X-ray emission processes in stars and their immediate environment

Paola Testa
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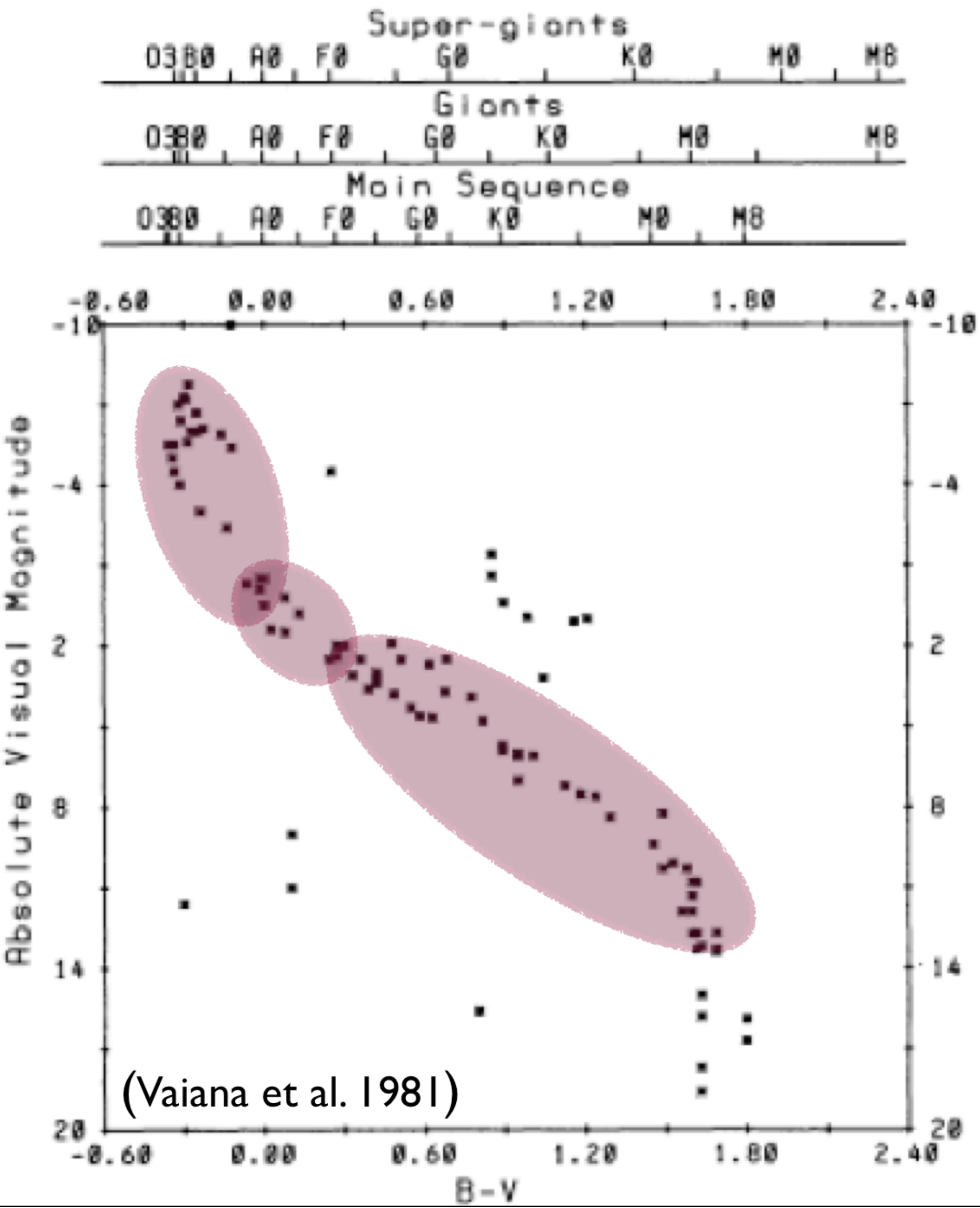
Chandra's First Decade of Discovery, September 22nd 2009

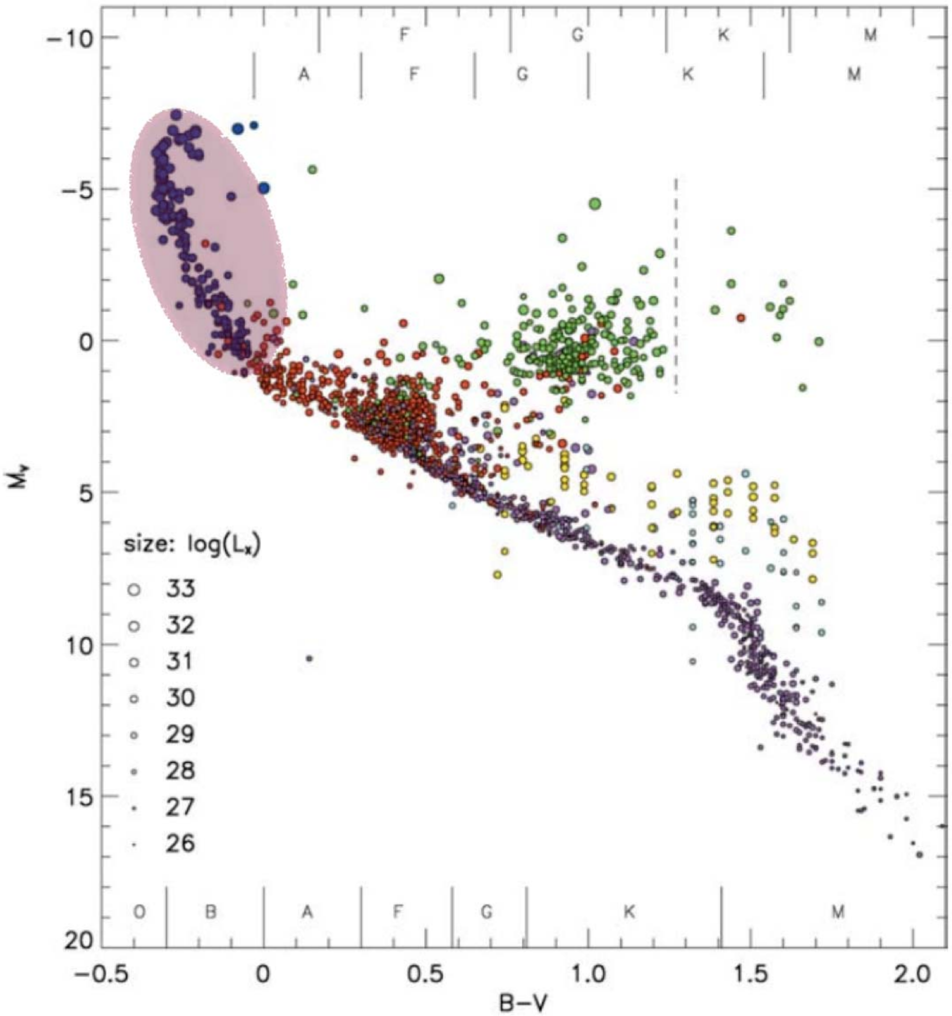
X-ray Emission from Stars



- X-ray emission present across entire HR diagram
- X-rays from early-type stars: $L_X/L_{bol} \sim 10^{-7}$
- main sequence A-type stars weak X-ray emitters
- X-rays from late-type stars: highly variable, L_X/L_{bol} spans a wide range and saturates at $\sim 10^{-3}$

X-ray Emission from Stars

(Güdel et al. 2004)



- <u>X-rays from early-type stars:</u>

  wind shocks, magnetic fields

- <u>X-rays from cool stars:</u>

  coronal physics

- <u>X-ray from pre-main sequence stars:</u>

  coronal physics, accretion, jets, magnetically confined winds

X-rays from Early-type Stars
Standard wind-shock model

(e.g. Lucy & White 1980, Owocki et al. 1988)

X-rays from shocks in radiatively driven stellar wind

- line formation radius
- overall wind properties
- absorption of overlying cool material

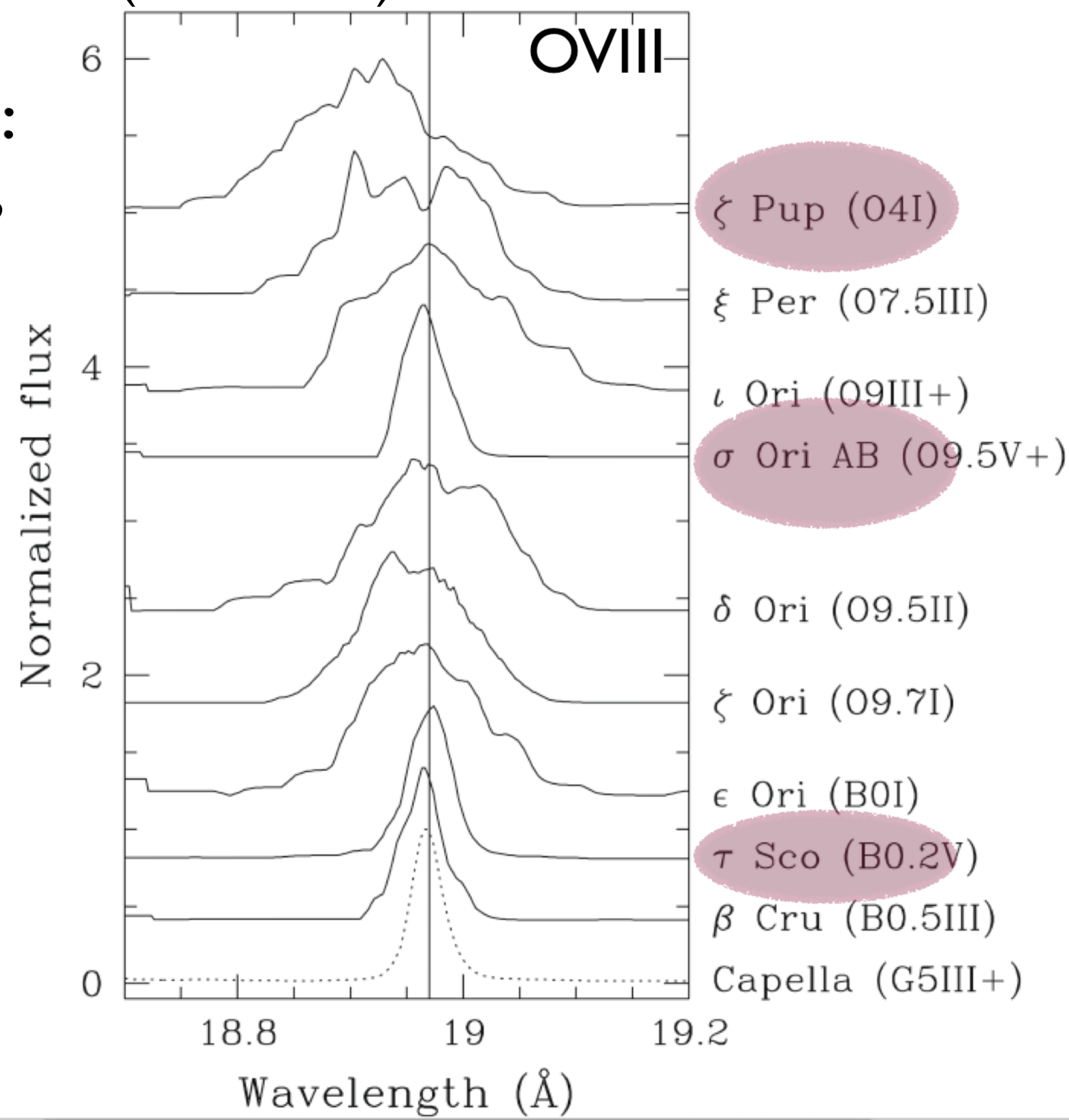
→ precise predictions for T, and line shifts and shapes

see Lidia Oskinova's talk

X-rays from Early-type Stars Chandra and XMM high resolution spectra

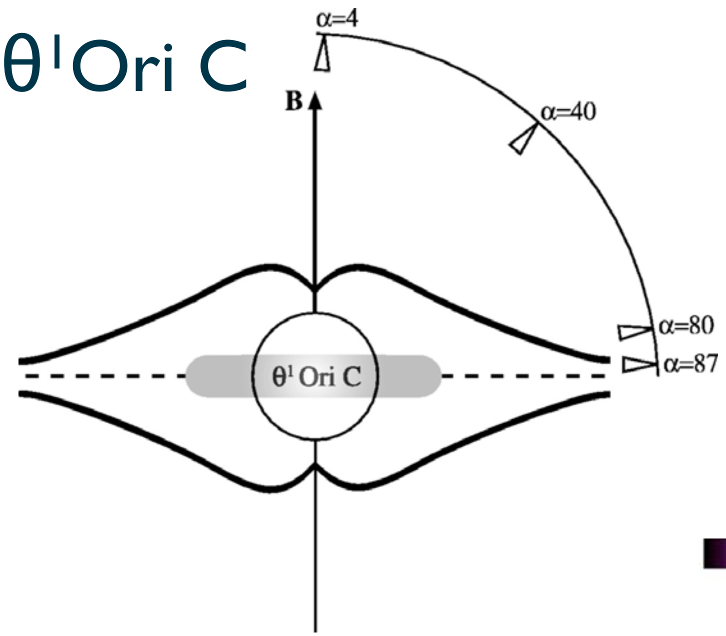
(Güdel 2004)

- mostly consistent with model: soft spectra with blue-shifted, broad (~1000 km s^{-1}), asymmetric lines
- soft sources, but lines unshifted, symmetric, and narrower than expected
- sources harder and brighter, and with lines narrower than predictions



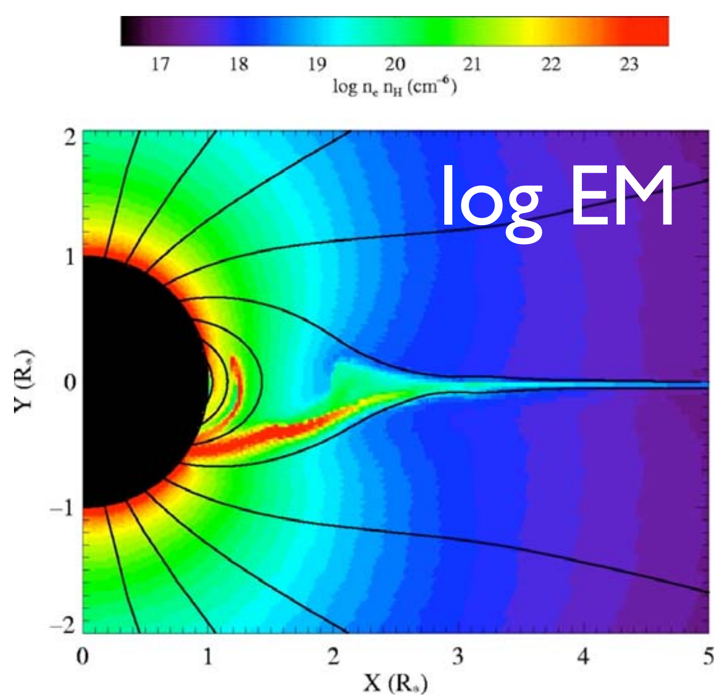
X-rays from Early-type Stars
Magnetic Stars: θ^1 Ori C (O5.5V)

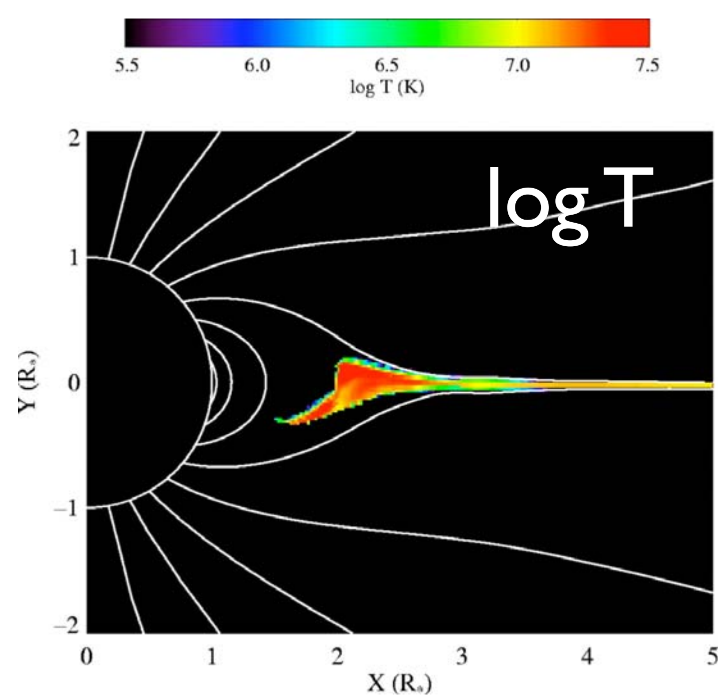
θ^1Ori C



magnetic field confines the wind yielding hotter plasma and narrower lines

(Gagné et al. 2005)





The model (2D MHD simulations) reproduces T, L_X, and the observed rotational modulation

X-rays from Early-type Stars

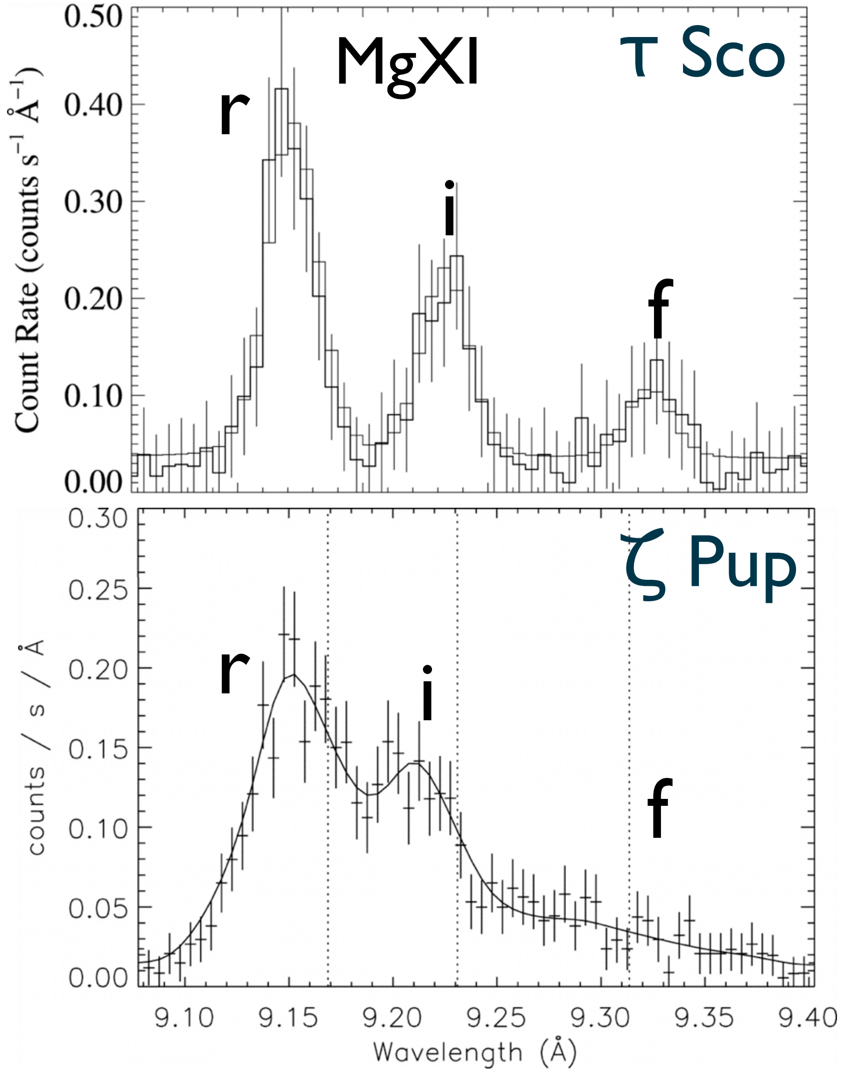
He-like triplet diagnostics:

confirm the wind-shock model, when taking into account the spatial distribution of the X-ray emitting plasma (Leutenegger et al. 2006)

however (low) opacity from X-ray observations is incompatible with known mass loss rates (e.g. Owocki & Cohen 2001) — porous wind models

see Lidia Oskinova's talk

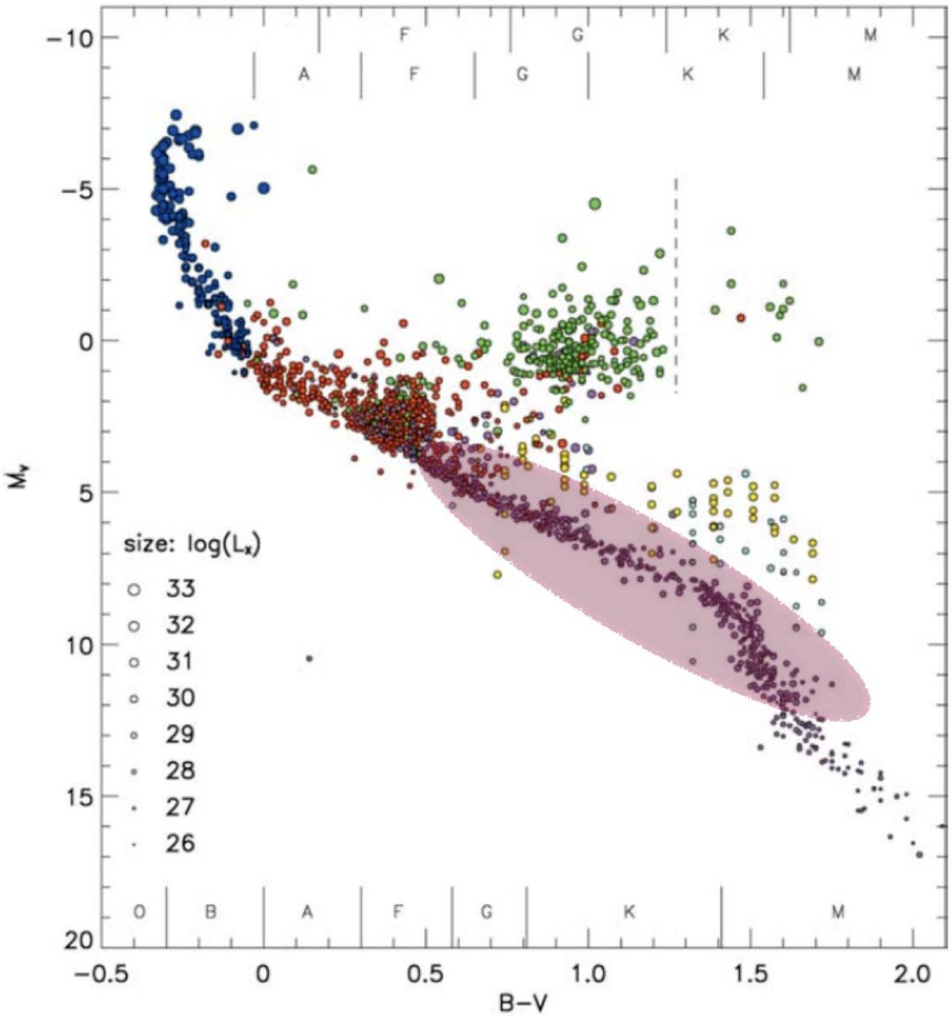
(Cohen et al. 2003)



(Leutenegger et al. 2006)

X-ray Emission from Stars

(Güdel et al. 2004)



- X-rays from early-type stars:

  wind shocks, magnetic fields

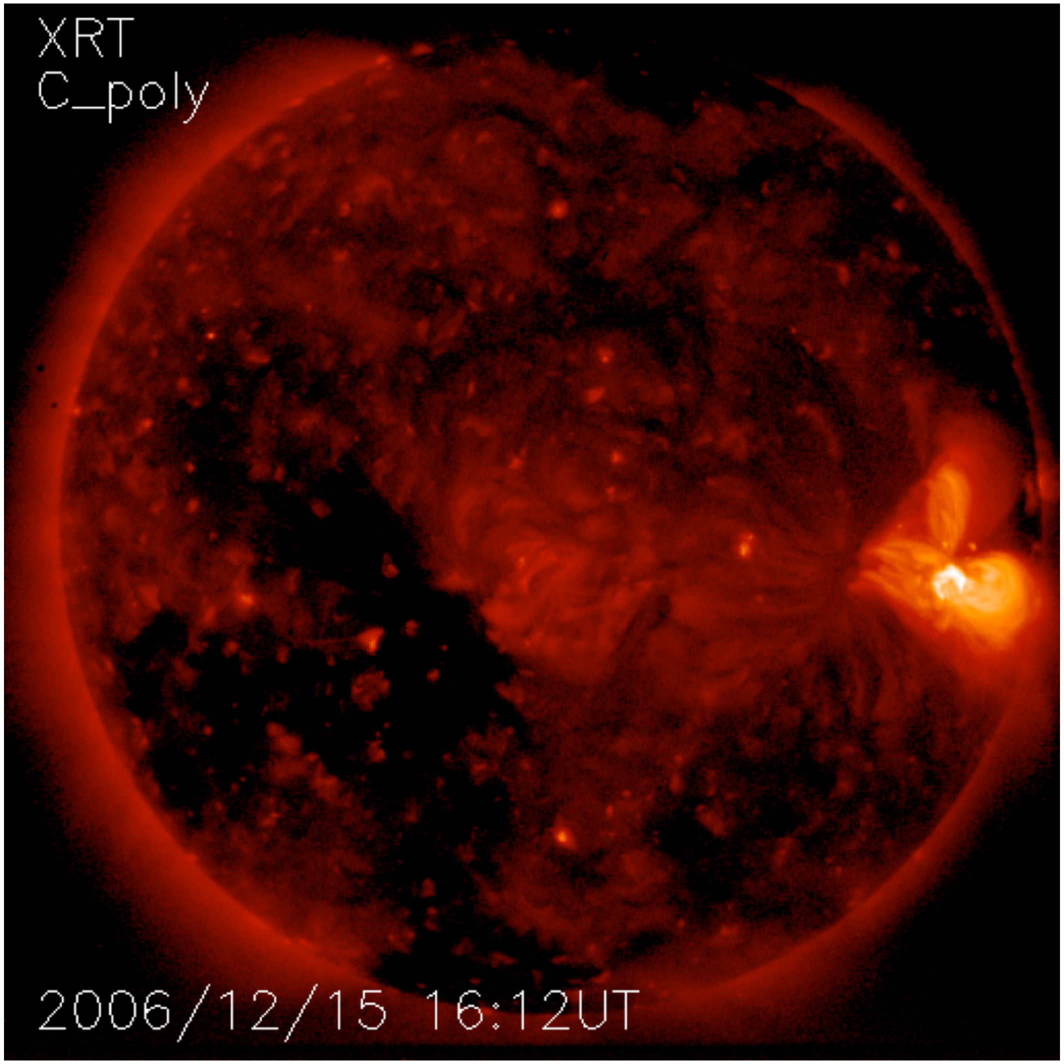
- X-rays from cool stars:

  coronal physics

- X-ray from pre-main sequence stars:

  coronal physics, accretion, jets, magnetically confined winds

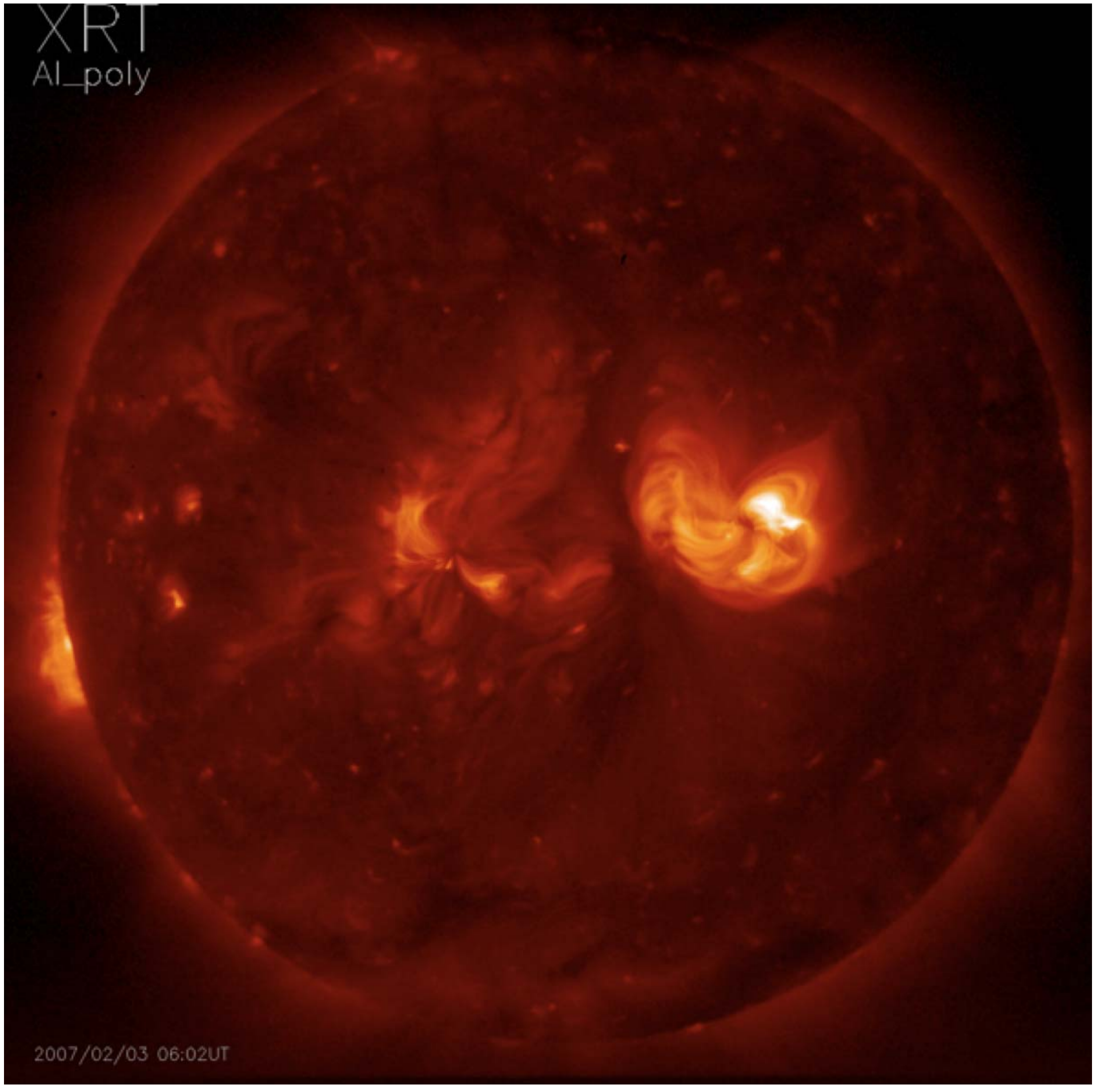
X-ray Emission from Cool Stars



Solar analogy:

- how far does it apply? how different are the underlying processes?

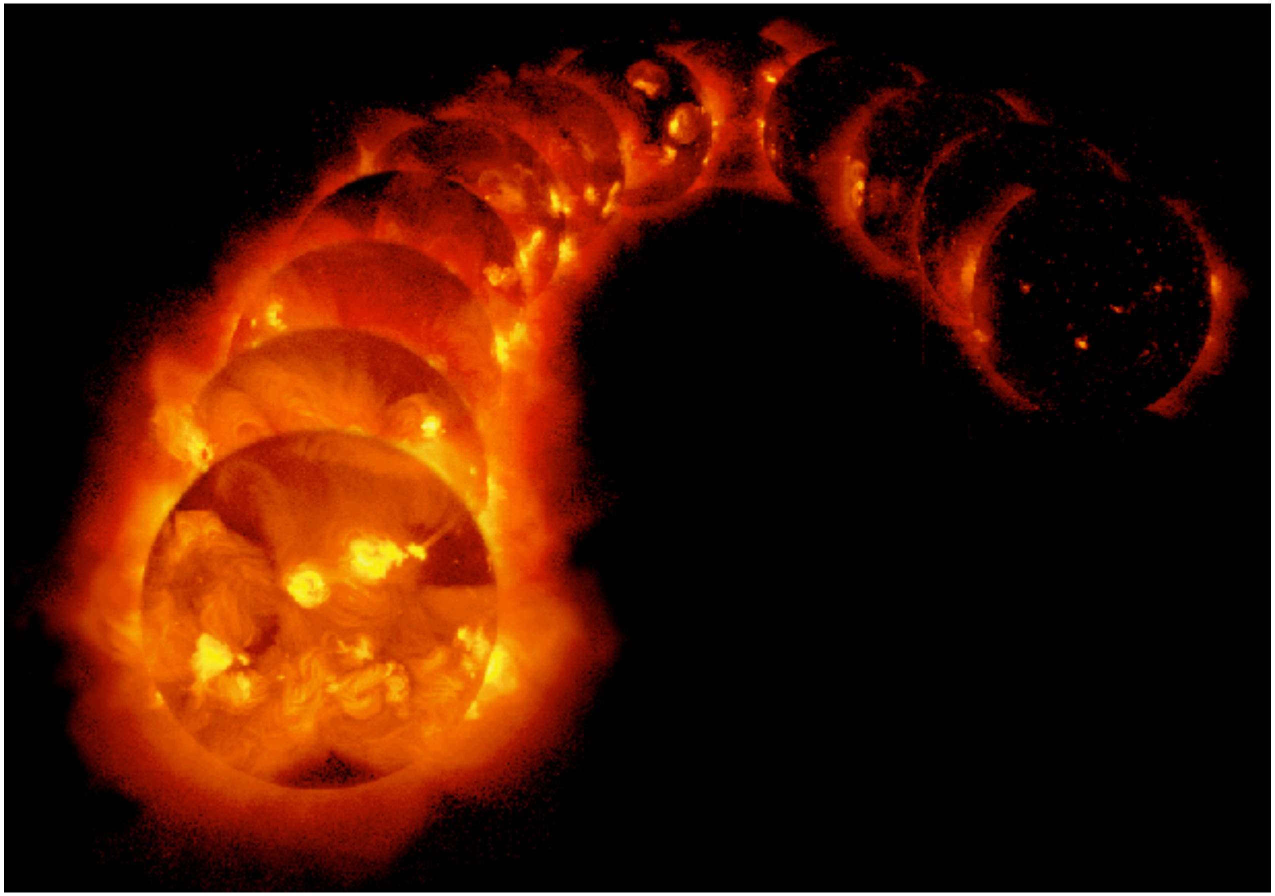
X-ray Emission from Cool Stars



- X-ray activity cycles
- the Sun in time
- abundances
- structuring of coronae and flares

X-rays from Cool Stars
Activity Cycles

http://www.lmsal.com/SXT/html2/The_Changing_Sun.html

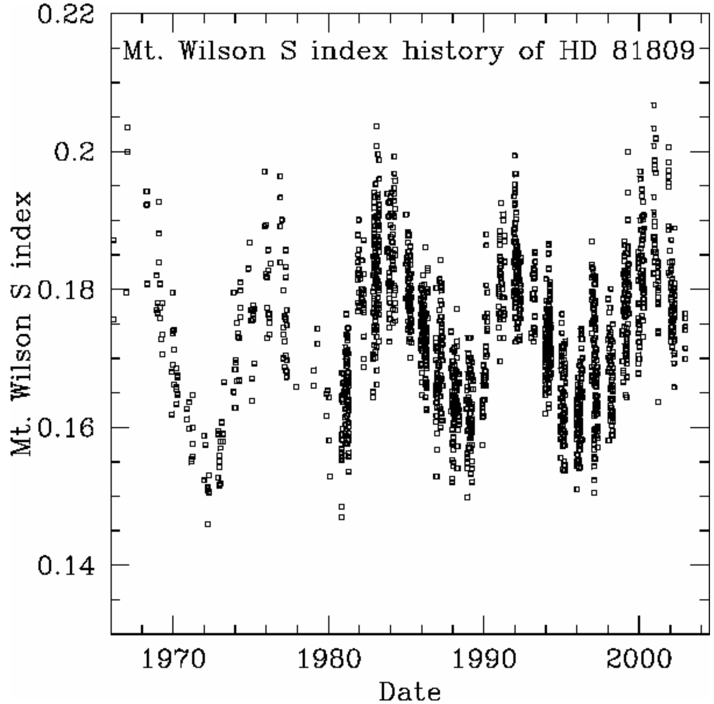


the Sun observed with Yohkoh between 1991 and 1995

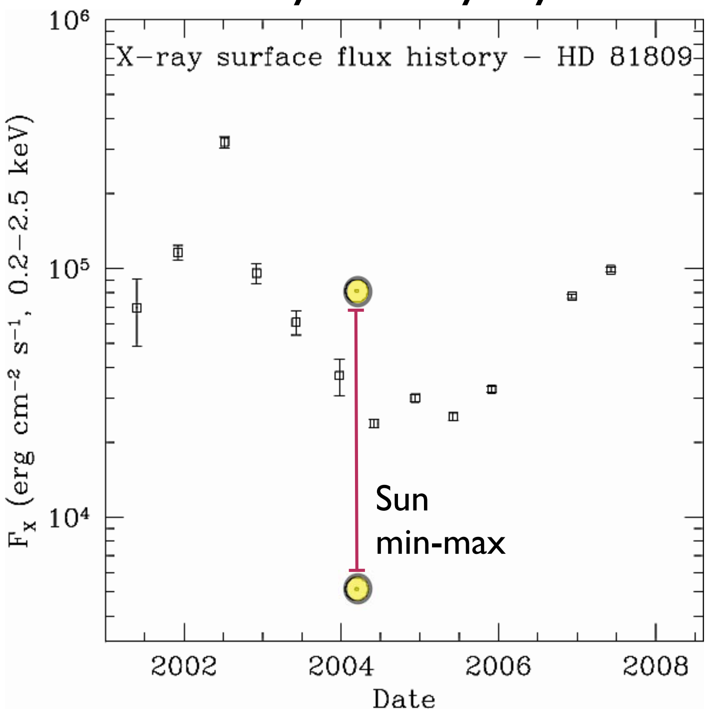
X-rays from Cool Stars
Activity Cycles

Long term X-ray monitoring shows cycle similar to the Sun's: 61 Cyg A (K5V) (Hempelmann et al. 2006), HD 81809 (G5V) (Favata et al. 2008) (see also Ayres 2009 on α Cen)

Chromospheric Activity Cycle

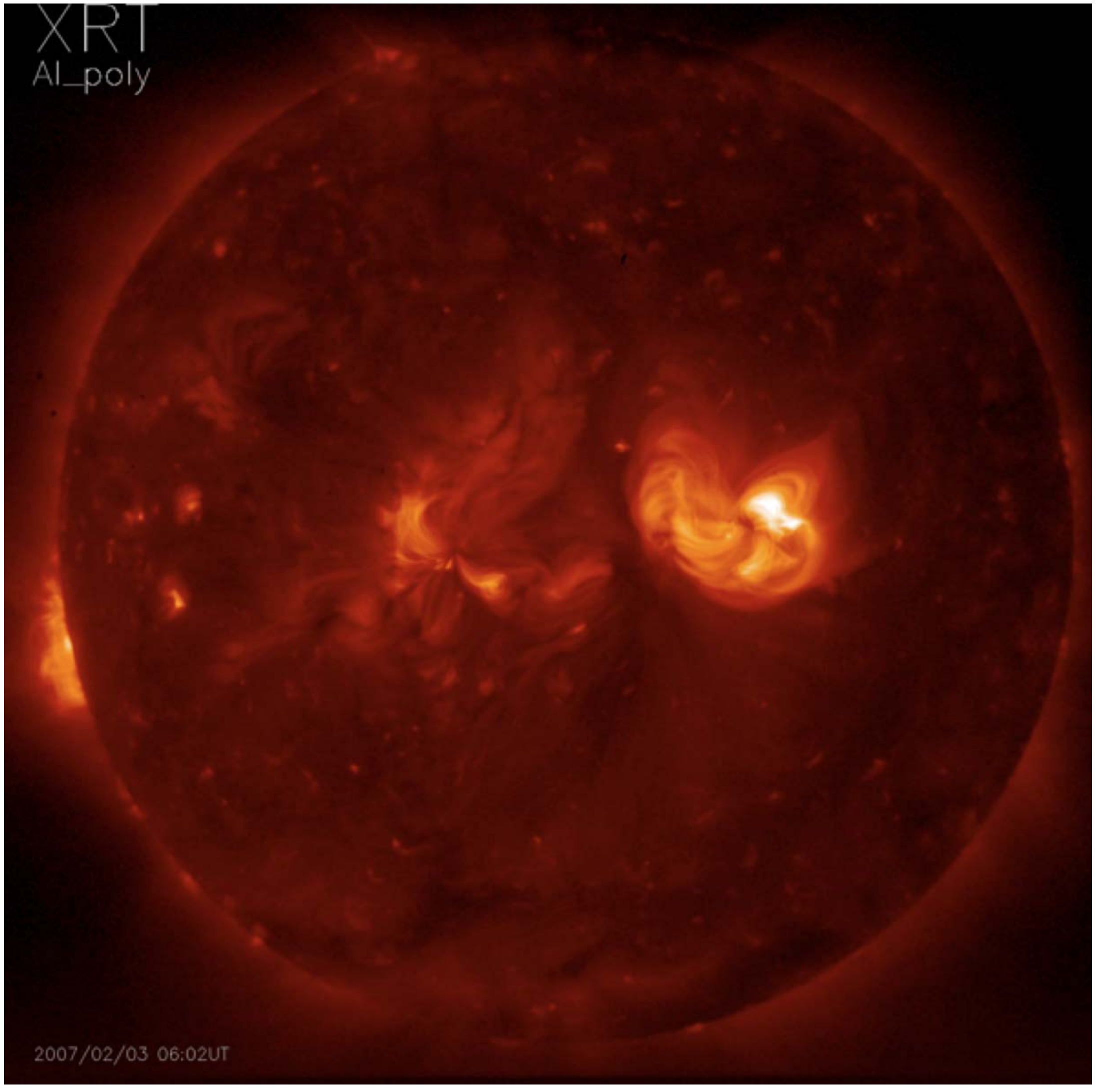


X-ray Activity Cycle



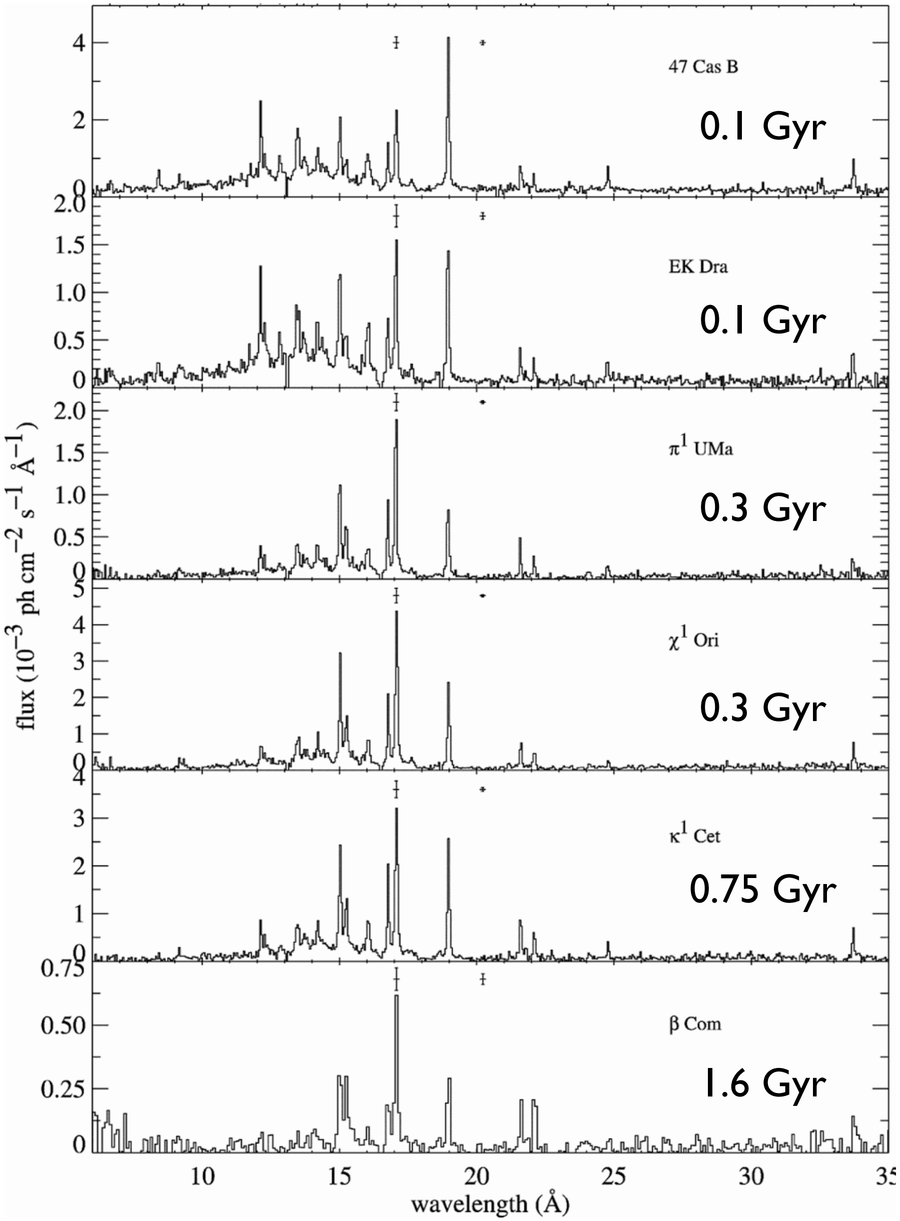
(Favata et al. 2008)

X-ray Emission from Cool Stars



- X-ray activity cycles
- the Sun in time
- abundances
- structuring of coronae and flares

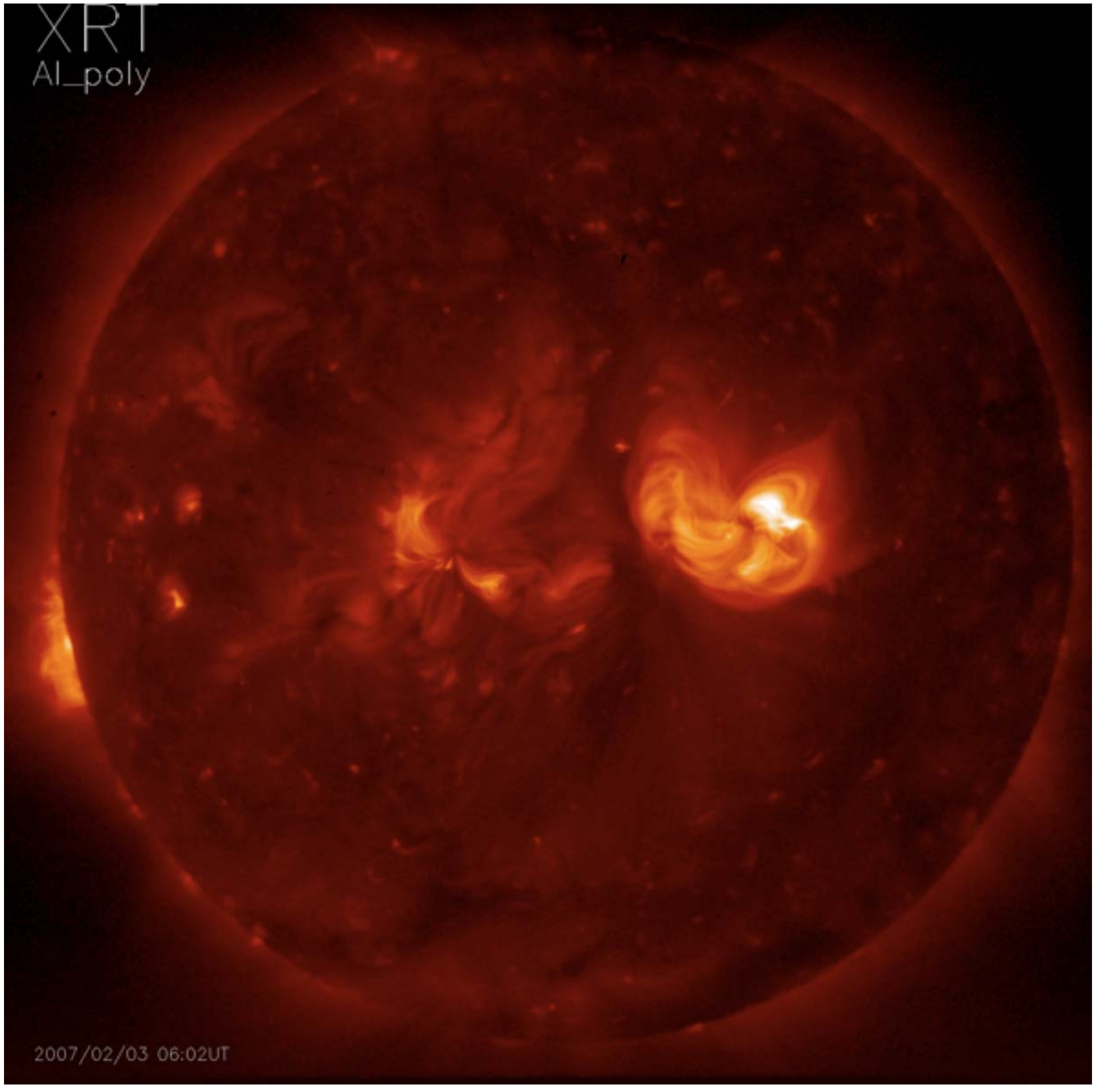
X-rays from Cool Stars
Solar Analogs: the Sun in time



- T_{peak} decreases 10MK → 4MK
- also flare rate and L_X decrease with age

Telleschi et al. (2005)

X-ray Emission from Cool Stars



- X-ray activity cycles
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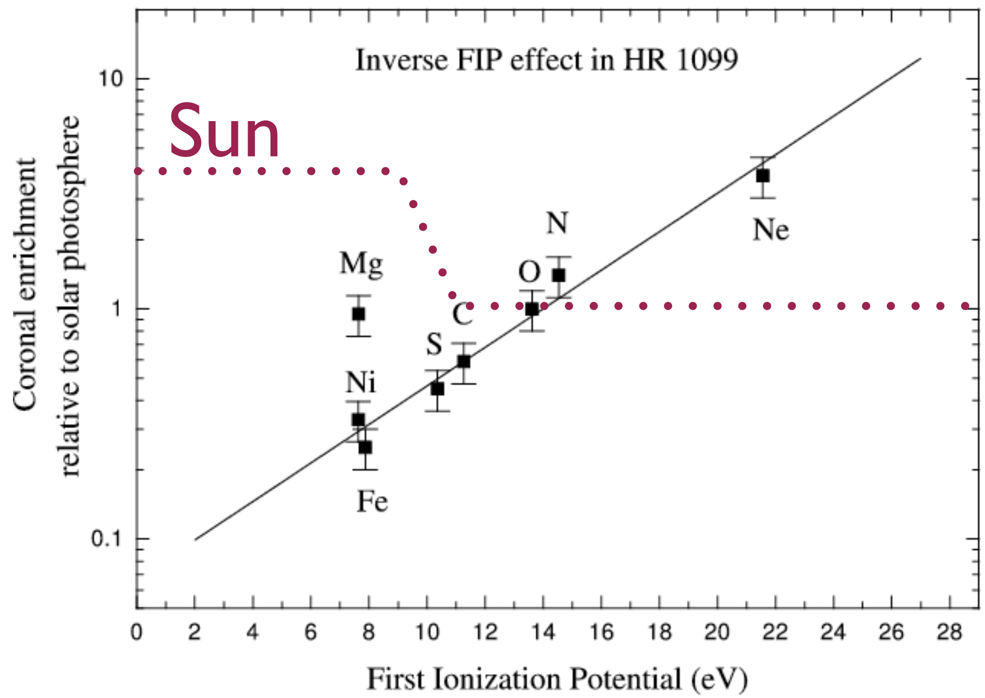
X-rays from Cool Stars
Abundances

- important e.g. for chemical enrichment of interstellar medium, and opacity, models of stellar structure
- in solar corona significant fractionation, function of the element First Ionization Potential (FIP) (e.g. Feldman 1992)

  → implications for the underlying physical processes

- in other stellar coronae?

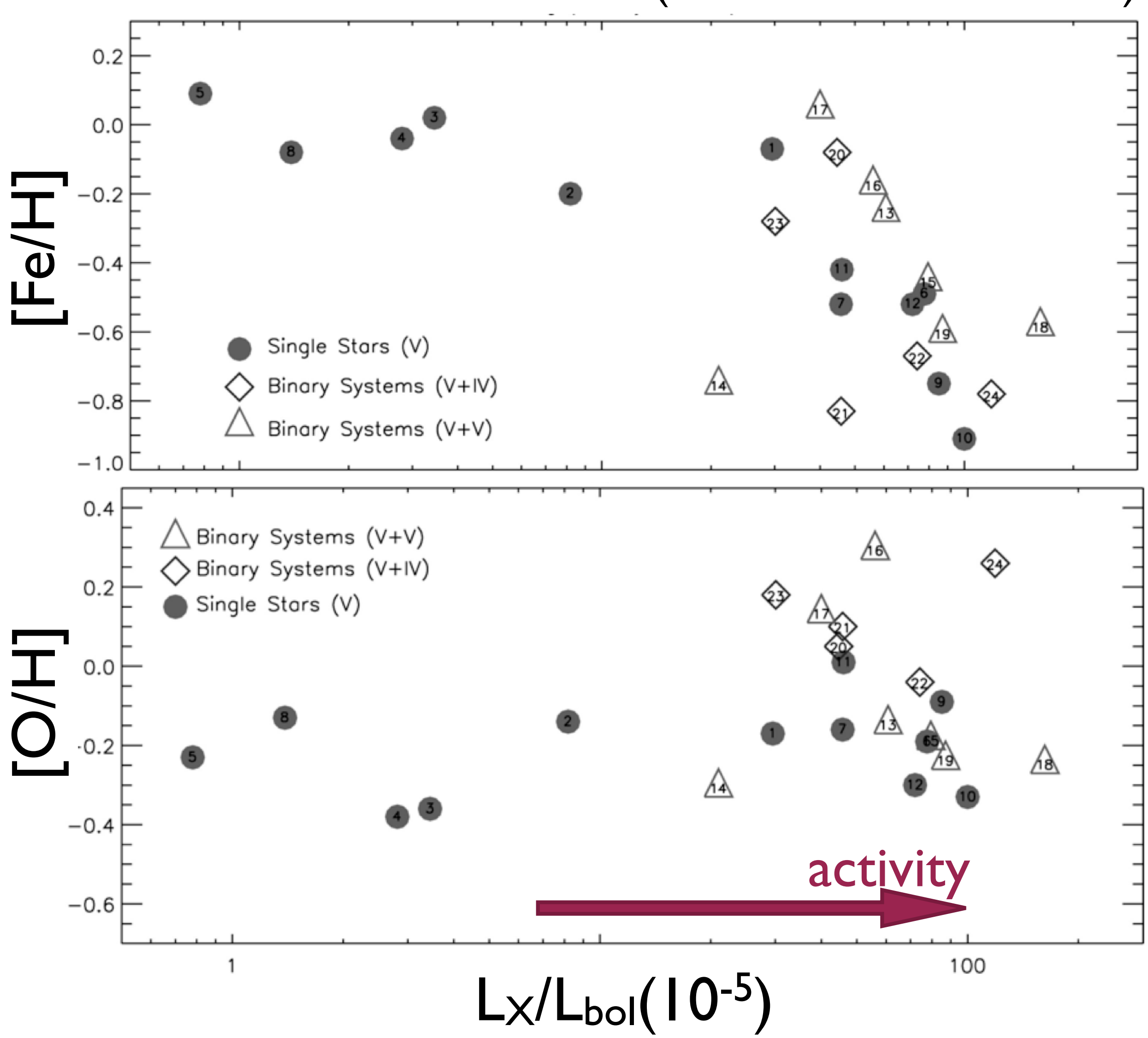
Brinkman et al. (2001)



X-rays from Cool Stars
Abundances

- active stars: inverse FIP effect (IFIP), i.e. low FIP elements (e.g. Fe, Mg, Si) are depleted in coronae
- IFIP effect function of activity: increases for increasing X-ray activity

(Garcia-Alvarez et al. 2008)

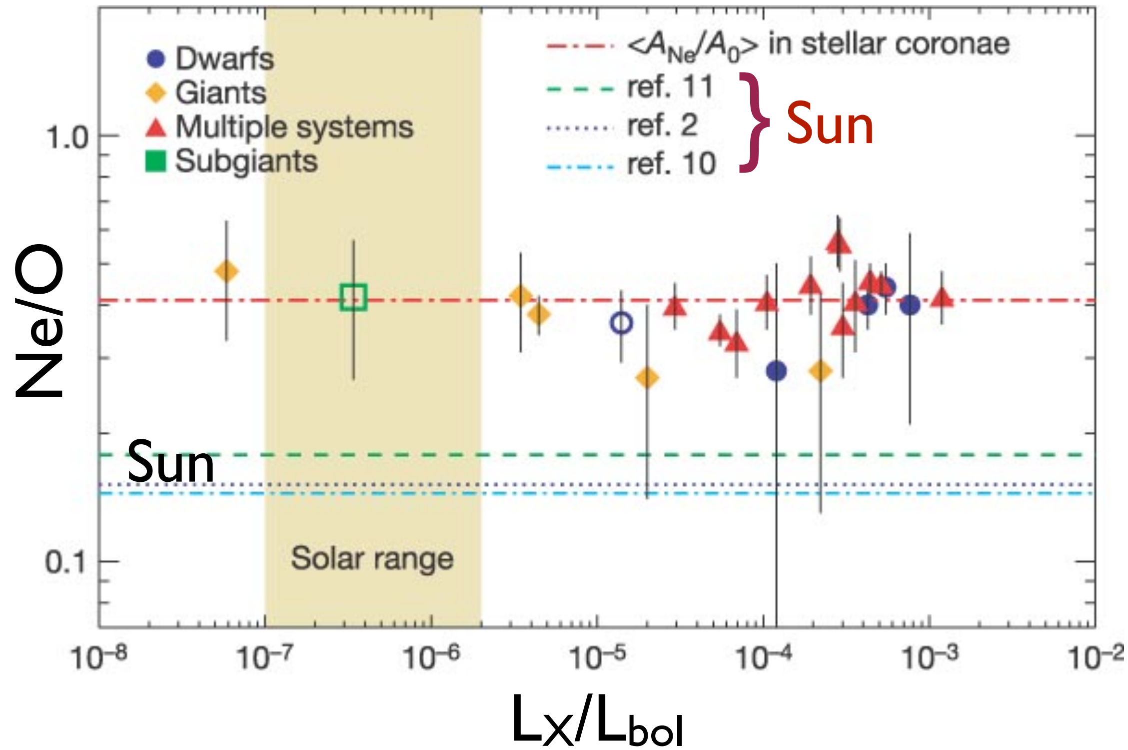


X-rays from Cool Stars
Abundances

(Drake & Testa 2005)

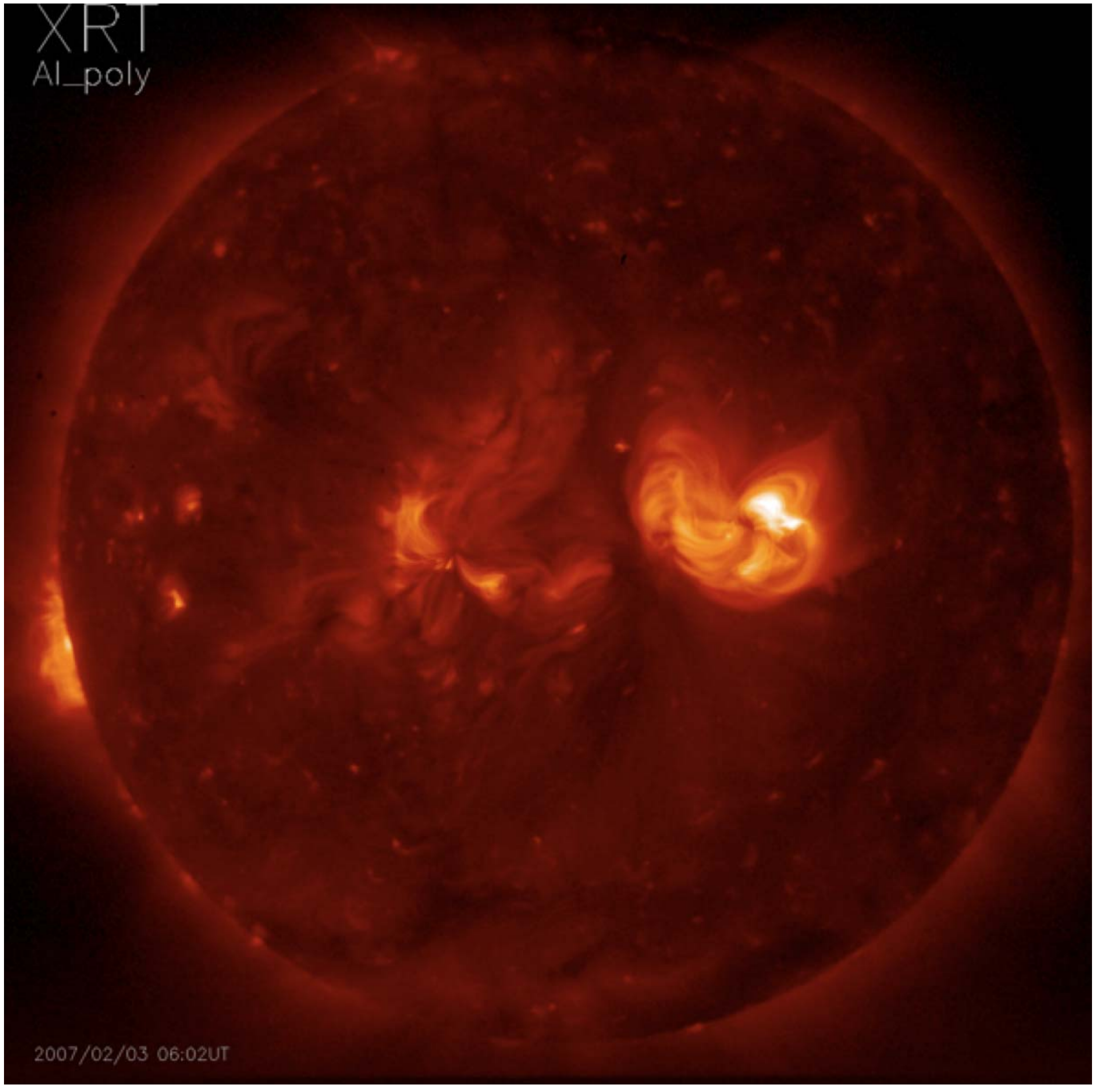
- Ne/O remarkably constant over a wide range of activity BUT ~2.7 times higher than in the solar corona

- Ne/O might have some dependence on activity (e.g. Robrade et al. 2008)



- Ne important for opacity: cannot be measured in solar photosphere, important parameter in models of solar interior (e.g. Bahcall et al. 2005, Antia & Basu 2005) — OPEN ISSUE

X-ray Emission from Cool Stars



- X-ray activity cycles
- the Sun in time
- abundances
- structuring of coronae and flares

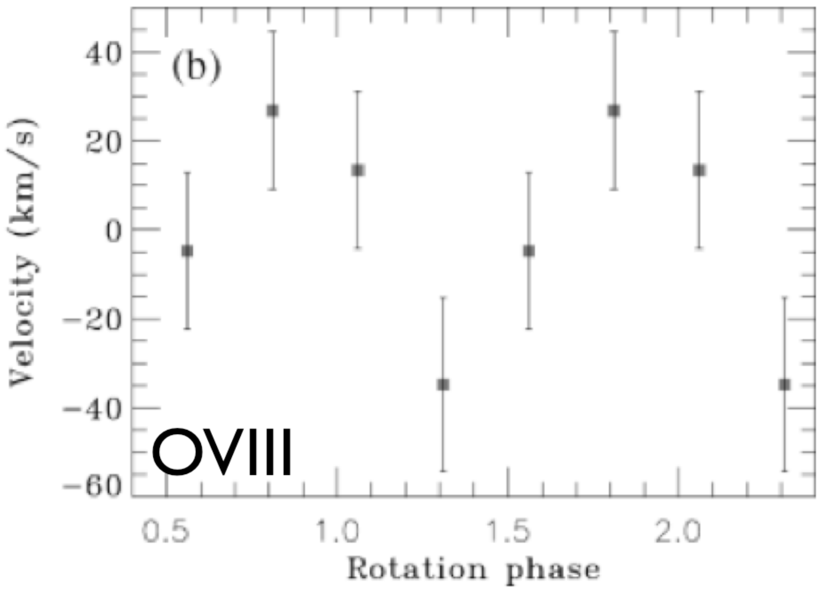
X-ray Emission from Cool Stars

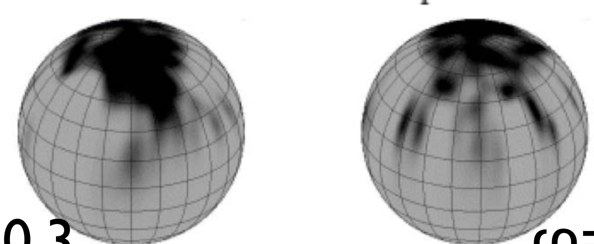
Spatial structuring gives us fundamental insights into the magnetic field properties

Diagnostics:

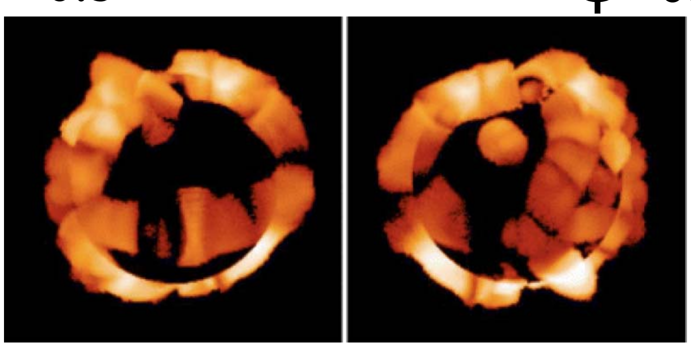
- rotational modulation, eclipse mapping
- resonance scattering
- velocity modulation
- spectroscopic density diagnostics
- flare modeling
- fluorescence

X-rays from Cool Stars
Coronal Structuring: Line Shifts



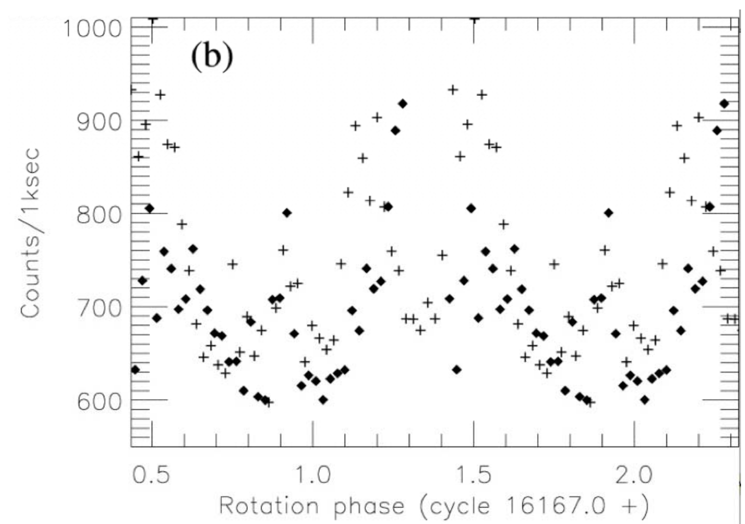


φ=0.3 φ=0.8



Simultaneous Doppler imaging and X-ray spectroscopy of AB Dor (Hussain et al. 2007) *Chandra* continuous observations for ~ 2 P_{rot} (88ks; LETGS)

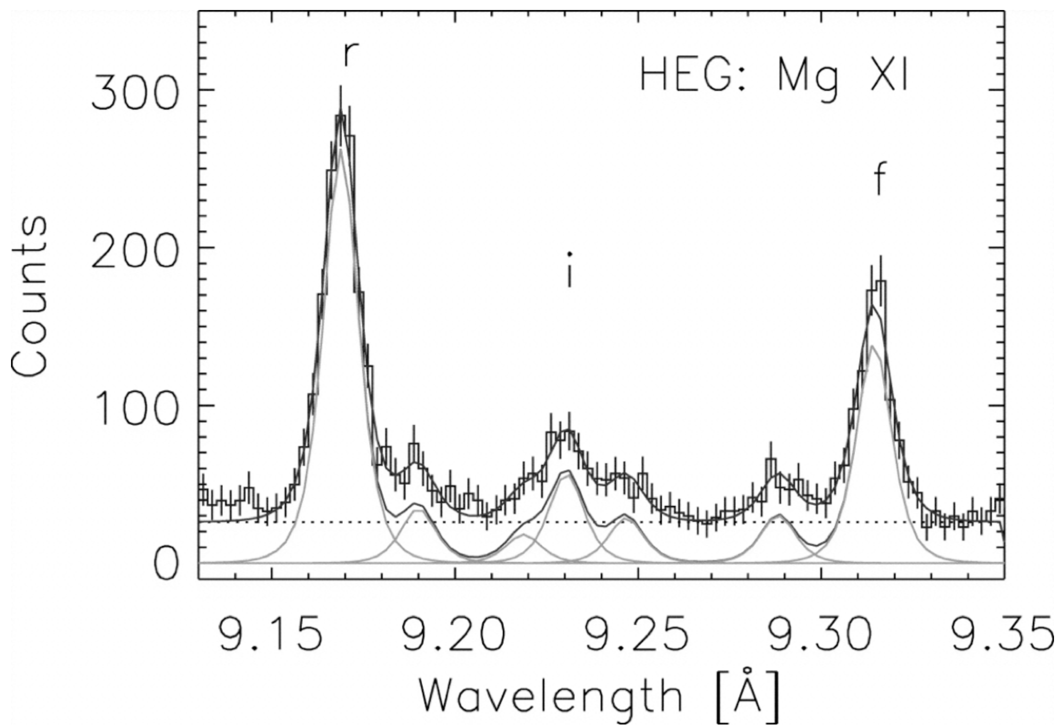
- evenly distributed coronal component with H<0.5R★
- 2 or 3 active regions with H<0.3R★



X-rays from Cool Stars
Coronal Structuring: Plasma Density

$I \propto n_e^2 V$

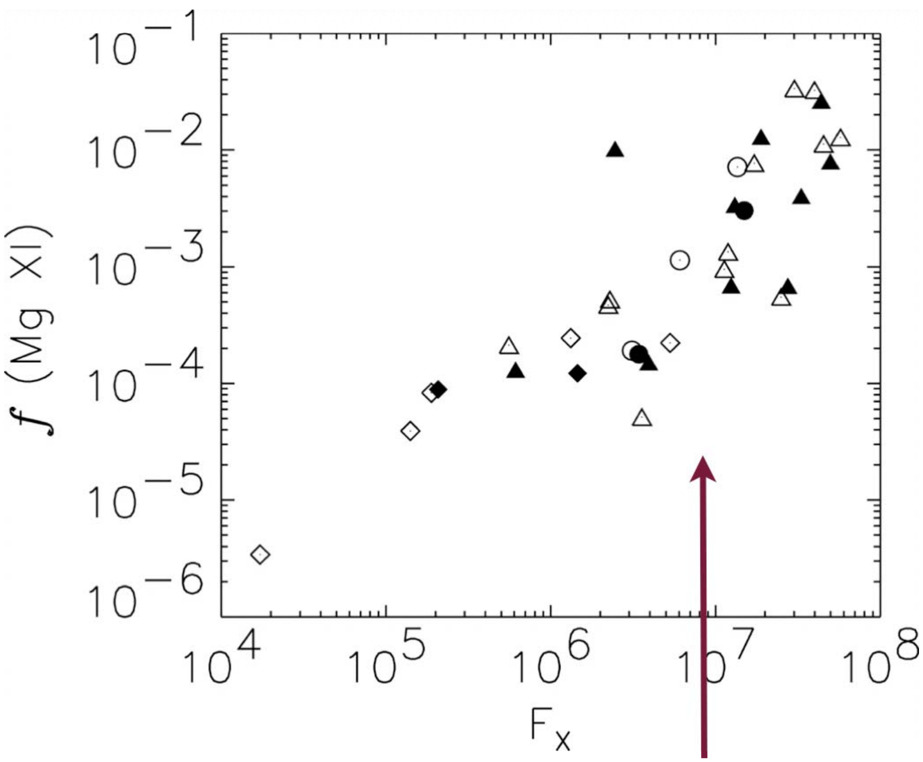
Ness et al. (2004) and Testa et al. (2004) have derived density from He-like triplets (f/i depends on n_e) for a large sample of late-type stars

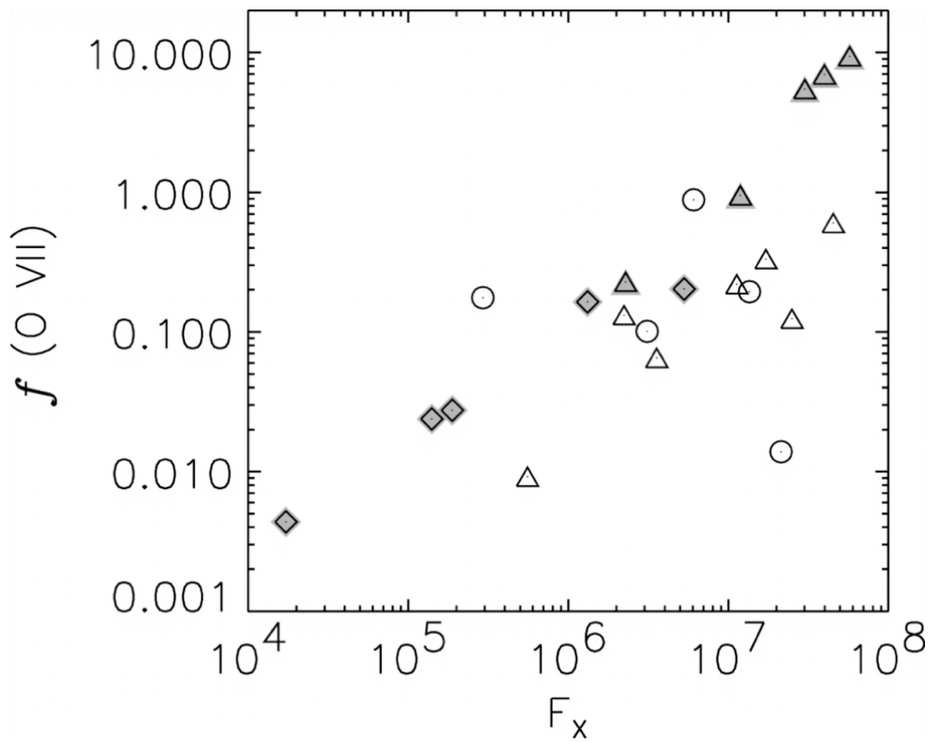


(Testa et al. 2004)

X-rays from Cool Stars: Coronal Structuring

Surface filling factors (*ff*) of coronae as a function of activity

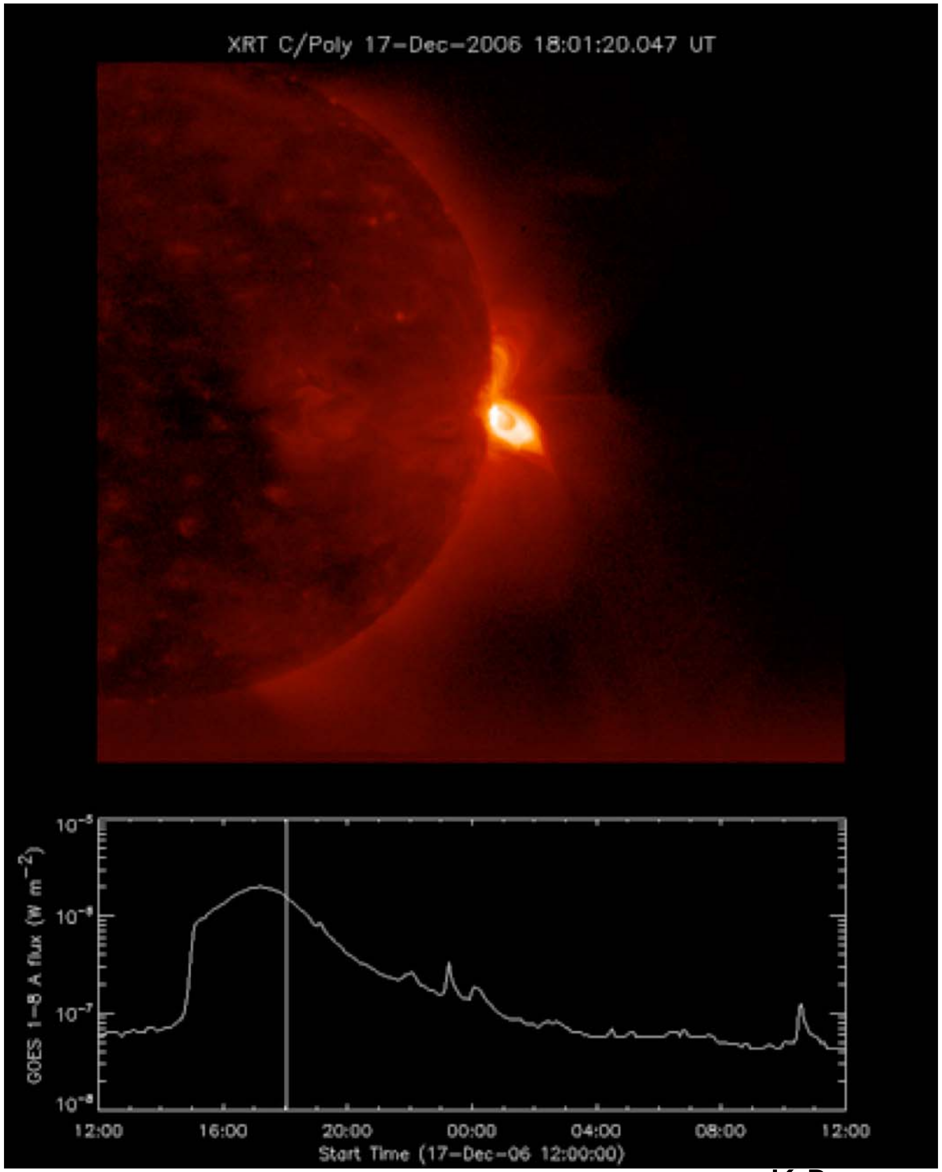




solar active region Fx (Withbroe & Noyes 1977)

(Testa et al. 2004)

X-rays from Cool Stars
Flares



courtesy K.Reeves

Are stellar flares in stars similar, scaled up version (e.g. Lx, T, τ_{decay},..), of solar flares?

What can we learn from disk integrated lightcurves and from high resolution spectroscopy in particular?

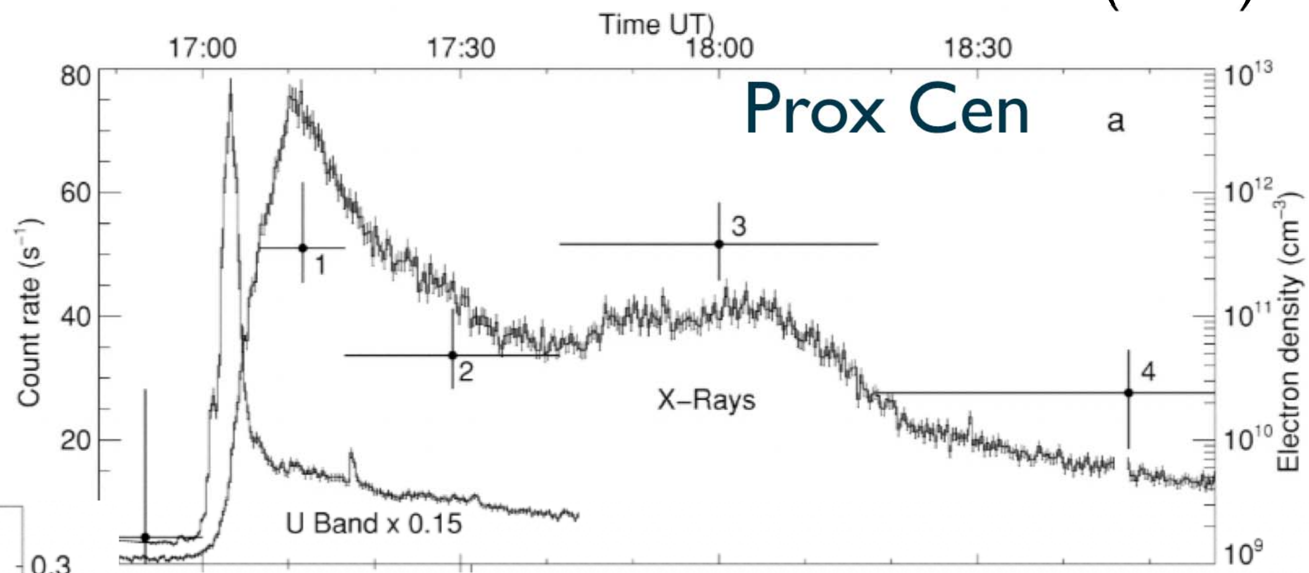
X-rays from Cool Stars
Flares

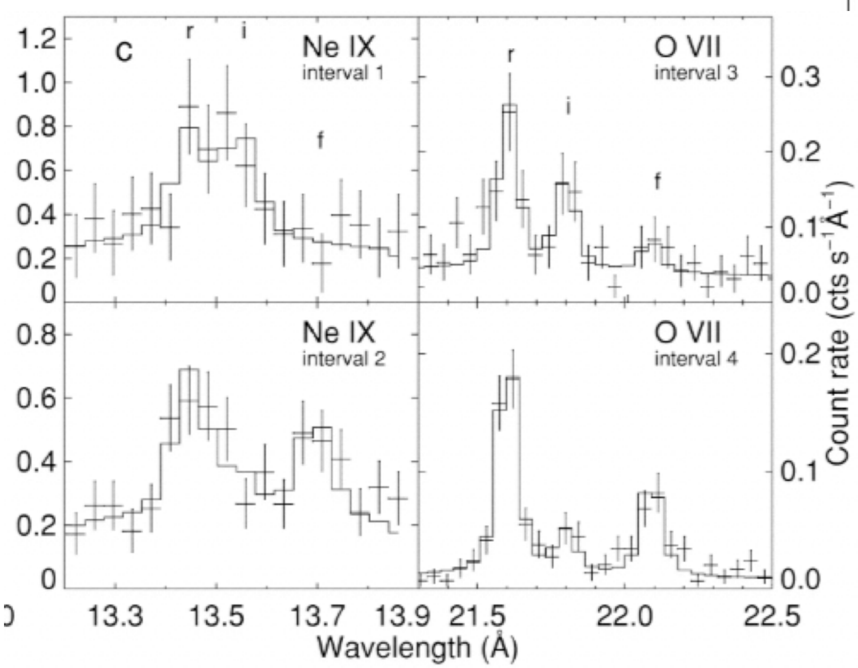
Güdel et al. (2002)

Neupert effect:

soft X-rays ∝ integral of non-thermal emission

(e.g. Hudson et al. 1992)

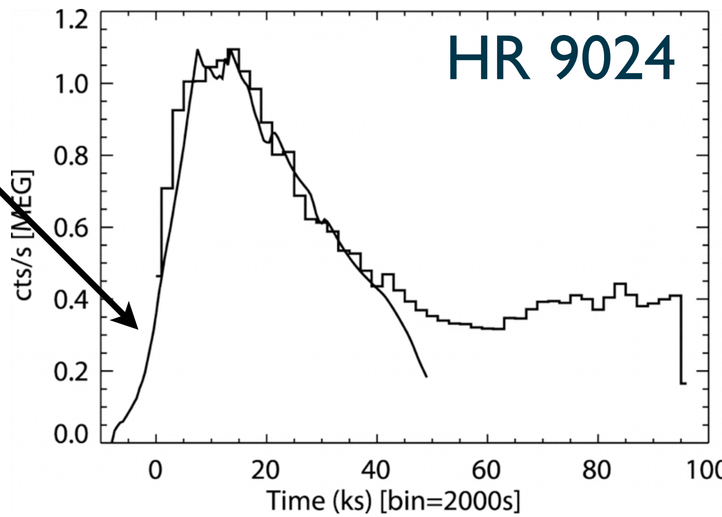


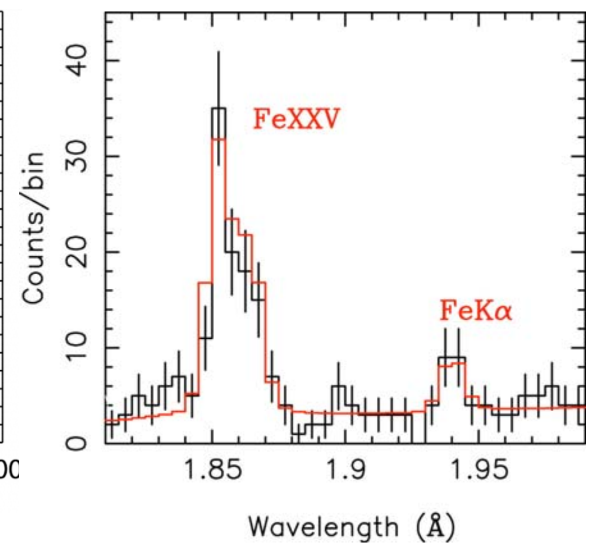


n_e enhancement during the flare supporting the scenario of chromospheric evaporation analogous to solar flares

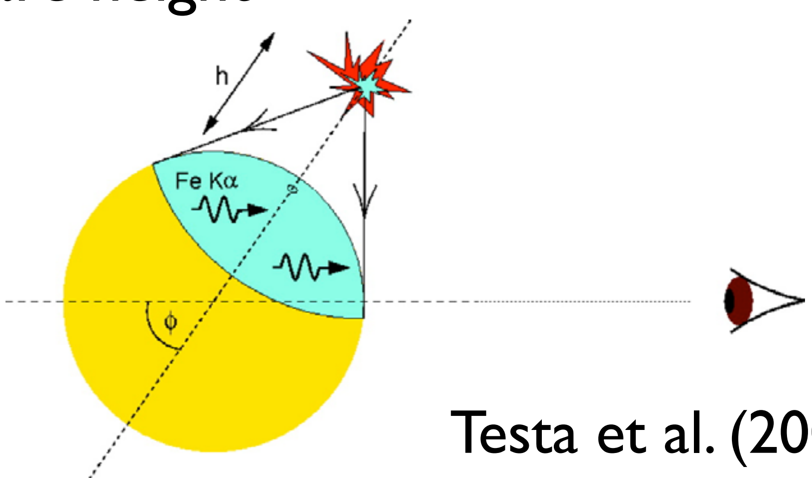
X-rays from Cool Stars
FeKα Fluorescence

Hydrodynamic loop modeling of the flare
L ~ 0.5R★

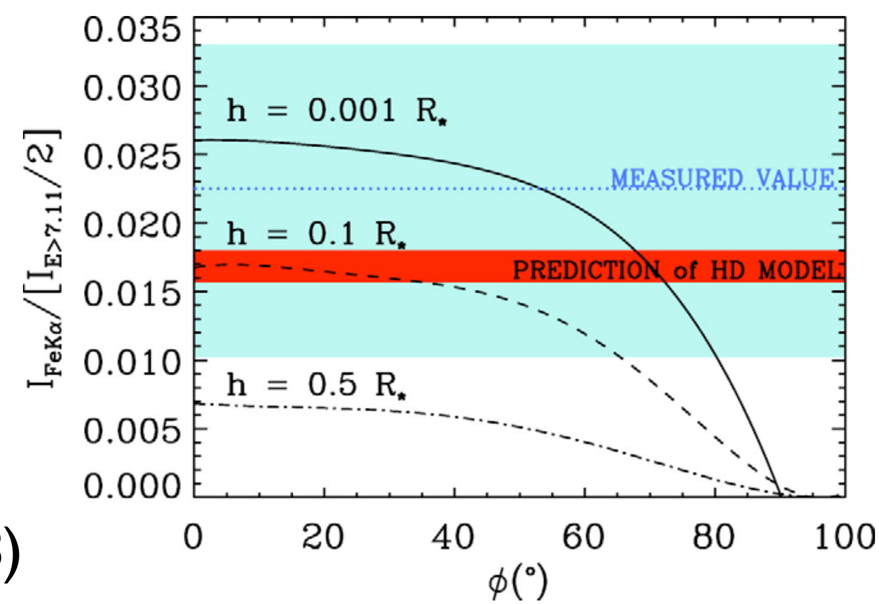




Fe Kα provides an independent diagnostic of the flare height

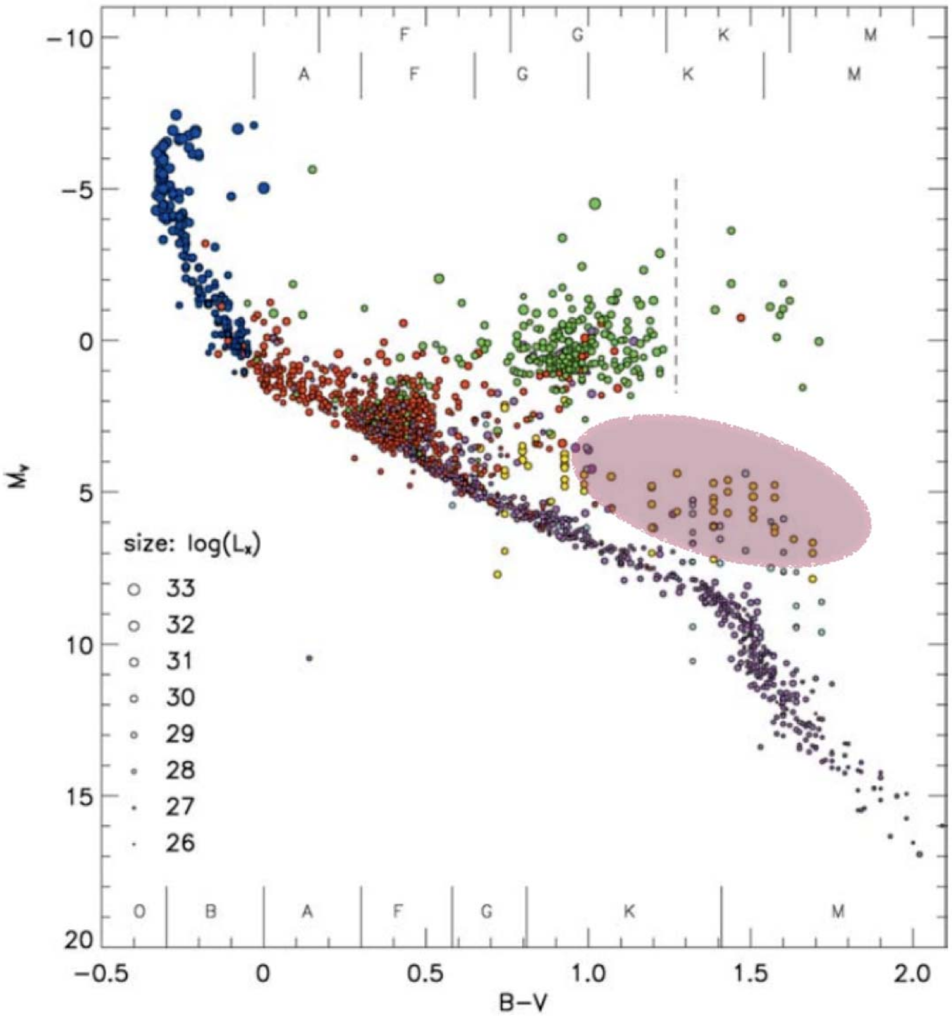


Testa et al. (2008)



X-ray Emission from Stars

(Güdel et al. 2004)



- X-rays from early-type stars:

  wind shocks, magnetic fields

- X-rays from cool stars:

  coronal physics

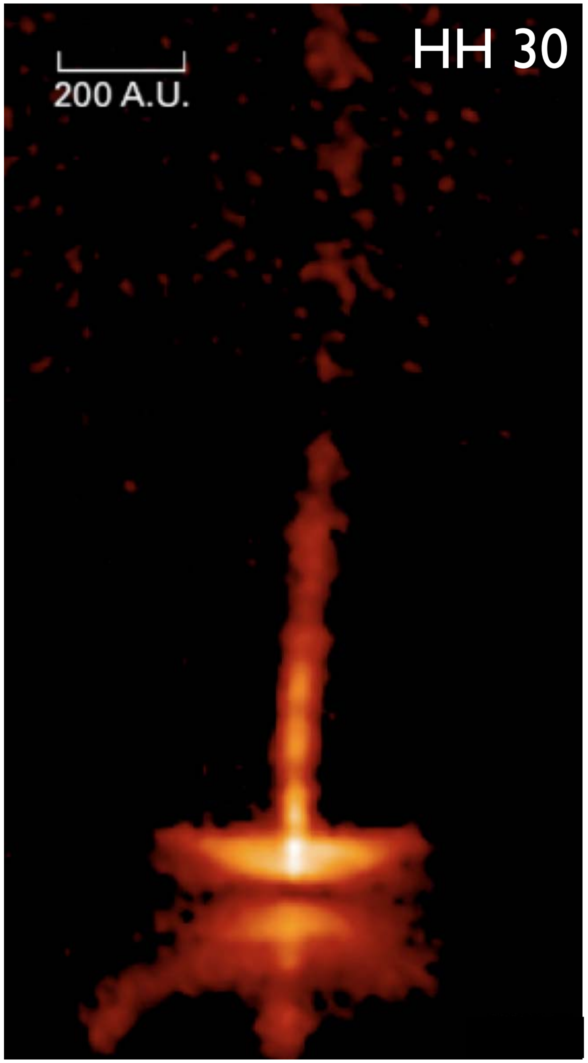
- X-ray from pre-main sequence stars:

  coronal physics, accretion, jets, magnetically confined winds

X-rays from Young Stars

- X-ray emission mechanisms in pre-main sequence stars (see also review by Eric Feigelson):
  - are they analogous to main sequence cool stars?
  - role of accretion

HST WFPC2



Burrows et al. (1996)

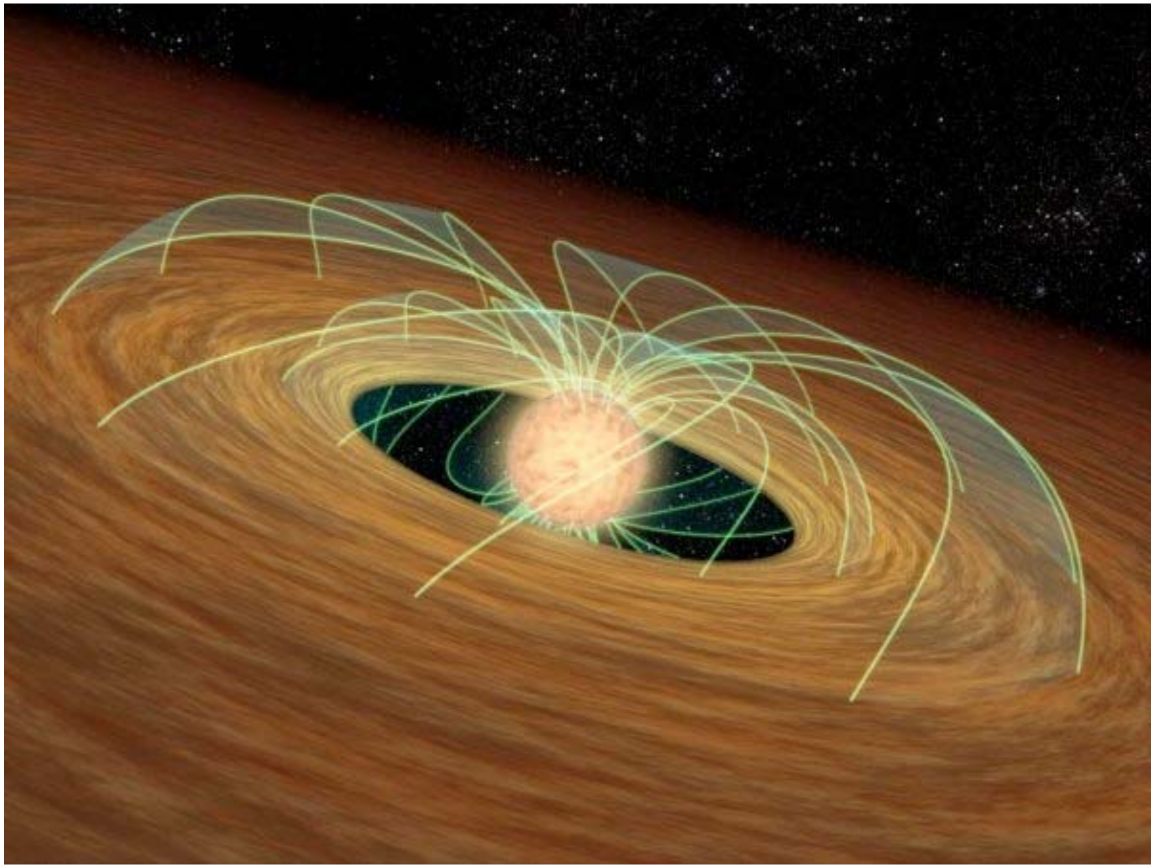
X-rays from Young Stars

High-resolution spectra of TW Hya have revealed peculiar characteristics (Kastner et al. 2002):

- very soft emission
- high n_e
- anomalously high Ne

interpreted as X-ray emitted by shocked accreting plasma

(see models by Günther et al 2007, Sacco et al. 2008)



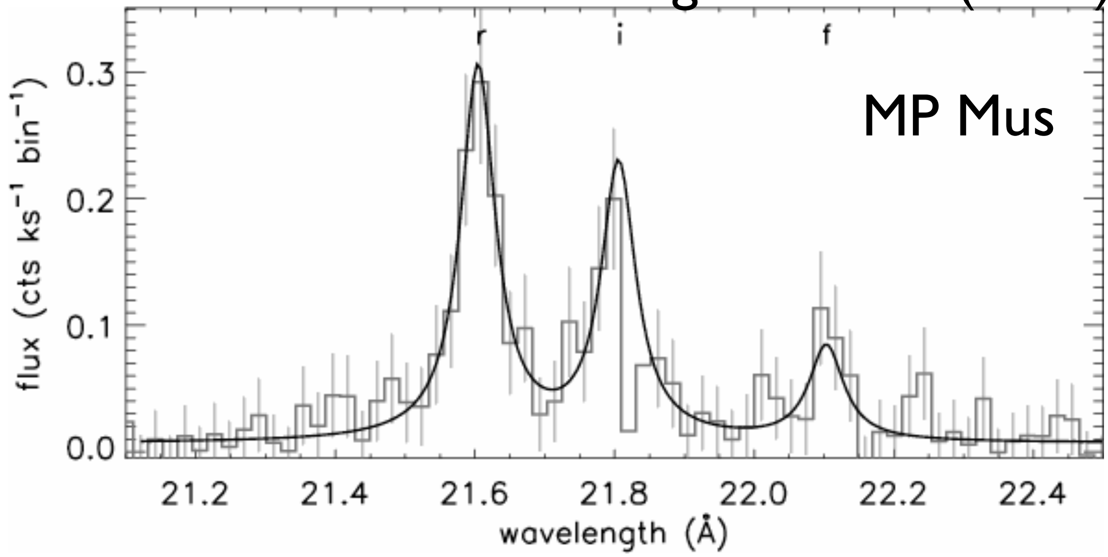
see Nancy Brickhouse's talk

X-rays from Young Stars

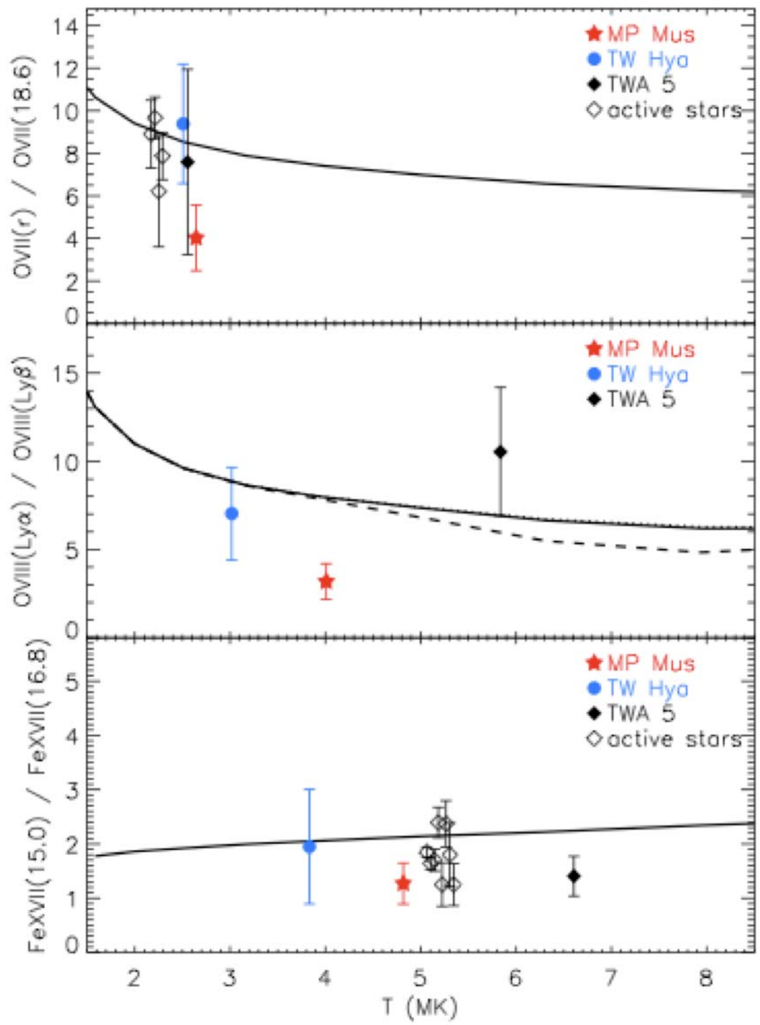
X-ray spectra of other CTTS:

- TW Hya-like unusually high n_e from OVII
- strong coronal component

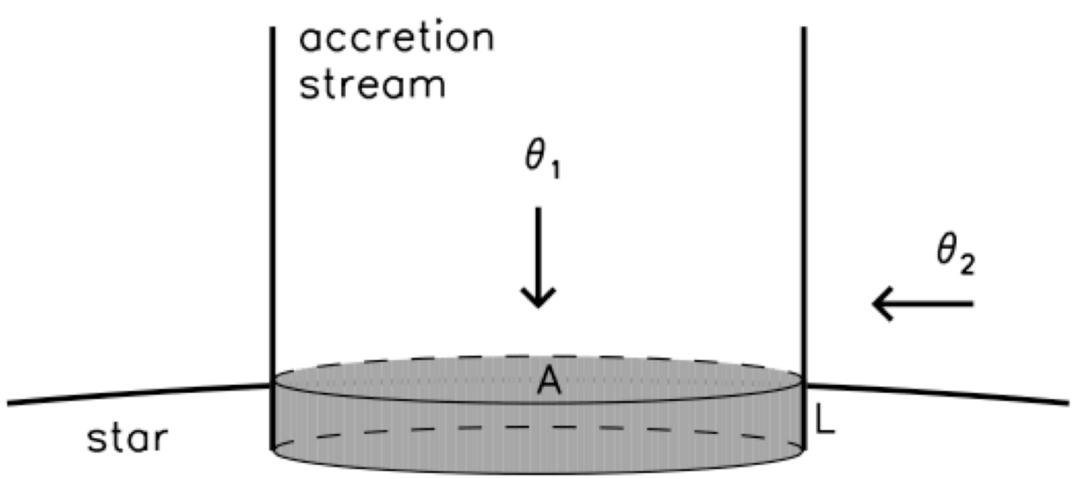
Argiroffi et al. (2007)



X-rays from Young Stars



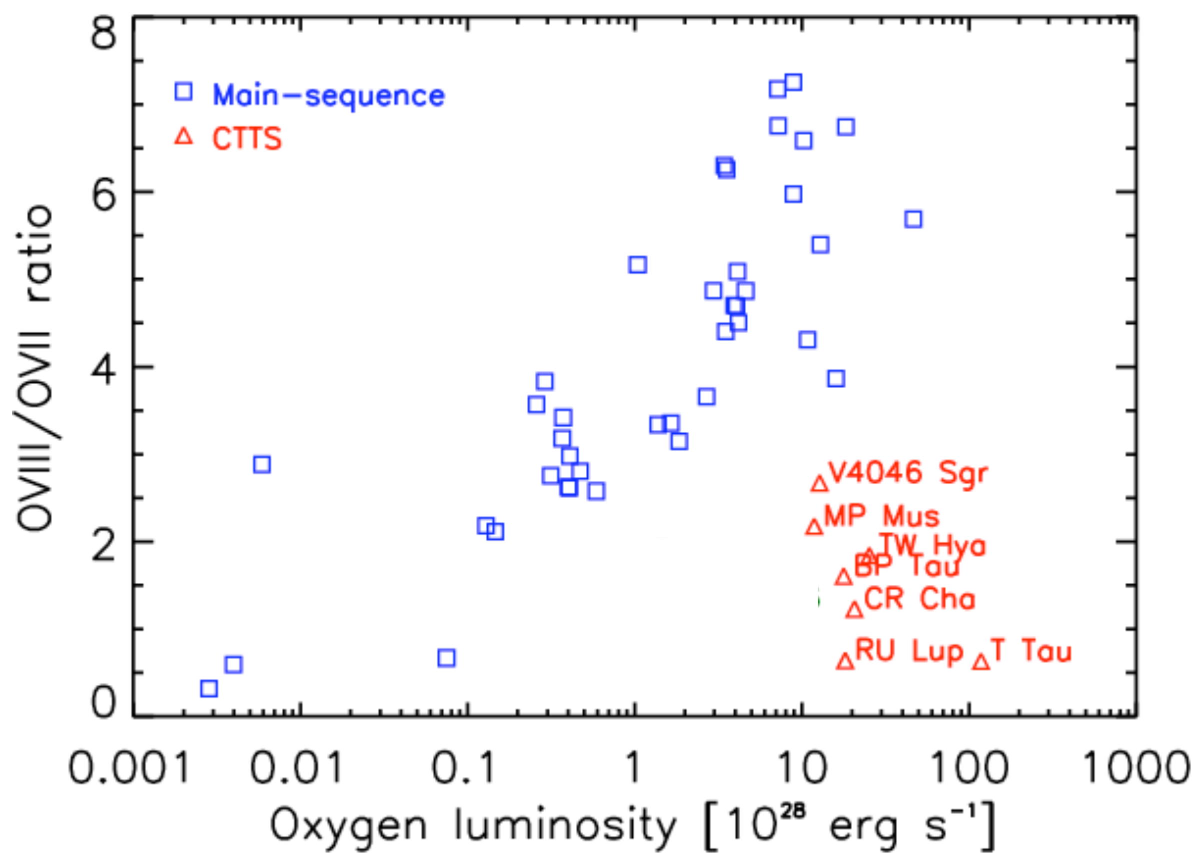
Argiroffi et al. (2009) find evidence of optical depth, expected for the high n_e, for the CTTS MP Mus, not for TW Hya and interpret it as due to different inclination and therefore line of sight



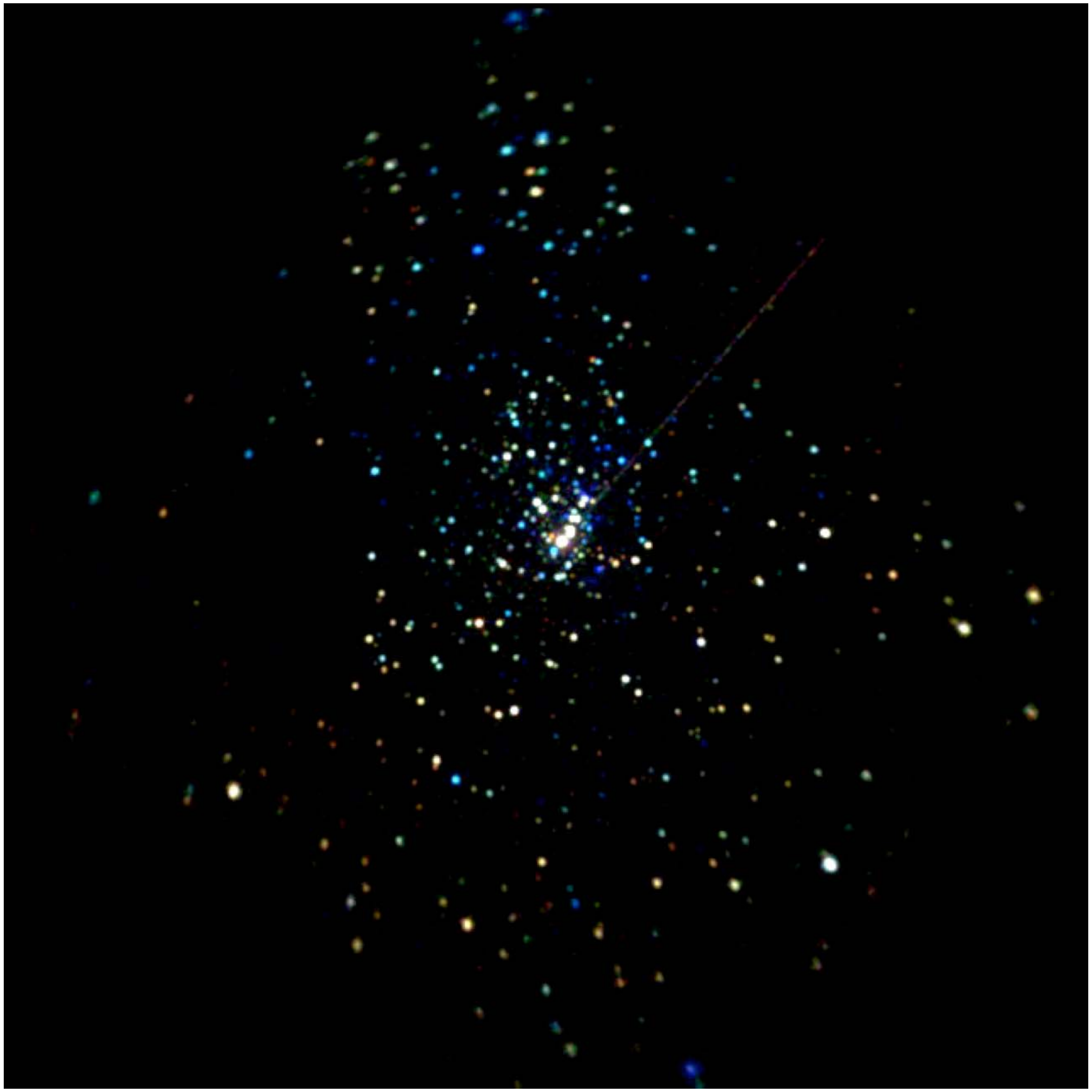
X-rays from Young Stars

CTTS have a soft X-ray excess, as measured from higher OVIII/OVII ratios compared to WTTS and main sequence stars (Güdel et al. 2007; Güdel & Telleschi 2007)

Robrade & Schmitt (2007)



X-rays from Young Stars
Flares

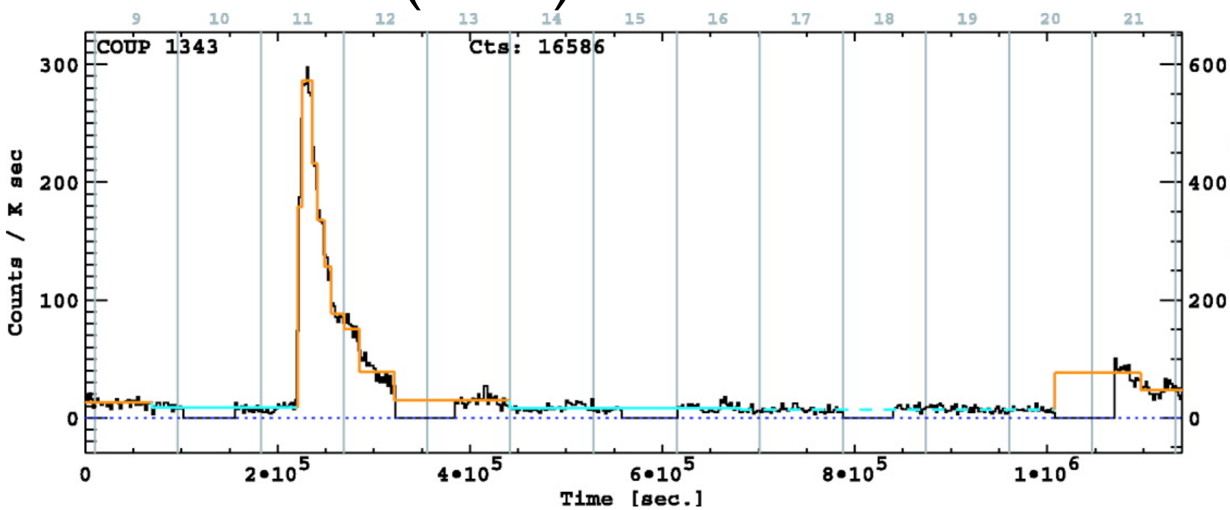


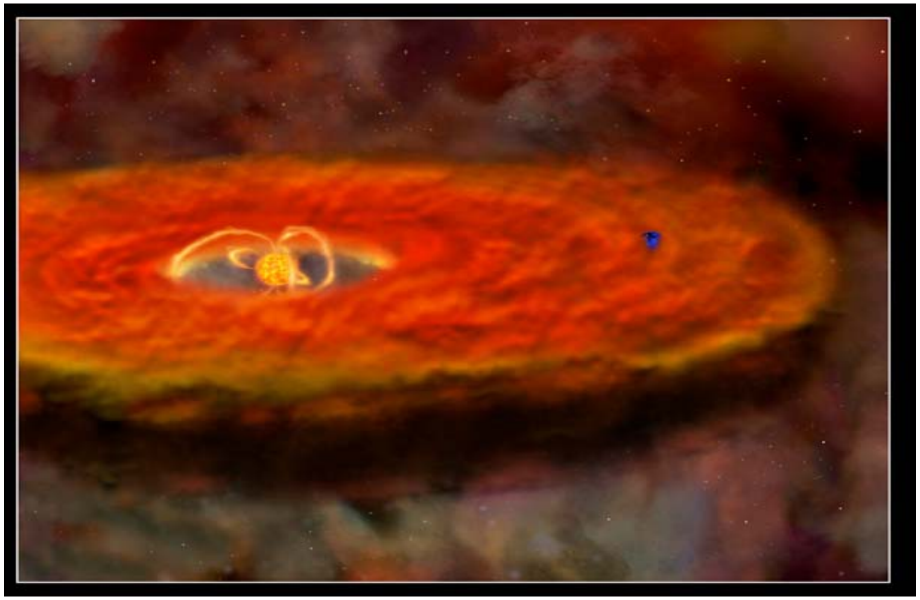
(http://www.astro.psu.edu/coup/)

X-ray emission of young stars is characterized by very high level of variability, as shown e.g. by the Chandra Orion Ultradeep Project (~13 days)

X-rays from Young Stars
Flares

Favata et al. (2005)





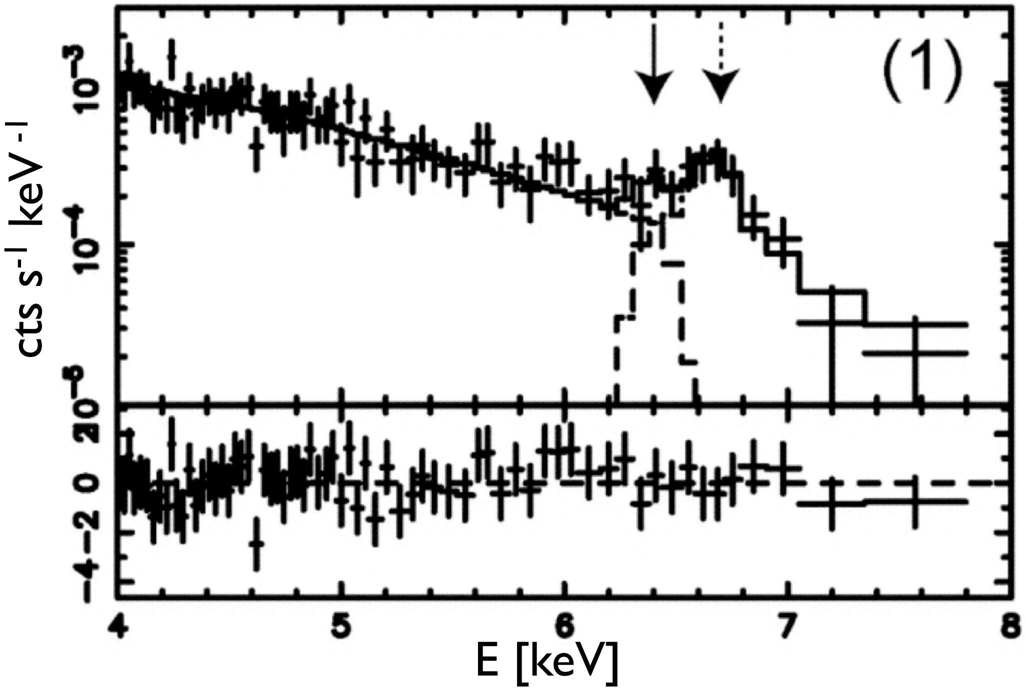
Several large flares, modeled with 1D HD model imply very large loop length, of the order of ~10 stellar radii

is this evidence of star-disk connecting loops?

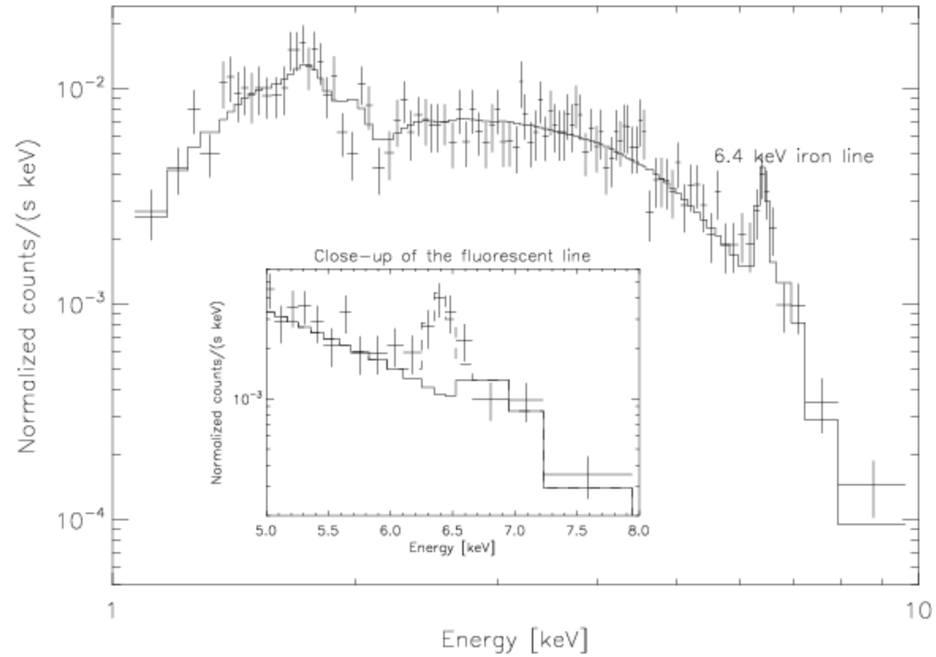
Getman et al. (2009) find that larger loop sizes correspond to non-accreting sources

X-rays from Young Stars
FeKα

Tsujimoto et al. (2005)



Czesla & Schmitt (2007)



V1486 Ori: total spectrum (*left*), and spectrum during the flare (*right*)

During the flare FeKα EW extremely high (see also Giardino et al. 2007):

- -Fluorescence from disk? possibly obscuration of the hard X-ray source
- -Different underlying physics? impact excitation extremely inefficient though

X-ray emission from stars

Importance of X-ray high resolution spectroscopy of stars

- Stringent test for standard wind-shock models:

  scenario of X-ray emission processes in early-type stars is far more complex than in the pre Chandra-XMM era

- Detailed diagnostics for coronal models and underlying processes:

  new or much more refined diagnostics (abundances, density, opacity, line shifts, FeKα, DEMs,...)

  BUT effective area is crucial together with high spectral resolution! IXO will allow enormous progress!

- High-resolution spectroscopy fundamental to study accretion related X-ray emission processes, and effects of X-rays on circumstellar environment

X-ray emission from stars

Outstanding issues

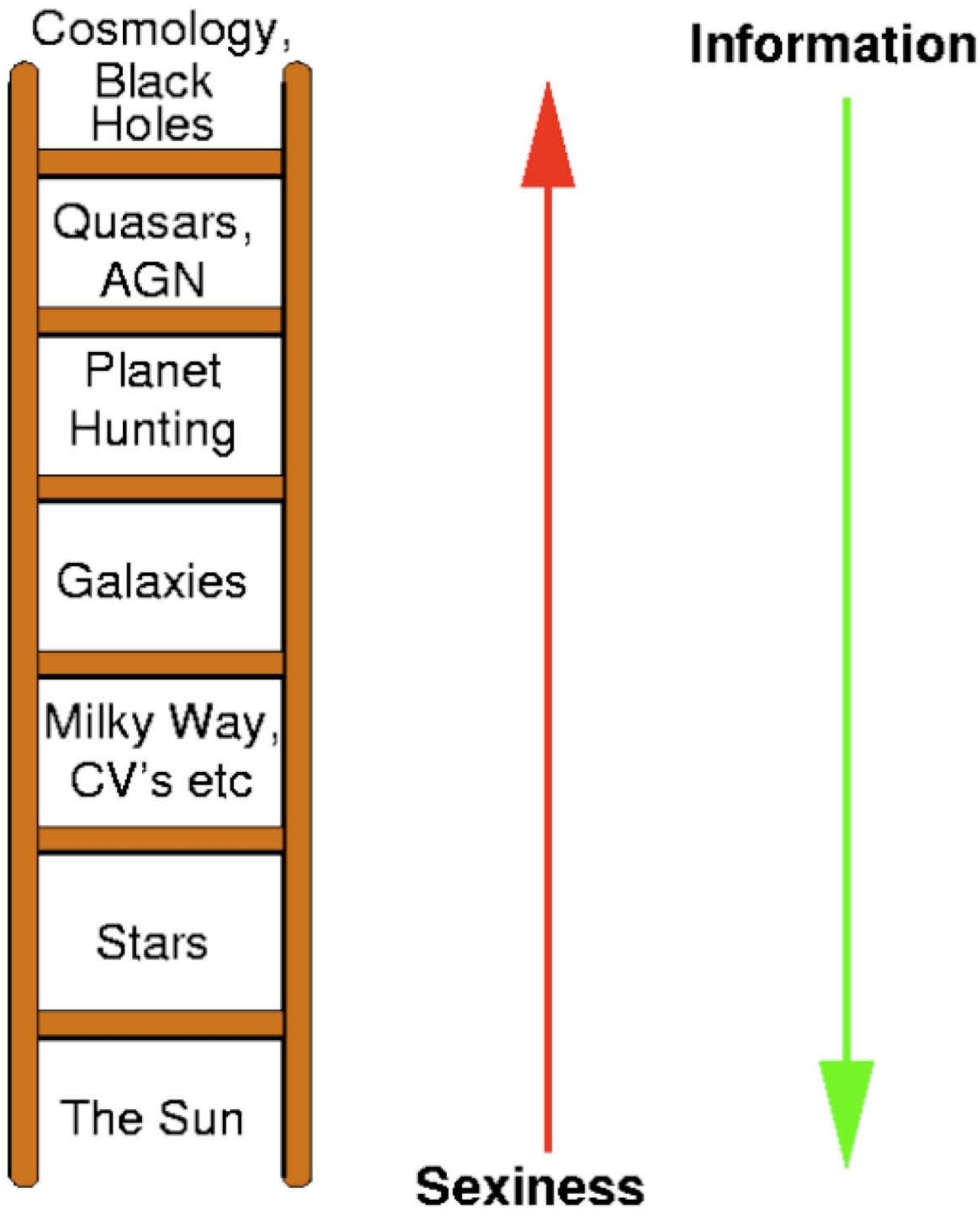
- Need for improved models of X-ray emission in massive stars to explain e.g. narrow lines, hard and variable emission from non-magnetic stars
- Abundances and physical processes leading to chemical fractionation
- Activity cycles and dynamo models

  even for the Sun we lack a satisfactory understanding of cycle — see peculiarities of current solar cycle
- Flare physics

  are extreme (T, energy) stellar flares involving different physics?
- Physical processes at work in young stars

  accretion, jets, interplay between accretion and X-ray activity, influence of X-rays on disk and planets, extremely large X-ray emitting structures

The Cosmic Sexiness Ladder



J. Drake