braking most likely due to more efficient dynamos and lower masses

✓ Solar analogs: X-ray luminosity decreases by ≈10^3 times from the youngest to the solar-age stars

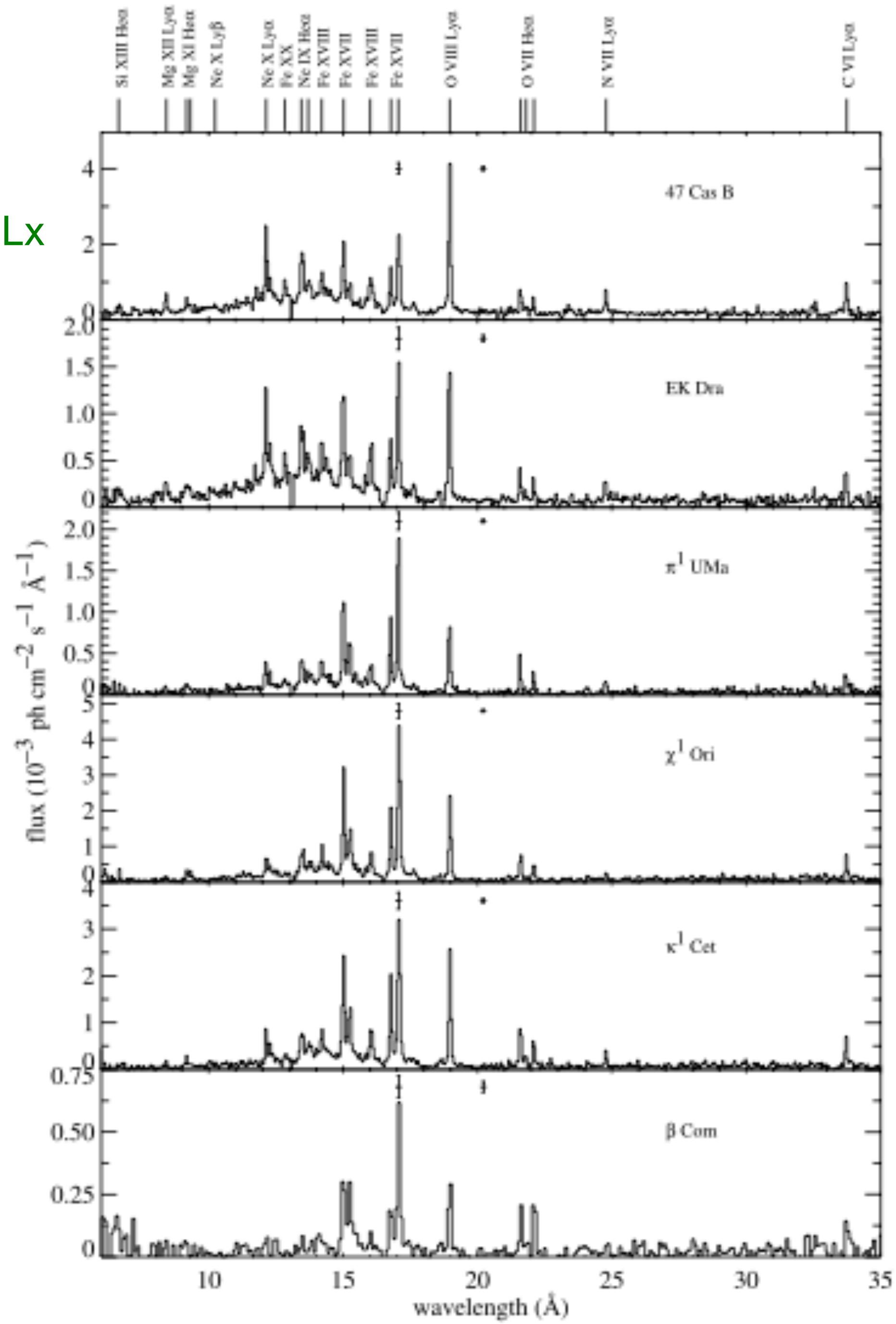
RS CVn binary systems (giant+MS stars): similarly to the Sun, it is possible to observe the signature of (gigantic) starspots in a solar-like cycle of years

abundancies
densities
opacities

Decreasing Lx

Hot plasma + lines

Increasing Age



0.1 Gyr

0.1 Gyr

0.3 Gyr

0.3 Gyr

0.75 Gyr

1.6 Gyr

Telleschi et al. (2005)

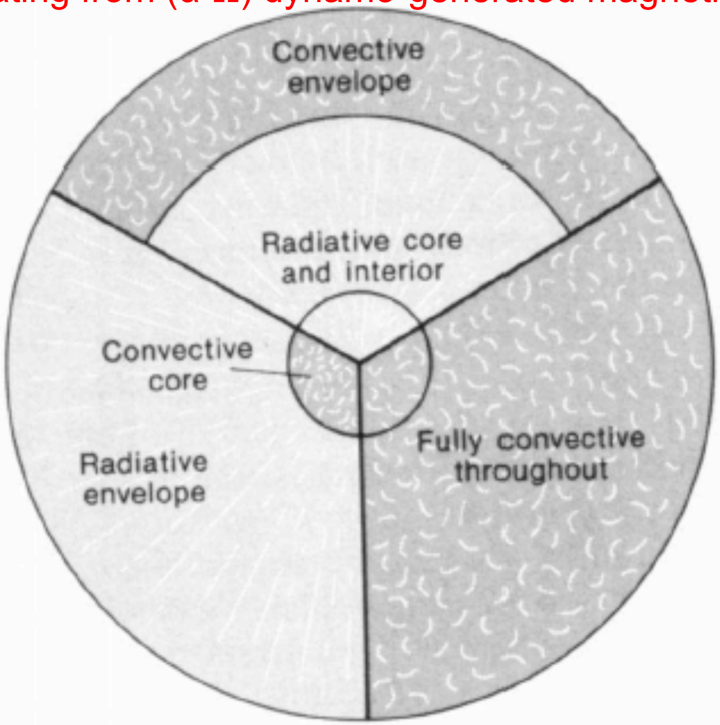
X-ray emission from cool stars

Stellar Structure

Solution of stellar structure equations for main sequence:

Solar (F, G) up to mid-M

Heating from (α-Ω) dynamo-generated magnetic fields



Early (O, B) Strong stellar winds

Late (M) Other kinds of dynamo (turbolent?)

Upper main sequence ($M > 1.5\,M_\odot$):

Core: Temperature very large

$\Longrightarrow$ CNO Cycle $\epsilon \propto T^{15}$

$\Longrightarrow$ convective cores.

Outside of core: radiative equilibrium, no convection.

O- and B-stars: strong stellar winds

Lower main sequence ($M < 1.5\,M_\odot$):

Core: Moderate temperatures

$\Longrightarrow$ pp-cycle ($\epsilon \propto T^6$)

$\Longrightarrow$ cores in radiative equilibrium.

Outer shells: Low temperature

$\Longrightarrow$ large opacity

$\Longrightarrow$ convection

✚ A-type stars: purely radiative

Giants/supergiants: not so many X-ray detections: turn-off of the dynamo, suppression by competing wind production (which might also absorb X-ray radiation), strong attenuation by an underlying thick chromosphere

F to mid-M stars: radiative interior + outer convective zone

solar-like dynamos ($\alpha\Omega$-dynamos) are localized in the interface region connecting the outer convection zones with the radiative interiors (dynamo driven by differential rotation at the “boundary” region)

MAGNETIC CORONAL HEATING

Cool field stars in the solar neighborhood: Results

- About 90% of the F to M stars in the solar neighborhood were detected in X-rays
- The formation of X-ray coronae appears to be universal for main-sequence stars

Intermediate-mass stars

A and late-B stars are fully radiative: no solar-dynamo is expected, but their detection rate in X-rays is ≈15%

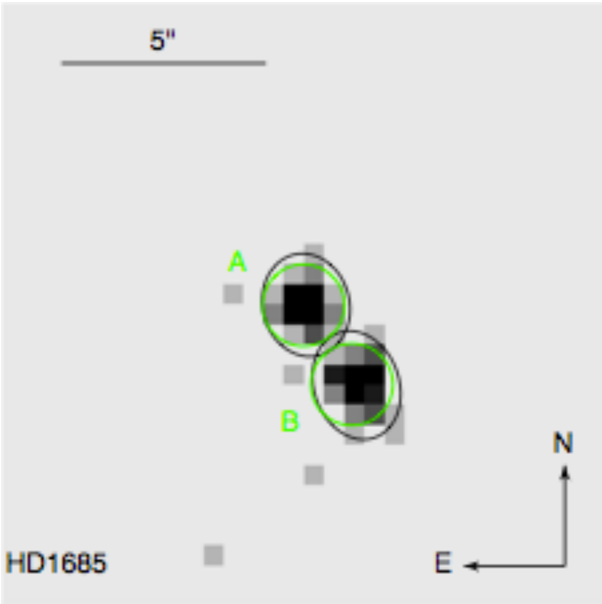
Possible presence of an optically weak late-type companion (producing the X-ray emission) - as sometimes revealed by lightcurve and X-ray imaging analysis

A stars evolve rapidly, a companion of K or M spectral type would still be quite active

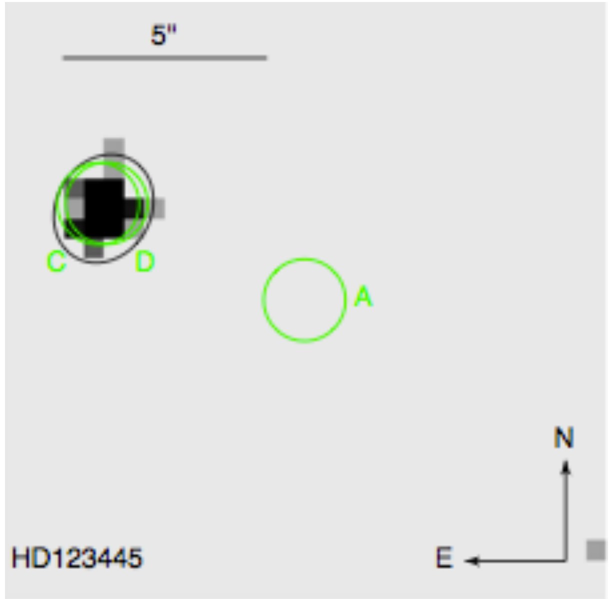
Presence of other processes (acoustic heating?)

➔ Still debated issue: even if magnetic fields existed in early A-type stars, efficient coronal energy release is not expected because no strong surface convective motions are present to transport energy into non-potential coronal fields.

X-rays from both stars



X-rays from companions only



Stelzer et al. 2003

Importance of high-resolution images (*Chandra*) in X-rays

X-ray emission from very low-mass (VLM) stars and brown dwarfs

(often referred to as “ultracool dwarfs”)

• In purely convective stars, X-ray emission via solar-dynamo mechanism is not expected because of the lack of a transition between a radiative and a convective region

• The transition occurs at **$M \approx 0.35\ M_\odot$** ($\approx$ M3 stars)

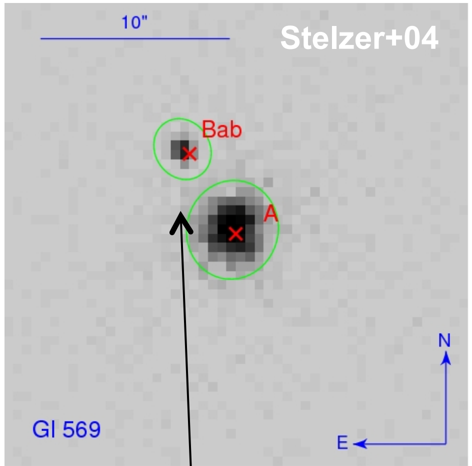
➔ **very low-mass (VLM) stars** below this mass threshold

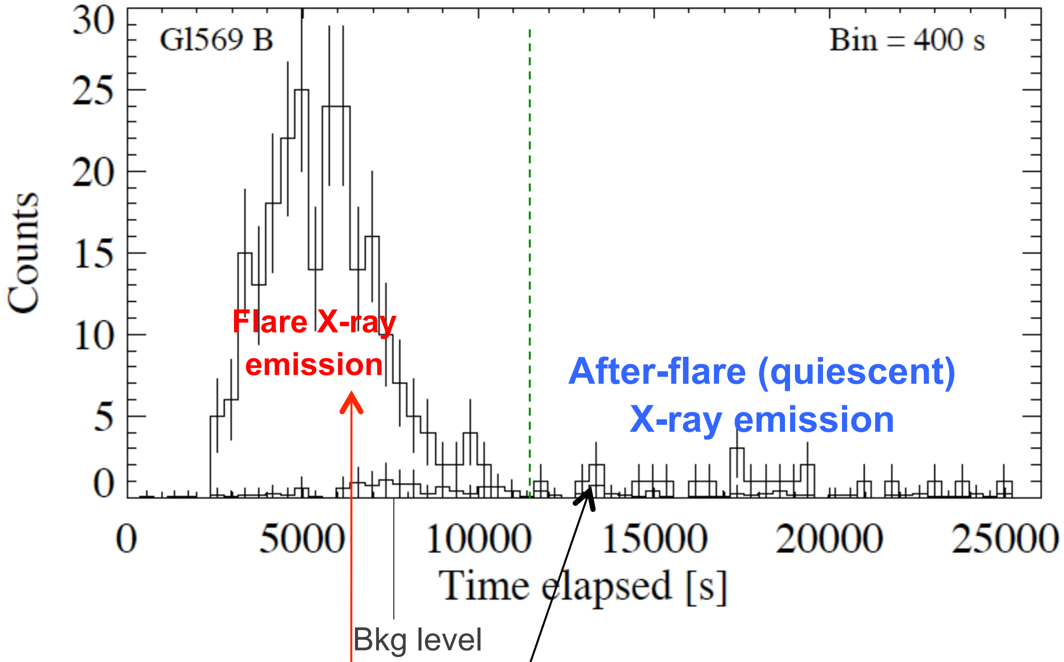
• Alternative field generating mechanisms (other kinds of dynamos) may be at work, but theory makes no testable predictions

• **$M<0.07-0.08\ M_\odot$**: **brown dwarf** regime: the interior temperature is lower than required to initiate H burning ($\approx 6\times10^6$ K). These stars cool down (with possible brief episodes of deuterium and Lithium burning), becoming fainter with age

• Most studies focused in the star-forming regions (young BD) within few hundred pc from the Sun (limiting sensitivity $L_x \approx 10^{28}$ erg/s)

X-ray emission from dwarf stars: quiescent vs. flare

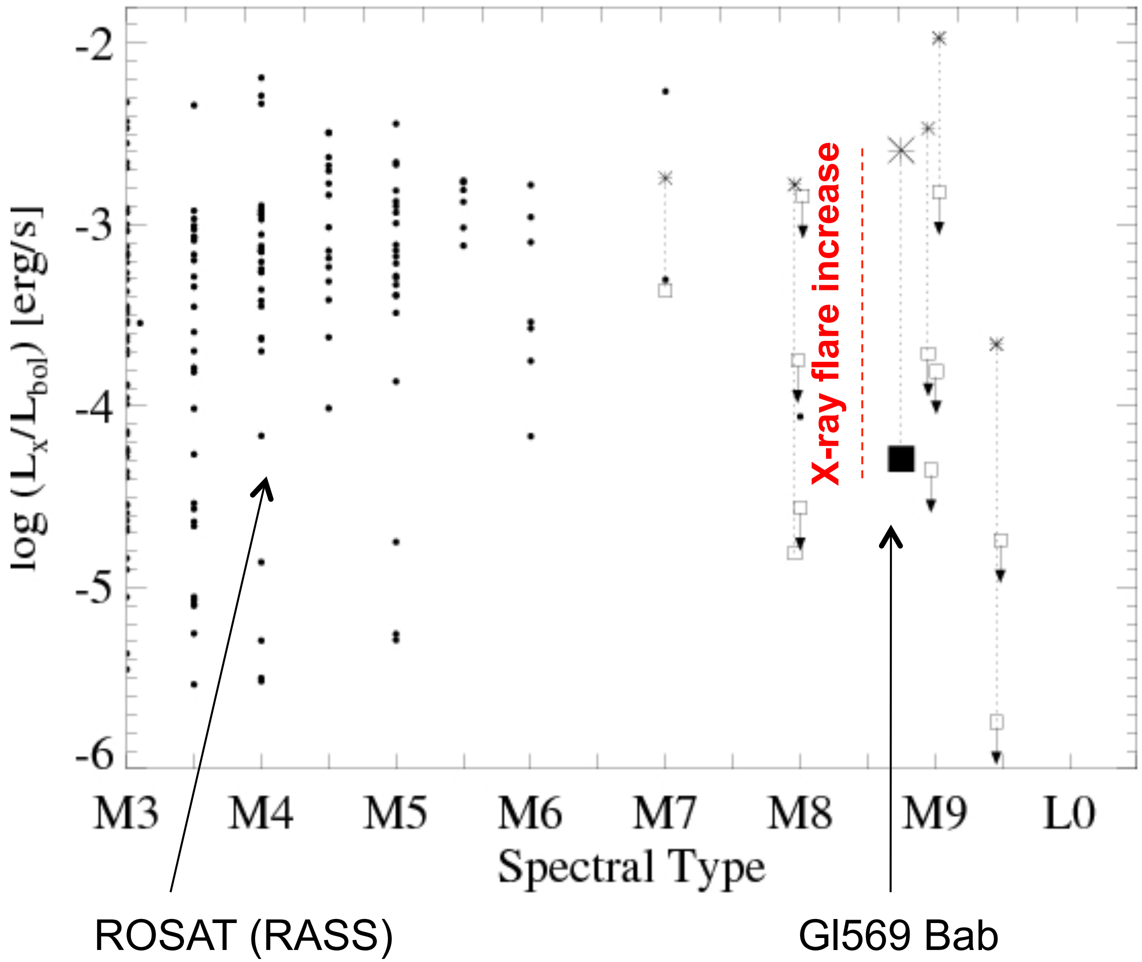




Binary brown dwarf system + Gl 569A star

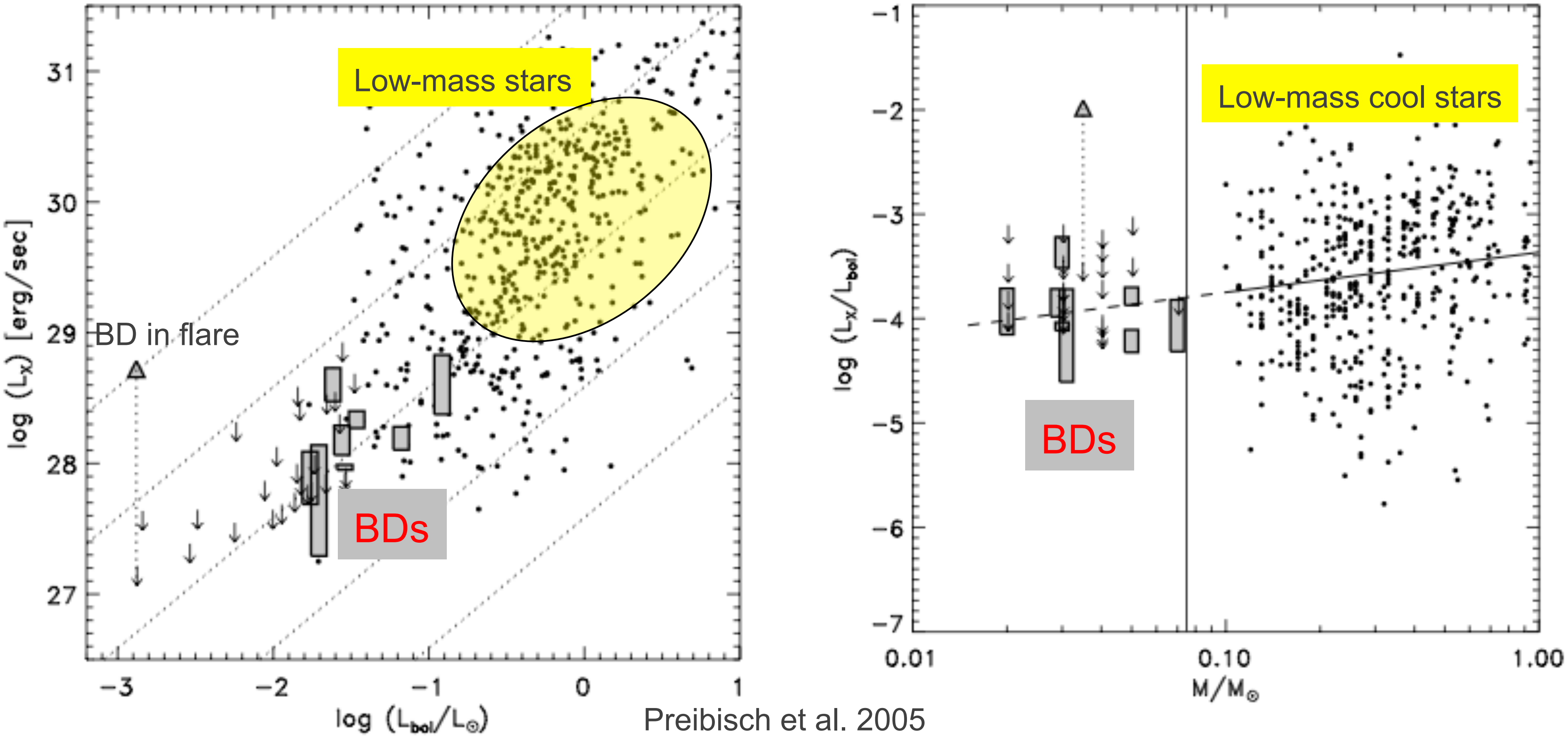
Gl 569 Bab has large-amplitude **X-ray variability** and shows the first **quiescent** X-ray emission from an evolved brown dwarf

X-ray emission from dwarf stars: quiescent vs. flare



Almost all X-ray detections of ultracool dwarfs are attributed to flares (asterisks; quiescent state: squares)

X-ray emission from BDs



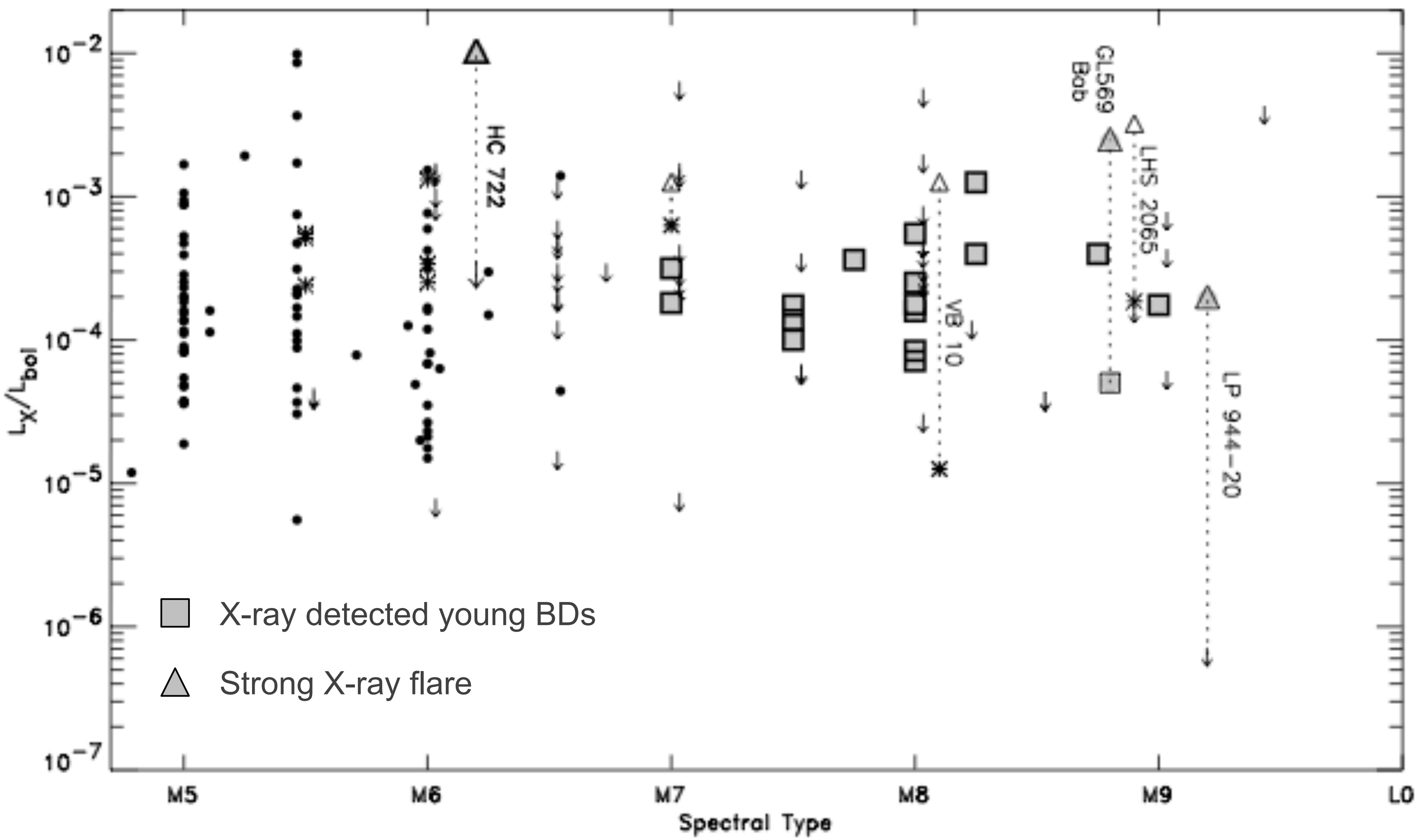
Preibisch et al. 2005

- Brown dwarves populate the low-L_X tail of the very low-mass cool star population (excluding periods of flares).
- L_X/L_{bol} is comparable between BDs and cool stars

Gl569 Bab

Comparing BD vs. VLM stars in terms of coronal temperature, flare frequency, and fractional X-ray luminosity indicates that likely the same mechanism is at work in both classes of sources

X-ray emission from VLM stars and BDs



Preibisch et al. 2005

Pre main-sequence stars

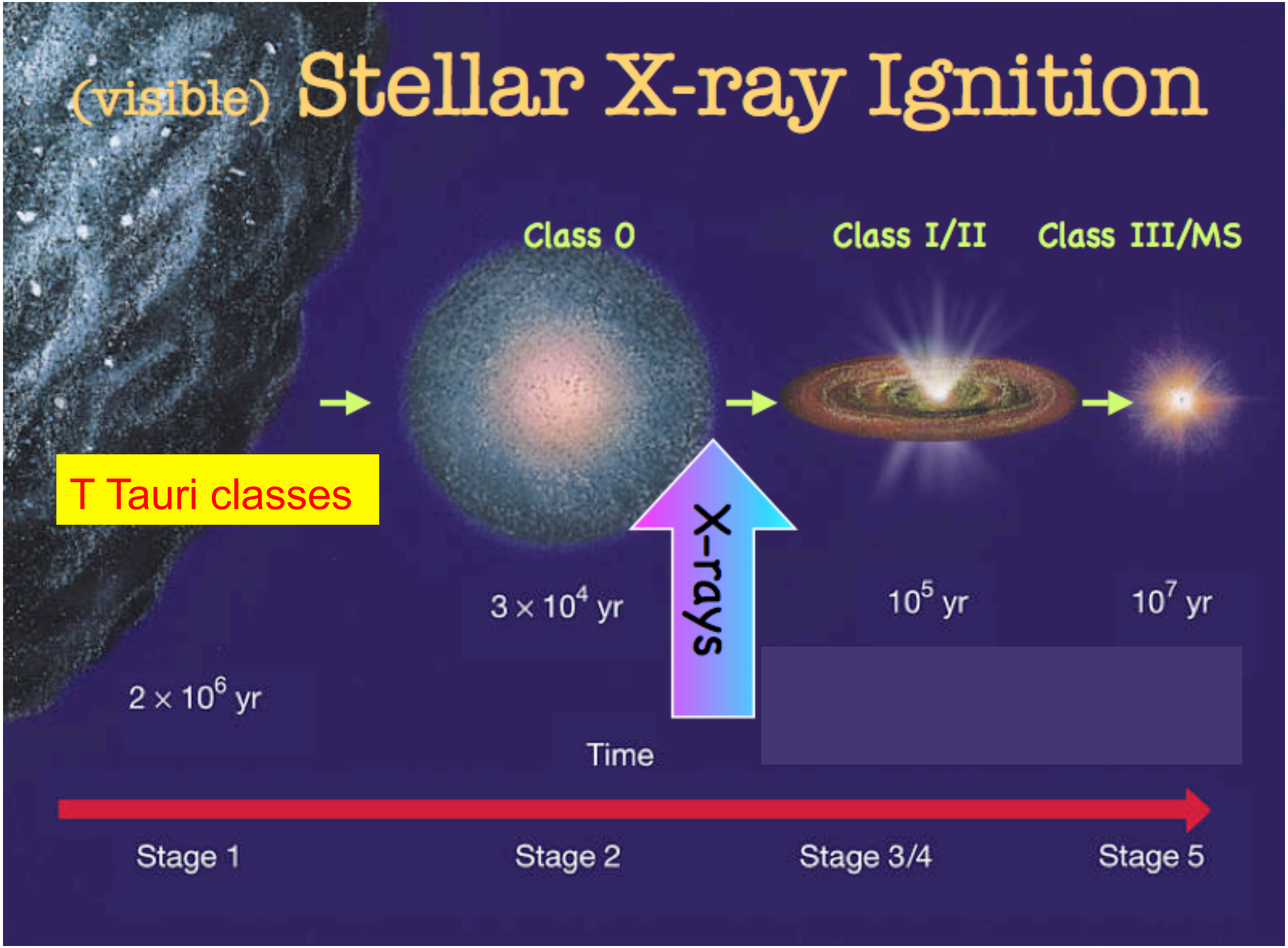
Before nuclear burning, stars pass through several phases (where contraction of the original molecular cloud is the main source of radiation)

YSO (Young Stellar Objects): M<2 $M_\odot$, completely hidden in their initial stages. Several milion years required to reach the MS

➔once the forming star emerges from the envelope, the object enters the classical T Tauri phase (**cTTS**: age≈10^{6-7} yr), where strong IR emission is likely associated with a disk – F, G, K, M types

➔ when all material has been expelled and/or accreted, the spectral energy distribution is similar to that of MS stars: weak-line T-Tauri phase (**wTTS**) – star still in contraction

Herbig Ae/Be stars (HAeBe): M≈2−10 $M_\odot$, whose evolutionary timescale ≈ dissipation timescale for their circumstellar matter (often observed). Main sequence reached after ≈10^6 years – A+B types



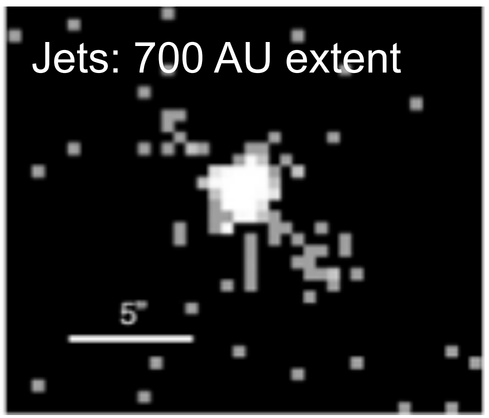
(visible) Stellar X-ray Ignition
Class 0
Class I/II
Class III/MS
T Tauri classes
X-rays
3 × 10^4 yr
10^5 yr
10^7 yr
2 × 10^6 yr
Time
Stage 1
Stage 2
Stage 3/4
Stage 5

• Class 0 stage: t≈10^4 years, can be observed only in the far-IR to mm bands. Quasi spherical infall and formation of a thick proto-planetary disk (hundreds AU in size). Hard to detect X-ray emission because of high obscuration

• Class 1 stage: t≈10^5 years, near- to far-IR emission from the accreting proto-planetary disk. Bipolar outflows common in Class 0−1 stages (hard to detect in the Class 0 because of obscuration)

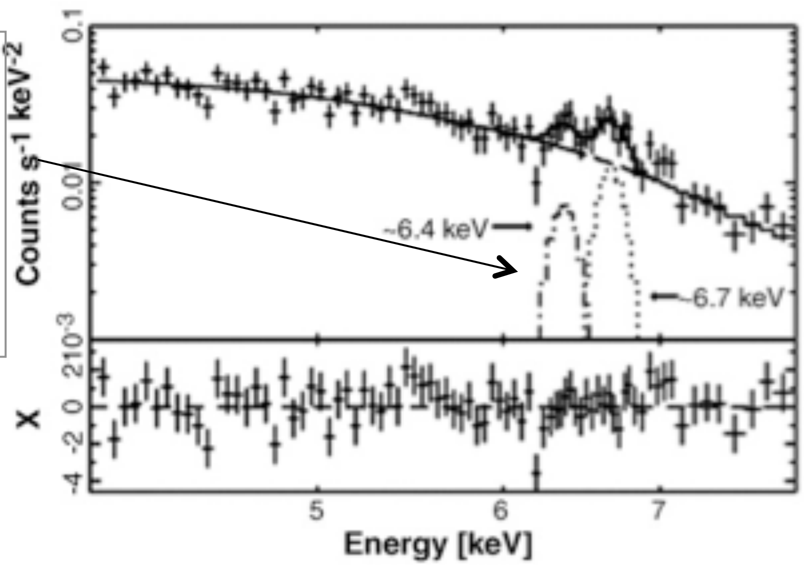
• Class 2 stage: t≈(0.5−1)10^6 years, accreting disk + stellar photosphere becoming visible in the optical band ➔ classical T-Tauri stars (cTTS)

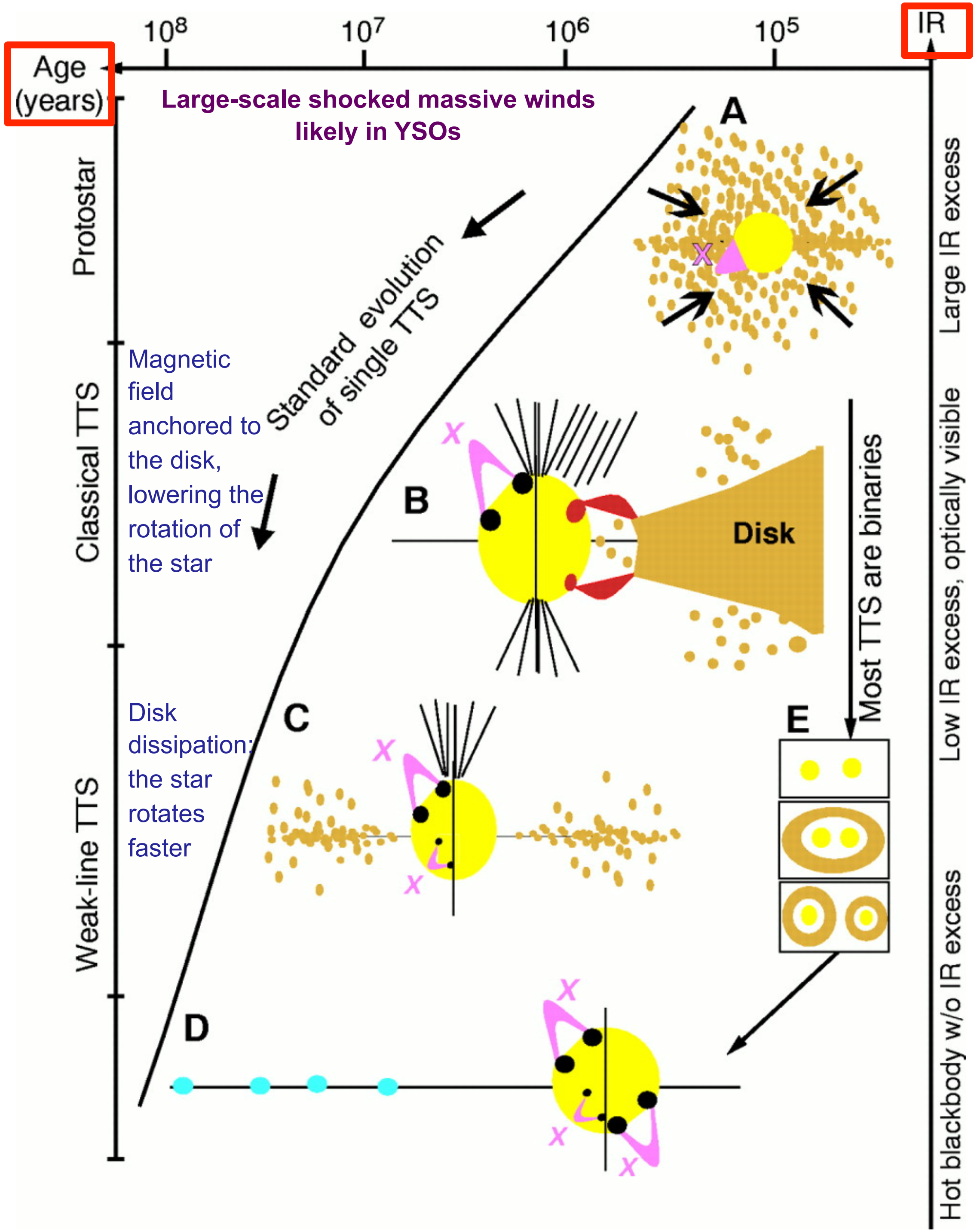
• Class 3 stage: accretion has stopped and the disk is dissipating ➔ weak-lined T-Tauri stars (wTTS)



Accreting Class II PMs DG Tau (Gudel et al. 2008): presence of two X-ray jets

Few cases of mostly neutral iron line from young class I protostars with heavy disks (Imanishi et al. 08)





No clear rotation-activity relation established yet in pre-MS stars

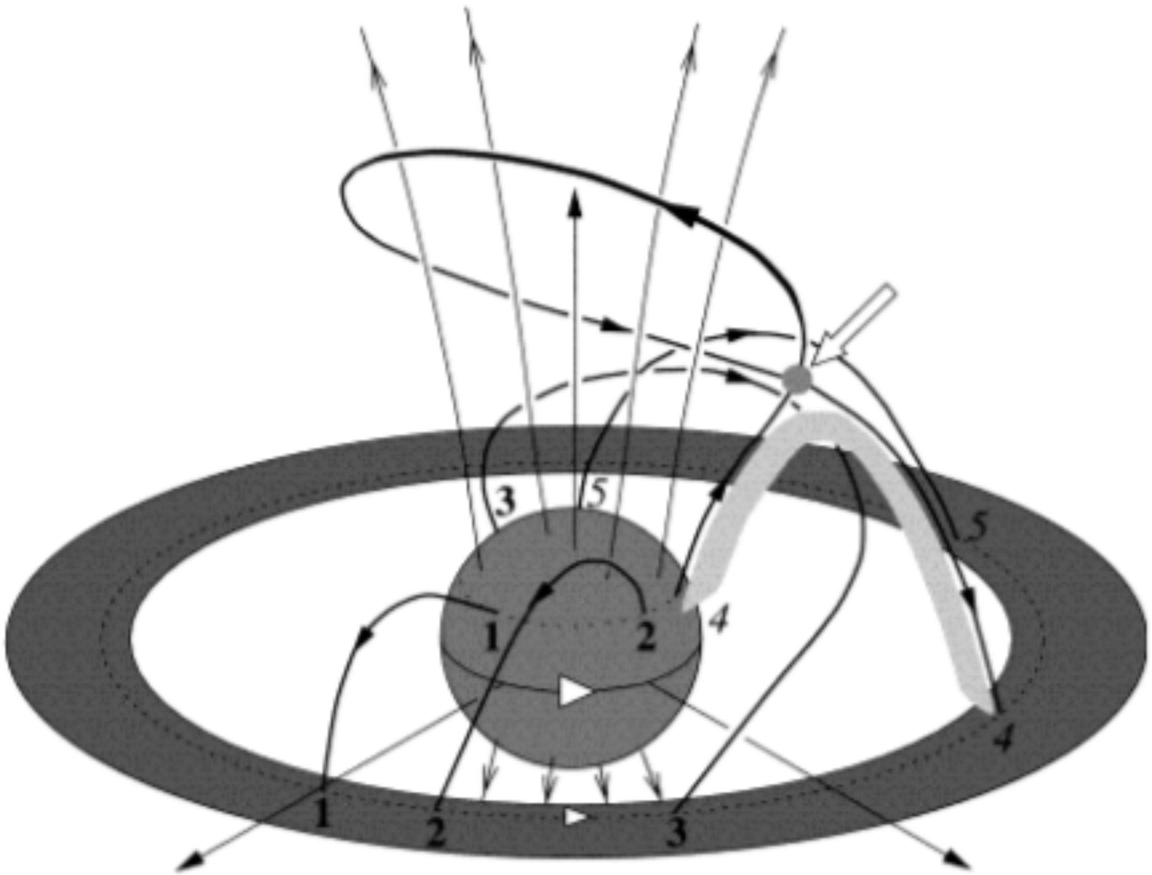
Class I protostar: "stellar" core from the collapsing cloud + some X-ray active regions

Class II protostar: *cTT phase*. Winds, accretion via funnels, hot spots, *magnetic loops where X-rays are produced* (more than in shocks)

Class III protostar: *wTT phase.* Stronger X-ray emission, shallow or no disk (photo-evaporation due to X-rays?)

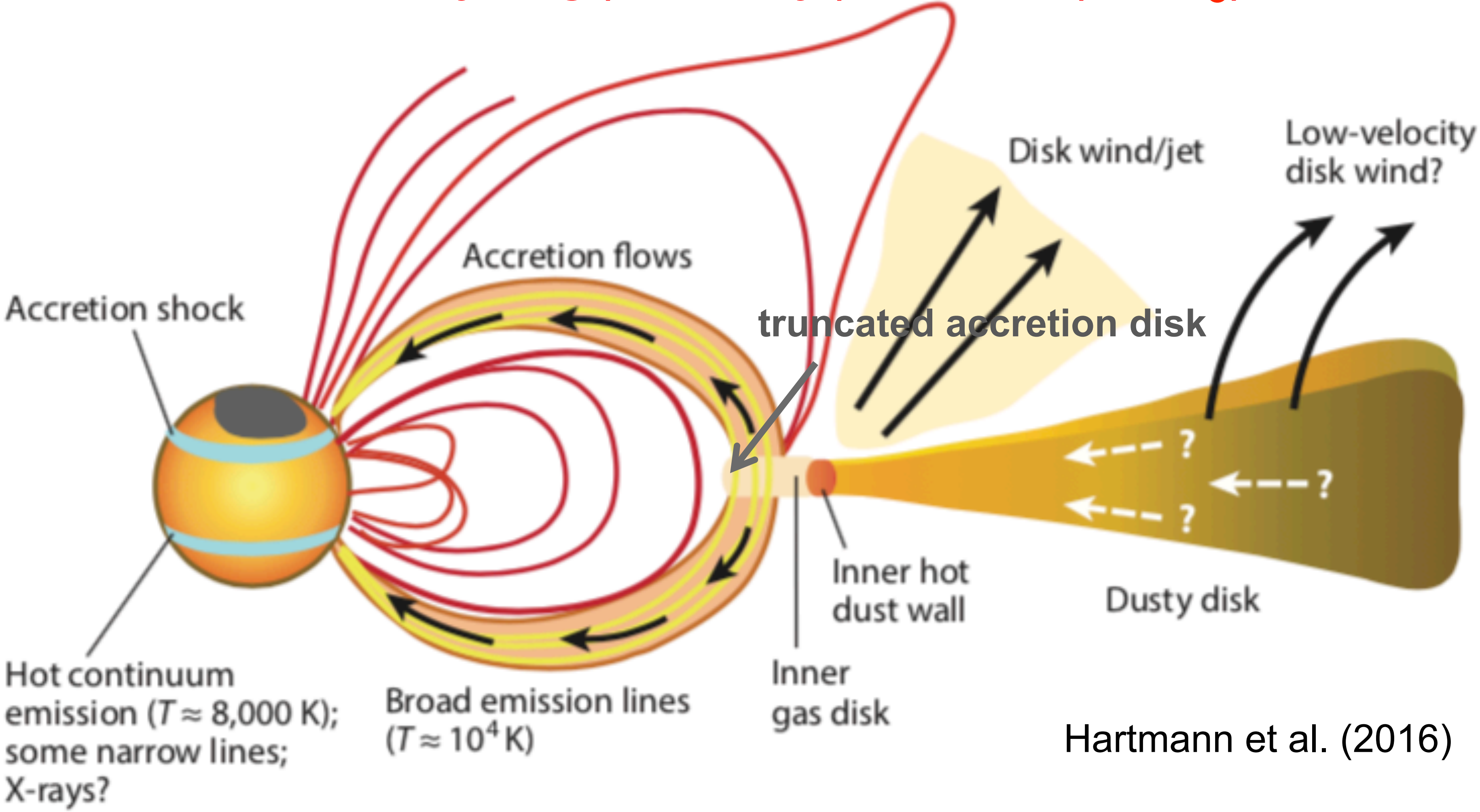
Naked TTS, evolving to a MS stars with planetesimals or planets (X-rays establish disk turbolence, hence regulate plane formation)

Neuhauser 1997



Star-disk magnetic-field model (from Montmerle et al. 2000)
Field lines wind up and reconnect (line labeled ‘5’) because the star rotates faster than the inner edge of the disk

Accretion onto a young (t≈1−10 Myr) low-mass ($M \lesssim 1 M_\odot$) star



Hartmann et al. (2016)

Accretion from a disk through stellar magnetosphere → large starspots. Magnetic field lines connected with the disk channel material at nearly free-fall velocities → shocks at the stellar surface and X-rays + optical/UV reprocessed emission. Magnetic field lines unconnected with the disk produce coronal X-ray emission and stellar winds; jets may be produced as well

T Tauri stars

• Along the Hayashi tracks the pre MS stars are fully convective ➔ no solar-type dynamo mechanism BUT possibly α^2-dynamos, turbolent dynamos (producing small-scale fields independent on rotation) and magnetic reconnection at work

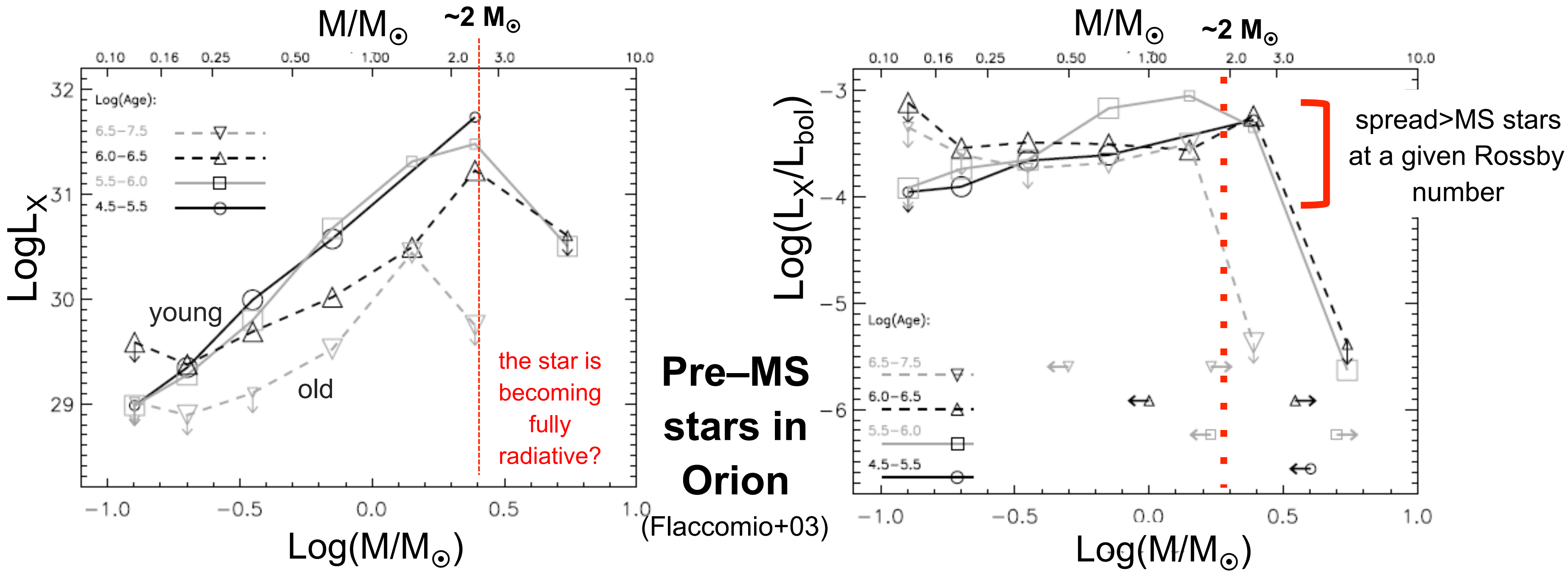
• In **cTTS**, accretion is likely to occur along the magnetic field lines onto the stellar surface, in the so-called **hot accretions spots** [free-fall velocity, infalling gas is *shocked* and heated, producing few MK temperatures, hence X-rays; *magnetic loops* ➔ *enhanced X-ray emission* (wrt MS stars) *due to high magnetic activity*]

Still debates on how much the accretion processes contribute to the energy budget of cTTS (probably limited contribution)

• **wTTS** [EW (Hα)<10Å] have spectra resembling those of evolved MS stars ➔ established as pre-MS stars on the basis of their strong X-ray emission ➔ possible bias towards the detection of the X-ray brightest wTTS in star-forming regions. Stronger X-ray emission because of faster rotation (no disk anchoring the magnetic fields)?

X-ray emission from $\approx 2 \times 10^7$ K optically thin plasma, $L_x \approx 10^{29-30}$ erg/s ($10^{-3 \div -5}\, L_{bol}$), and variable on hr-days timescales

X-ray emission from T Tauri stars vs. age and mass



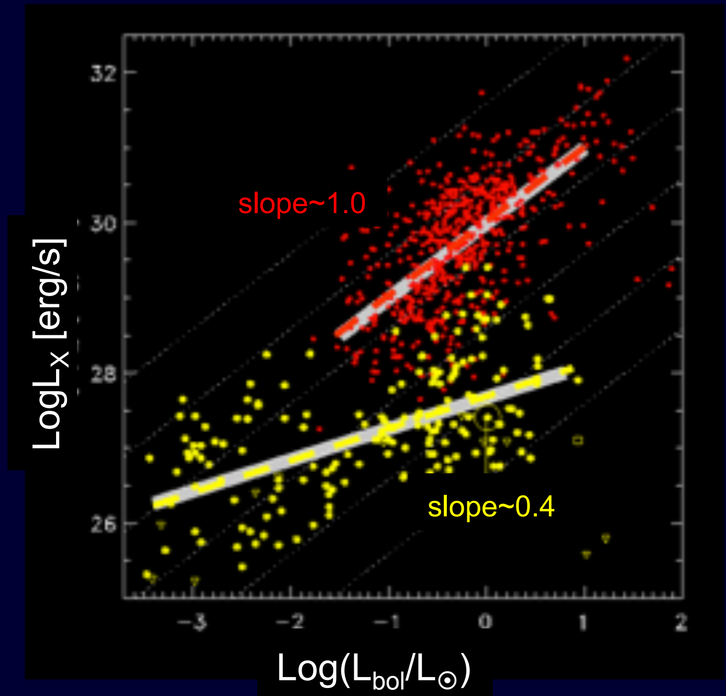
• M≤2-3 M$_\odot$: Lx increases with mass and decreases with age in each mass bin (and $L_X/L_{bol} \approx 10^{-3} \approx$ constant because also L_{bol} decreases approaching the MS).

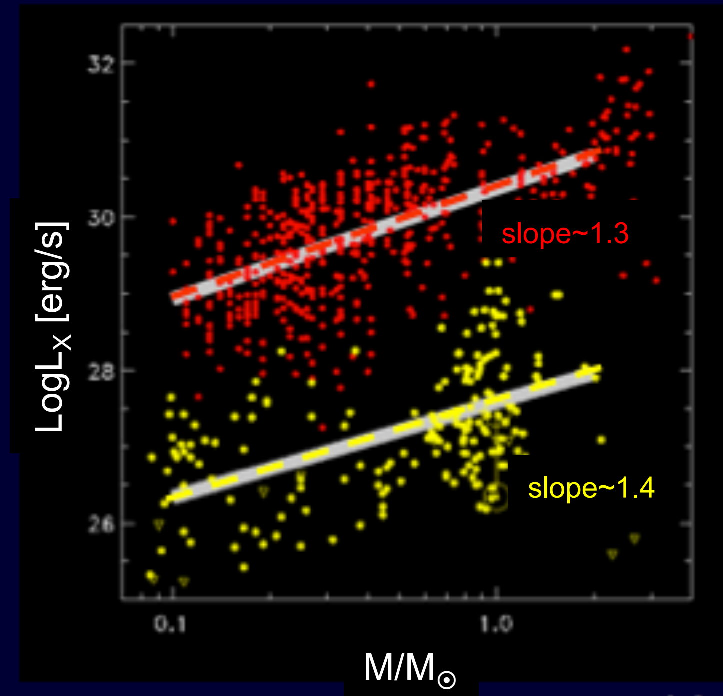
• A drastic drop in the Lx is observed close to 2 M$_\odot$: likely transition where the convective envelope disappears and the star becomes fully radiative

• No L_X vs. Period correlation in T Tauri stars

cTTS vs. main-sequence stars (I)

- COUP: *complete* sample of the ONC TT star population
- NEXXUS: *complete* sample of G,K,M main-sequence field stars (Schmitt & Liefke 2004)





COUP: $L_X \propto L_{bol}^{1.0}$

NEXXUS: $L_X \propto L_{bol}^{0.4}$

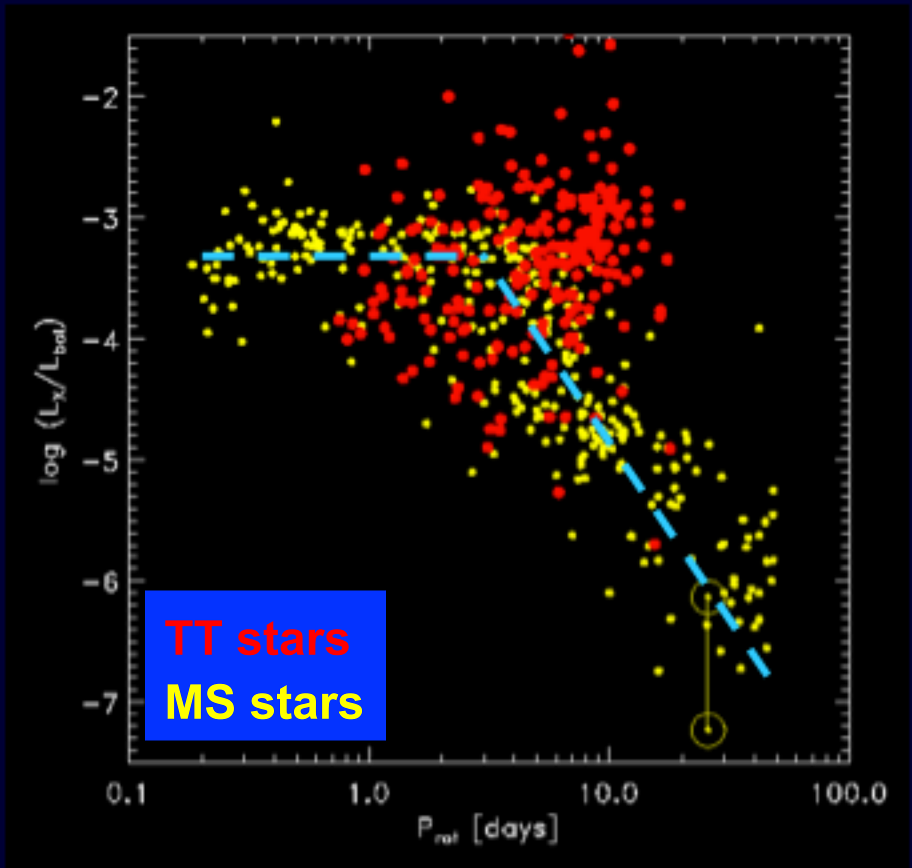
TT stars

MS stars

COUP: $L_X \propto M_\star^{1.3}$

NEXXUS: $L_X \propto M_\star^{1.4}$

cTTS vs. main-sequence stars (II)



- **Main-sequence stars:**

  activity - rotation relation

  - $L_X \propto P_{rot}^{-2}$
  - saturation at log (L_X / L_{bol}) ~ −3 for $P_{rot} \leq 3$ days

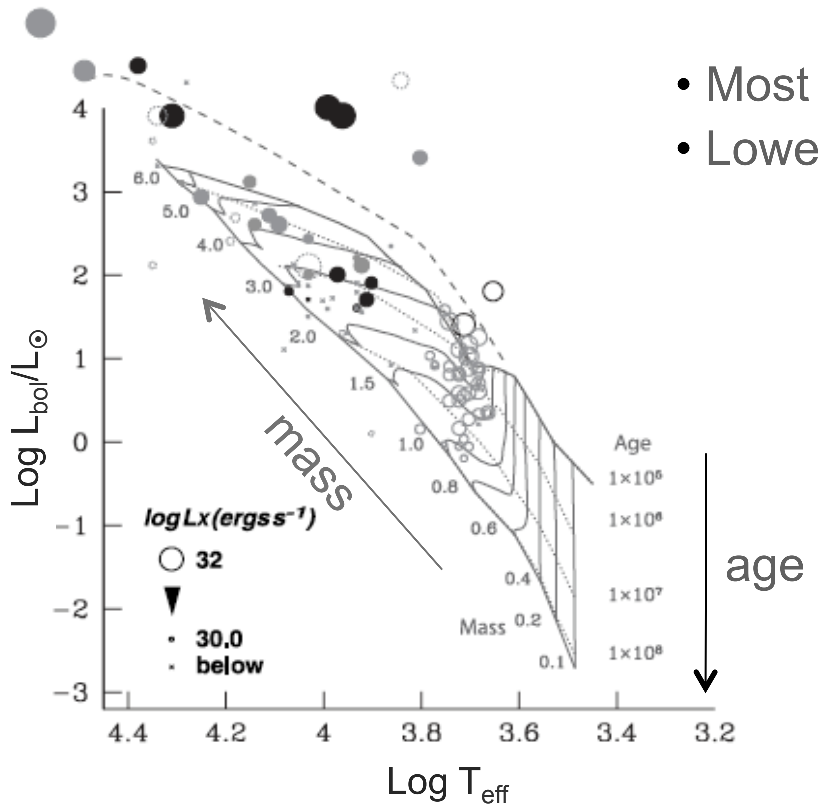
- **T Tauri stars:**

  no activity - rotation relation

  even slow rotators are highly active

Herbig Ae/Be stars

- Fully radiative ➔ no solar-type dynamo mechanism expected
- *Stellar (collading) winds + shocks, magnetic coronae, wind-fed magnetosphere, accretion shocks, shear dynamos, unknown late-type companion as possible models − some similar to TTSs*
- Magnetic fields may be fossil (remnants of those of the original molecular cloud)
- However, X-ray detections as high as 30-50% ($L_x \approx 10^{30-31}$ erg/s)
- Plasma temperatures of $\approx 5\times10^7$ K + iron 6.7 keV emission
- *Flares probably related to magnetic reconnection*



- Most massive stars have larger Lx (larger symbol size)
- Lower Lx at increasing ages?

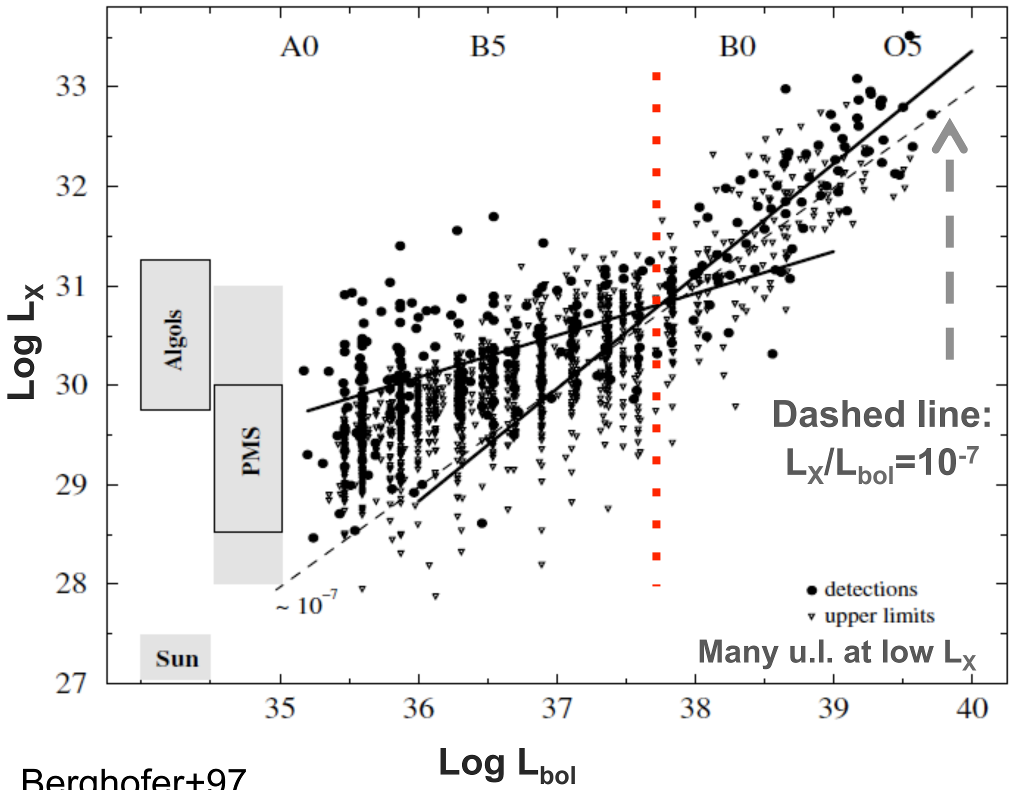
Stellar wind sources

O + early-B stars

Shocks produced by instabilities in radiatively driven winds

- Hot main sequence stars earlier than B3 were known X-ray emitters since *Einstein* ($L_x \approx 10^{-7} L_{bol}$)
- Lower L_x/L_{bol} than in late-type stars as well as lower spread of Lx ➔ indications of a different emission mechanism
- X-ray emission (kT≈0.5 keV) less variable than in low-mass stars
- Observed X-ray emission associated to a large number of small *shocks*, expected to form due to instabilities in the *radiatively-driven winds* from these hot stars
- Wind terminal velocities up to 3000 km/s
- The wind production requires high temperatures (>20000 K) in high-gravity stars
- High mass loss rates ($\approx 10^{-6}\ M_{\odot}$/yr)
- The transition fast wind-slow wind in MS takes place at T≈14000-18000 K, i.e., close to B3-B5 stars

OB stars from the RASS



Berghofer+97

Solid lines: regression lines at $L_{bol}<10^{38}$ erg/s and $L_{bol}>10^{38}$ erg/s

$L_{Bol} > 10^{38}\,\mathrm{erg\,s^{-1}}$:

$$\log(L_x) = \boxed{(1.13} \pm 0.10) \cdot \log(L_{Bol}) - 11.89 \pm 0.38$$

standard deviation: 0.40

$L_{Bol} < 10^{38}\,\mathrm{erg\,s^{-1}}$:

$$\log(L_x) = \boxed{(0.42} \pm 0.05) \cdot \log(L_{Bol}) - 14.87 \pm 0.46$$

standard deviation: 0.55

- Most luminous ($L_{bol}>10^{38}$ erg/s) OB-type stars follow the $L_X \approx 10^{-7} \times L_{bol}$ relation
- Late B-type stars ($L_{bol}<10^{38}$ erg/s) show larger X-ray luminosities “compared” to their L_{bol}

→ Sort of transition at $L_{bol} \approx 10^{38}$ erg/s, corresponding to ≈B1.5 type (from stellar-wind emission to MS star emission)

Summary

F to mid-M stars: solar-like dynamos (αΩ-dynamos), localized in the interface region connecting the outer convection zones with the radiative interiors
L_X proportional to P_{rot}, $L_X/L_{bol} \approx const \approx 10^{-3}$

A and late-B stars: fully radiative: no solar-dynamo expected, X-ray emission process still debated

VLM stars + brown dwarfs: similar mechanism (other dynamo than for G stars)
Most X-rays from flares, persistent X-ray emission likely faint

Pre main-sequence stars

- low masses: cTTS and wTTS: X-rays mostly produced in magnetic loops (but shocks in the free-falling gas still likely)
- High masses: accretion shocks/colliding winds/magnetic coronae producing X-rays

O, B stars: shocks in the high-velocity stellar winds
$L_X/L_{bol} \approx const \approx 10^{-7}$, $L_X \neq f(P_{rot})$