Stellar coronae and the Sun

solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

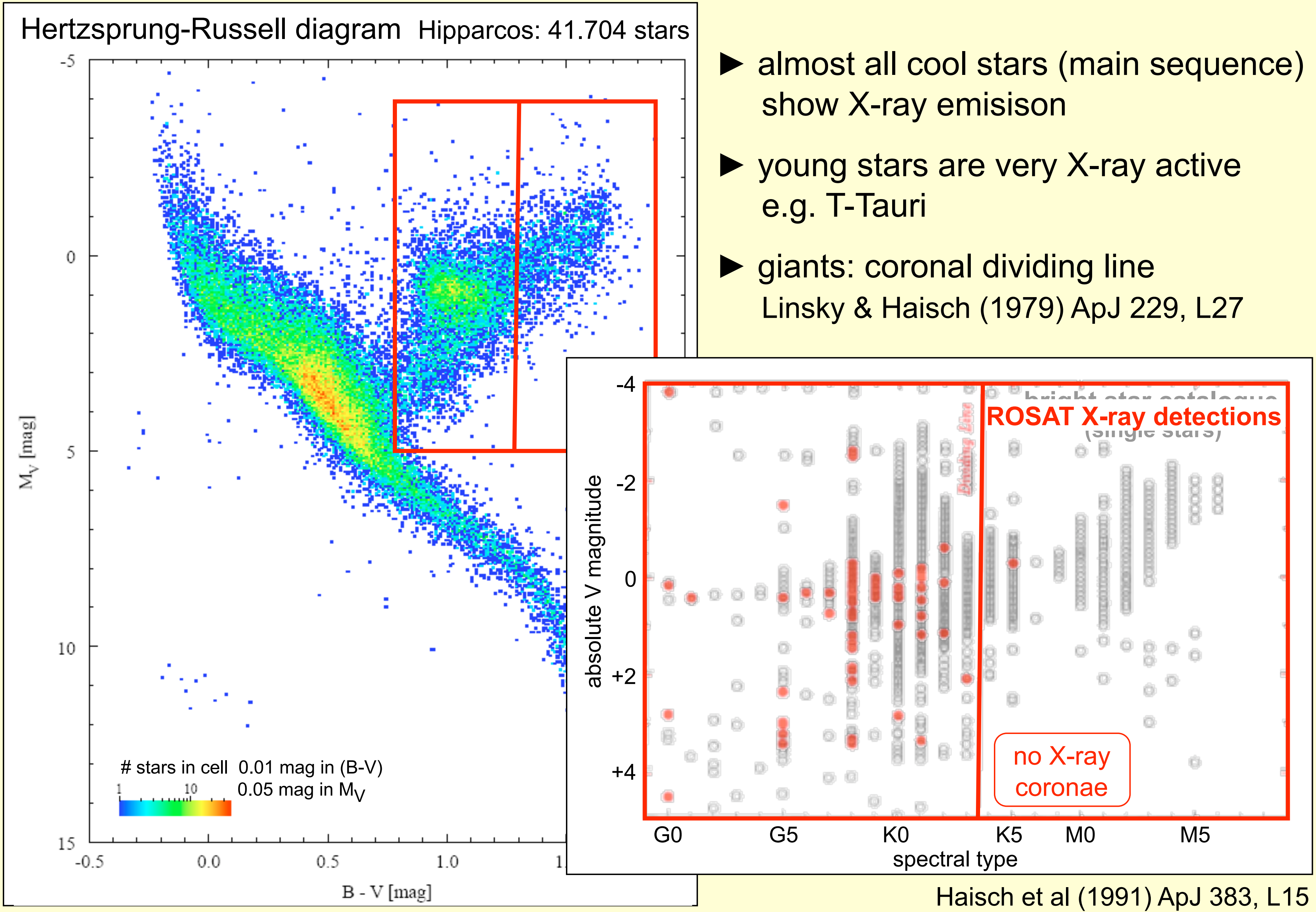
Hardi Peter

MAX-PLANCK-GESELLSCHAFT

Nice movie of αCenA in C IV (1548 Å) ☺

Tom Ayres (2004)

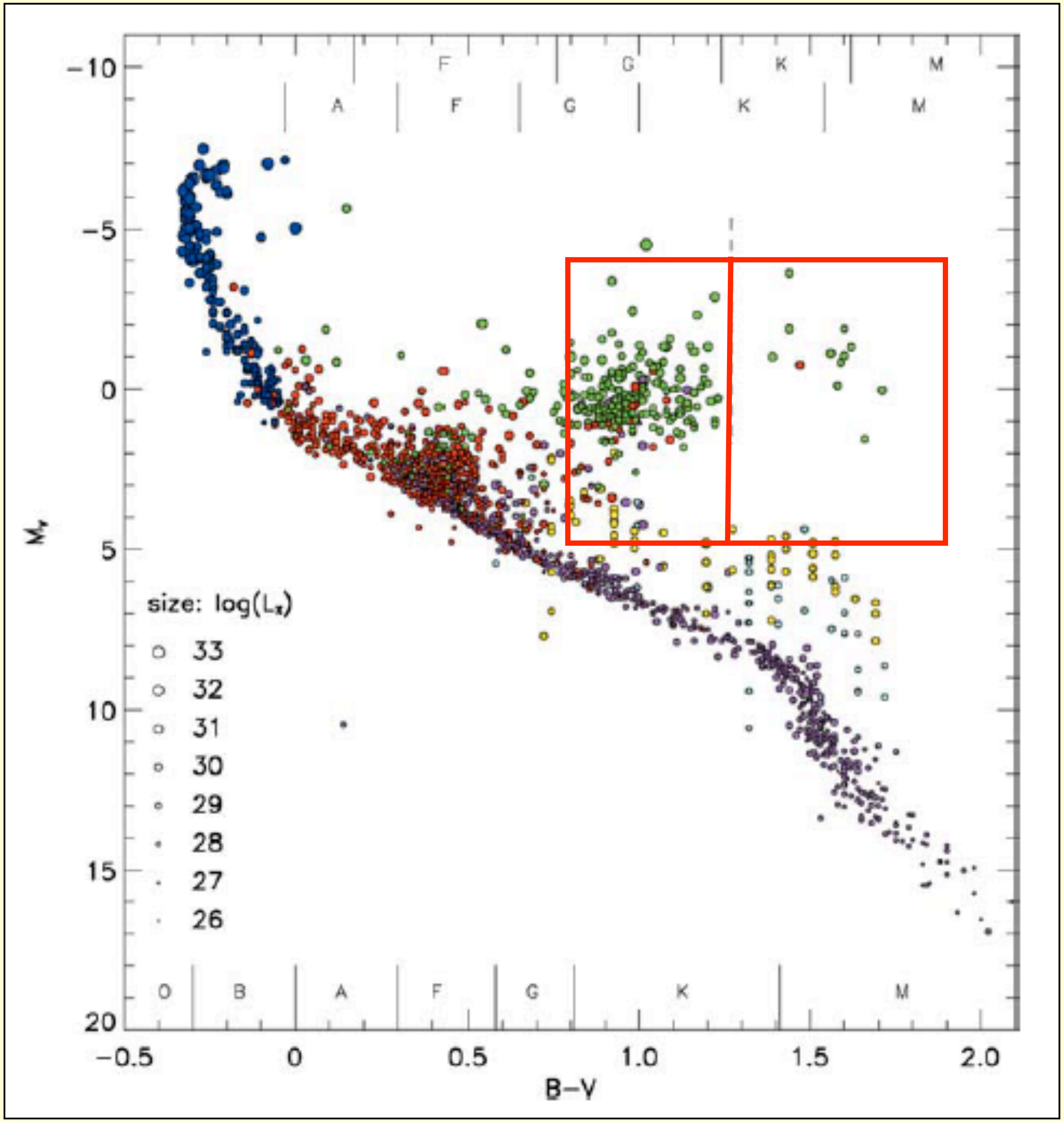
Stellar coronae in the HRD



- ► almost all cool stars (main sequence) show X-ray emisison
- ► young stars are very X-ray active e.g. T-Tauri
- ► giants: coronal dividing line Linsky & Haisch (1979) ApJ 229, L27

Haisch et al (1991) ApJ 383, L15

X-ray emission across the HRD



X-ray luminosities
for about 2000 stars

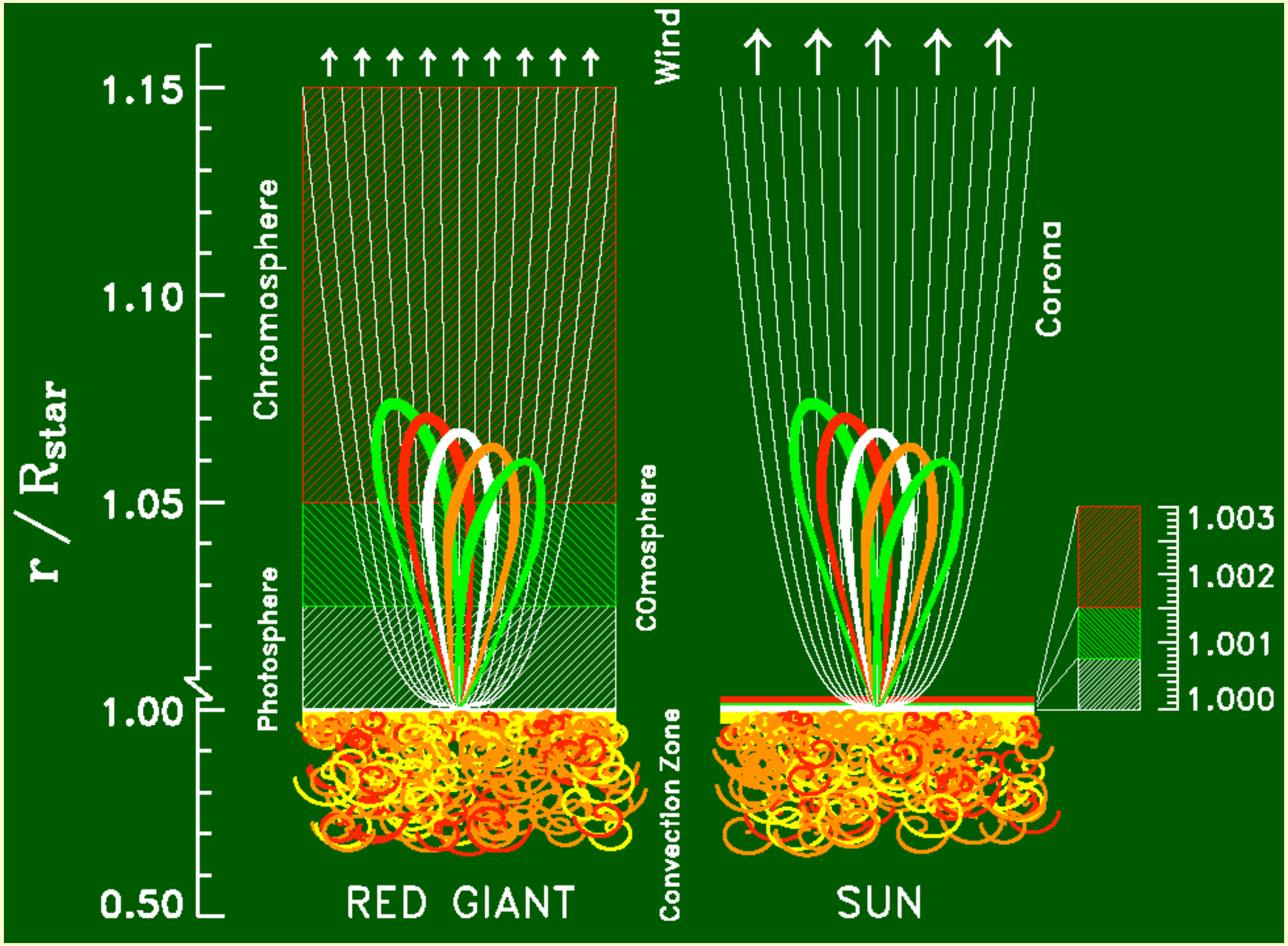
(Güdel 2004, A&ARv 12, 71)

different colors indicate different data sources (catalogs)

size of circles show X-ray luminosity

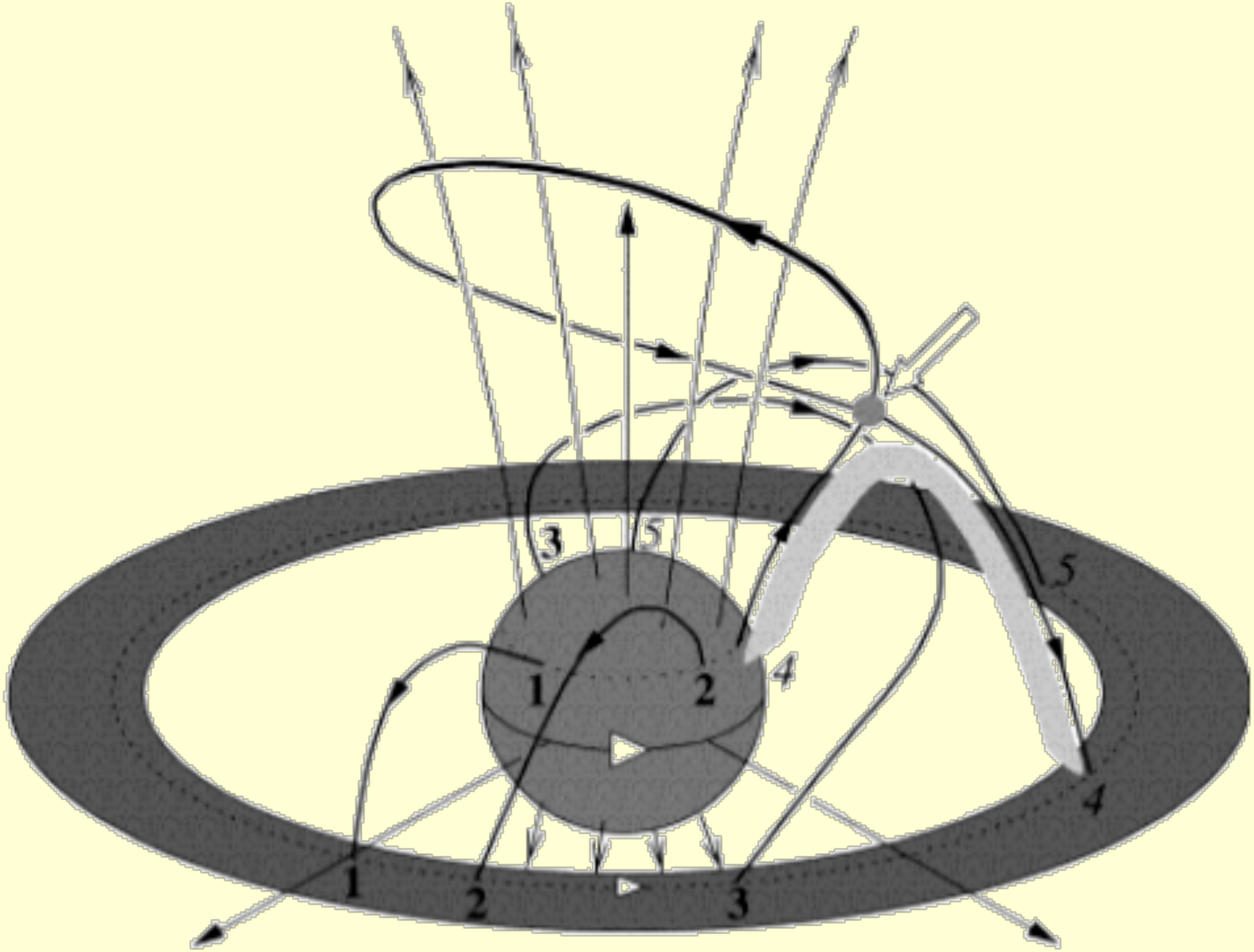
The coronal graveyard

- giants with strong winds: why do they not have coronae?
  - → does magnetic field play a role? → wind driven by luminosity…
  - → magnetic configuration → mainly open magnetic field ?
  - → low g → stretched chromospheres → "buried" magnetic loops



buried coronae:
Ayres (2004) ESA SP-575

Corona – disk interaction

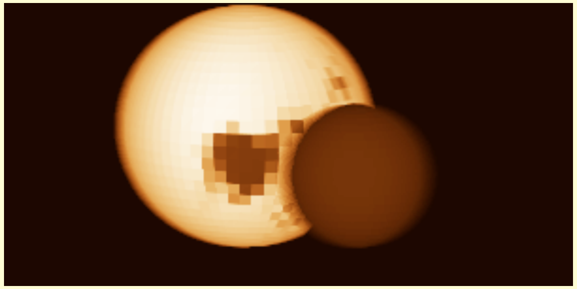


sketch for magnetic field “model” (Montmerle et al 2000)
→ due to stellar rotation (faster than disk) fieldlines reconnect (#4)

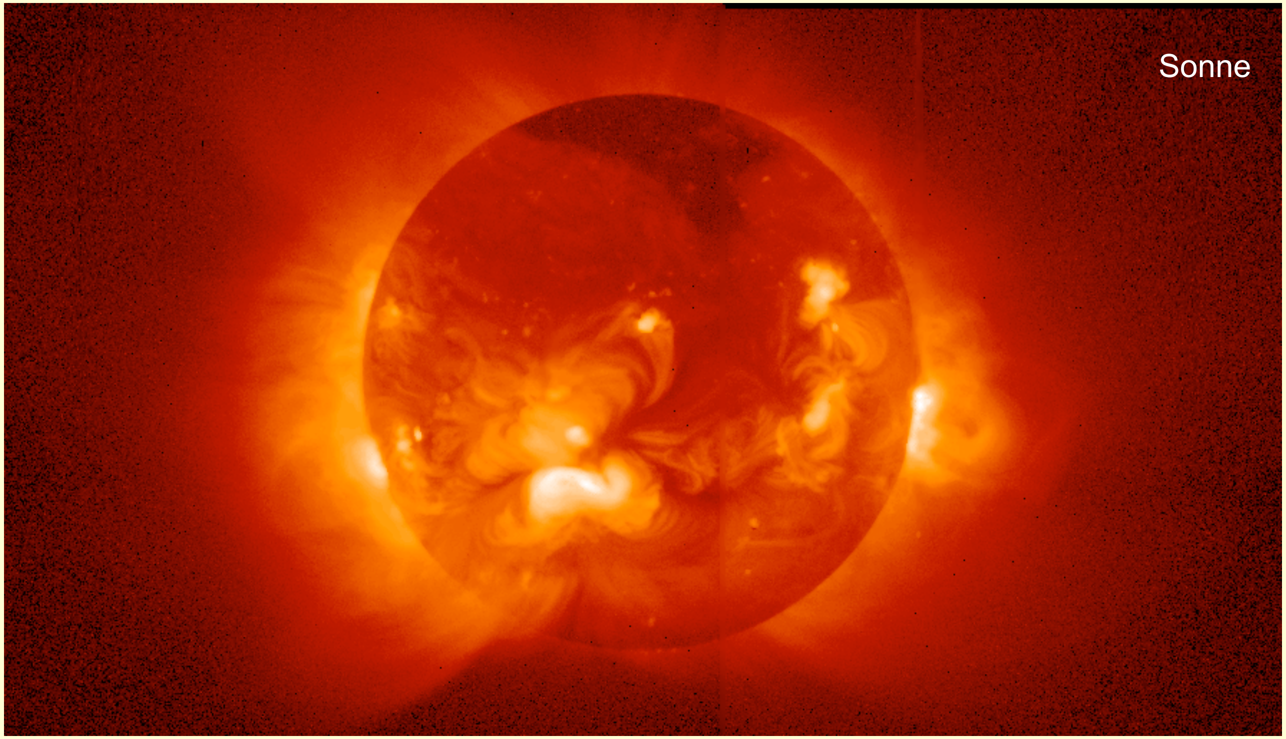
What do we see of a stellar corona ?

- photosphere: Doppler-(Zeeman)-Imaging:
  structures on stellar surface

- corona: emission concentrated in few active regions
  or dominated by flares:
  "point sources" in the corona



XY Ursa Major
(A. Collier Cameron)



Yohkoh Soft X-ray Telescope (SXT), ≈1 nm, $\approx 2 \cdot 10^6$ K

Stellar coronal observations in the radio

angular resolution of a telescope:

$$\phi \propto \frac{\lambda}{D}$$

Very Long Baseline Interferometry“

D = diameter of Earth

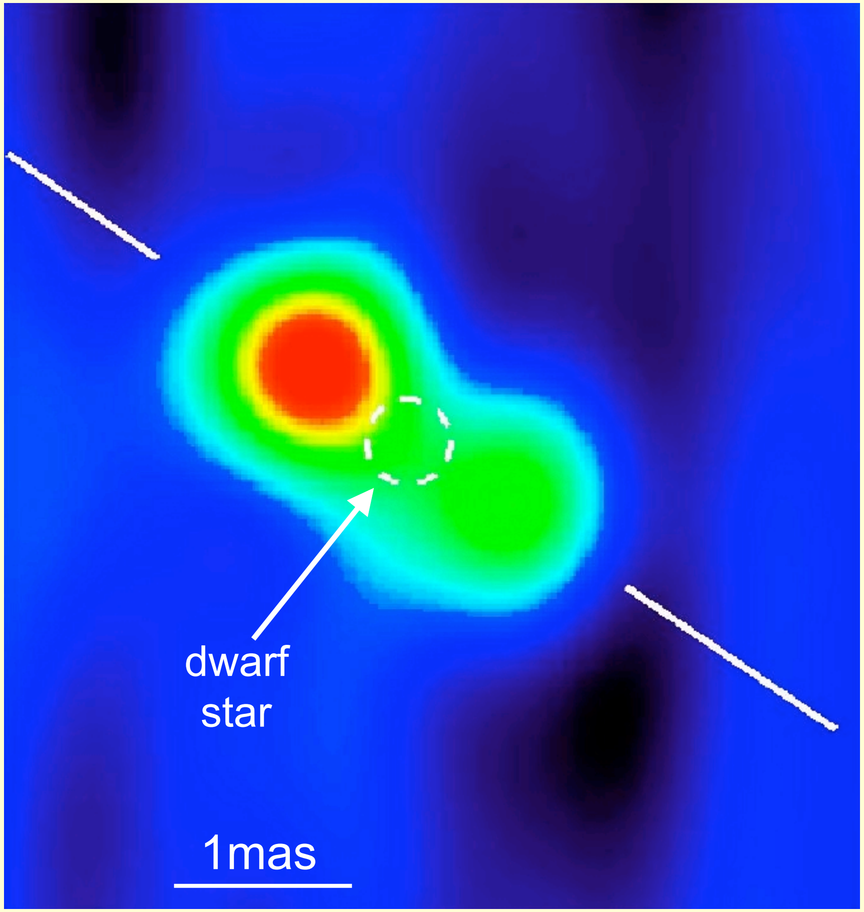
λ = 10 cm (typical radio)

➔ resolution ϕ down to 1/1000 arcsec (=mas)

radio corona:

radio emission of electrons circling around magnetic field

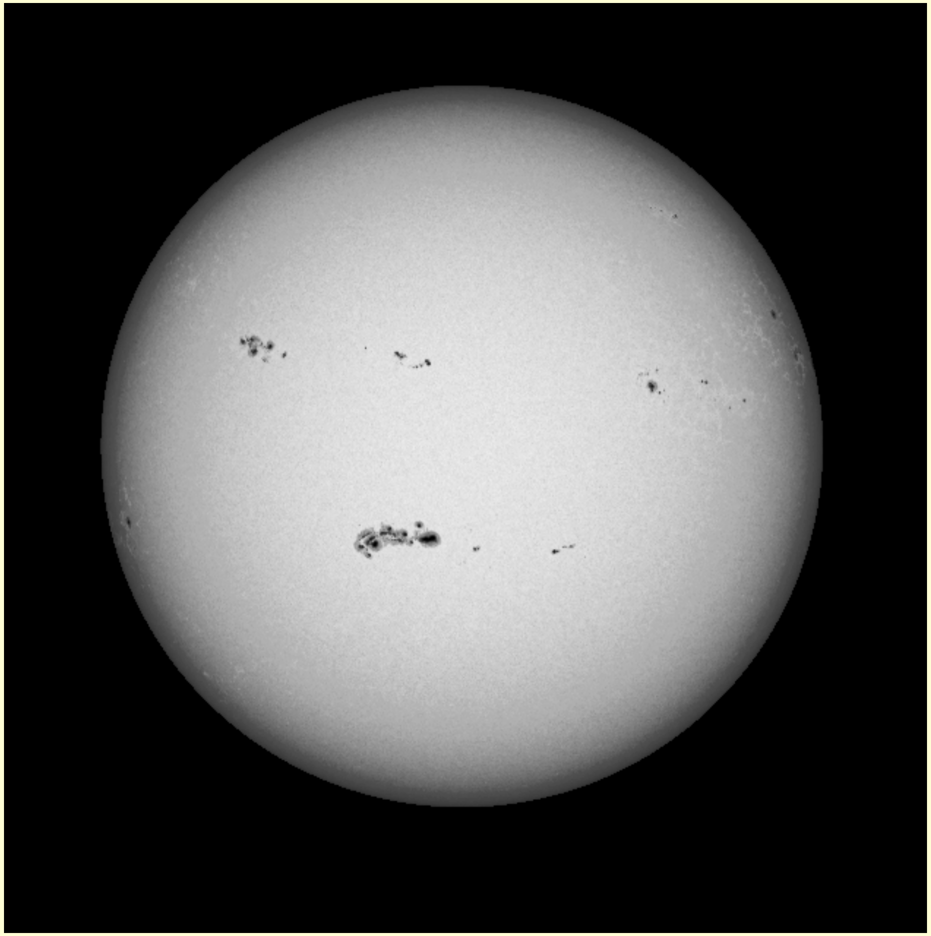
(where do all these speedy electrons come from… ?)

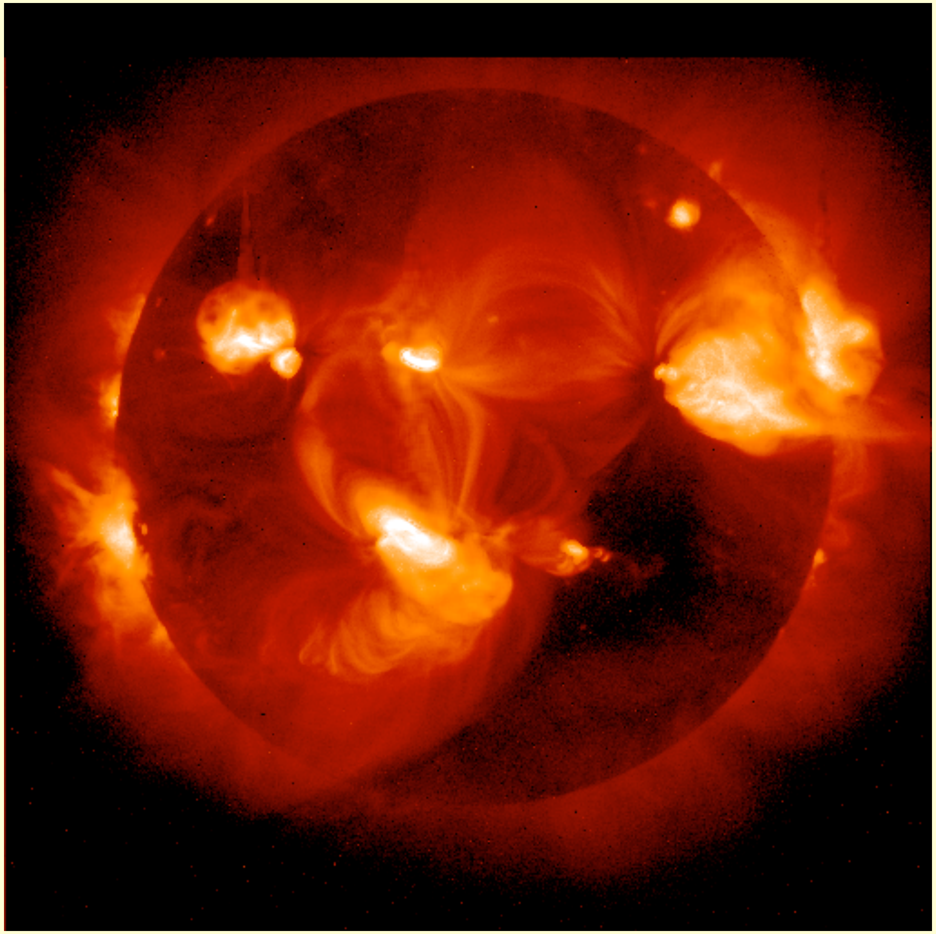


UV Cet

(Benz et al. 1998)

Comparing photosphere and corona: the Sun



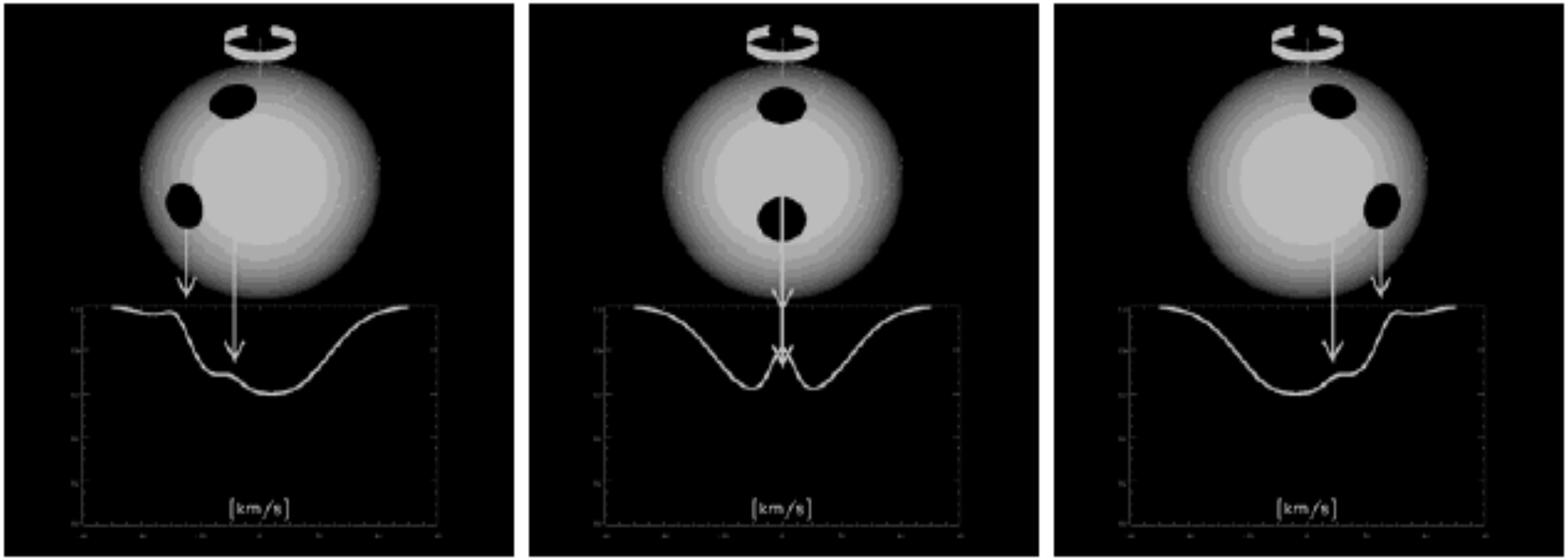


MDI / SOHO white light

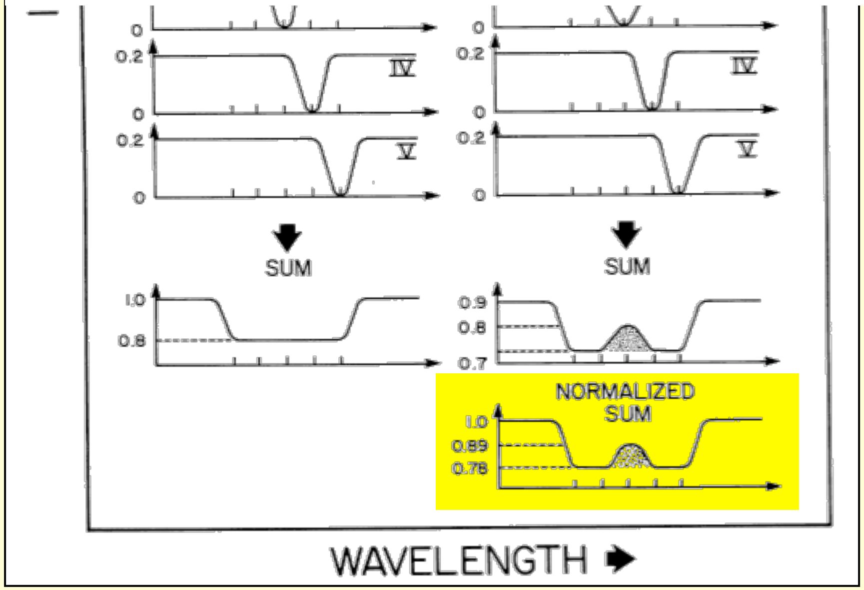
Nov 16, 1999

Yohkoh Soft X-rays

Doppler imaging – principles



J.B. Rice: Doppler Imaging Techniques



longitude: position of "bump"
latitude: way of "bump" trough profile

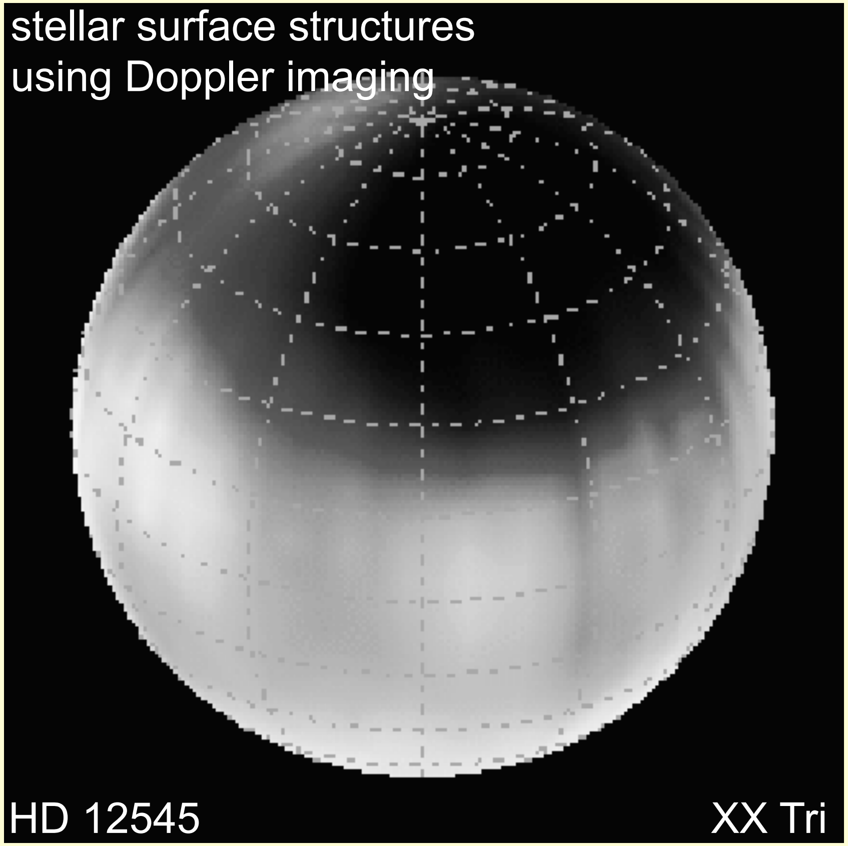
time series of spectra

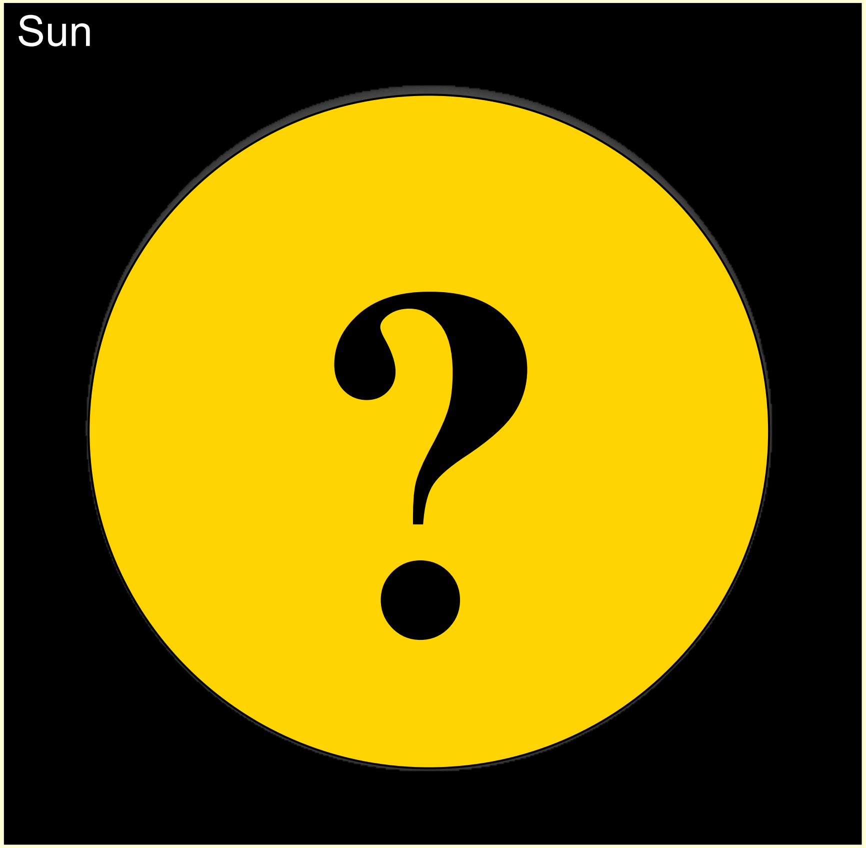
⇩

surface structures

Stellar photospheres ➞ stellar coronae

Strassmeier & Rice (2001) A&A 377, 264





stellar photospheres can look
quite different than the Sun !!

How do stellar coronae look like ??

3D stellar corona: Doppler-Zeeman-Imaging

- **AB Doradus**

  cool active star (K2V)

  $T_{\mathrm{eff}} \approx$ 4000K

  half as luminous as our Sun $(0.4\, L_\odot)$

  fats rotator $(50\, \Omega_\odot)$

  distance ≈ 49 light years

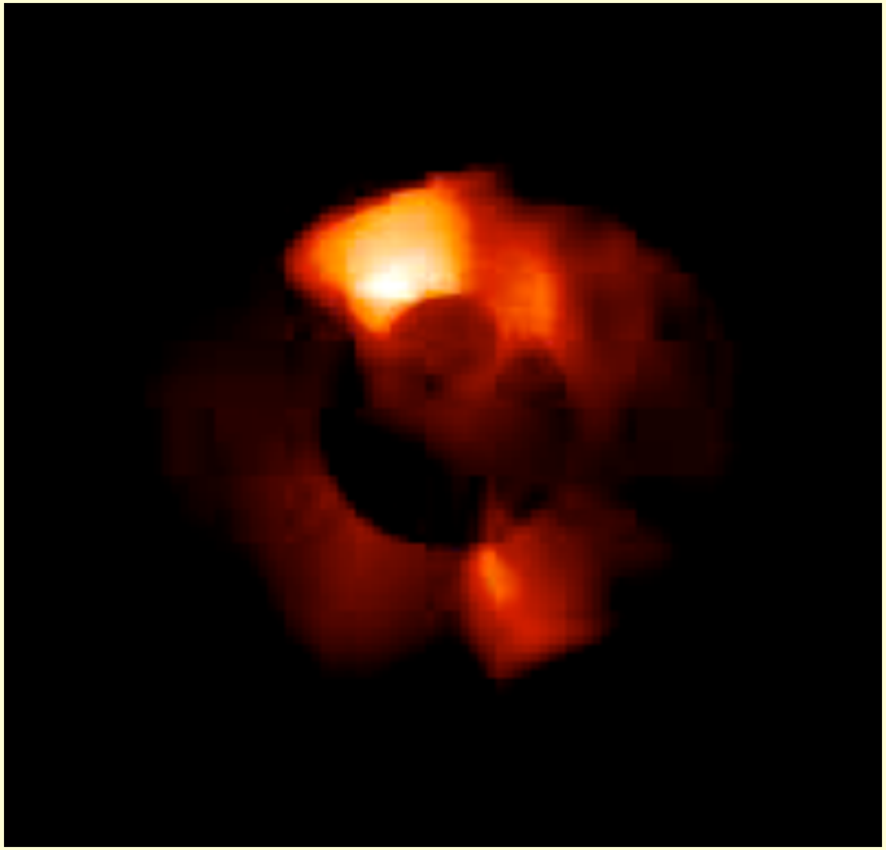
  observations: 7.–12. 12. 1995

- structures on the surface in intensity and magnetic field using Zeeman-Doppler-imaging (ZDI)

- potential field extrapolation (source surface at 5 R_*)

- pressure at coronal base: $p \propto B^2$
  at open field lines: p=0

- emissivity $\propto n_e{}^2$



Collier Cameron, Jardine, Wood, Donati (2000)

Appearance of corona in a multi-loop simulation

potential field extrapolation → simple 1D static loop models to many field lines

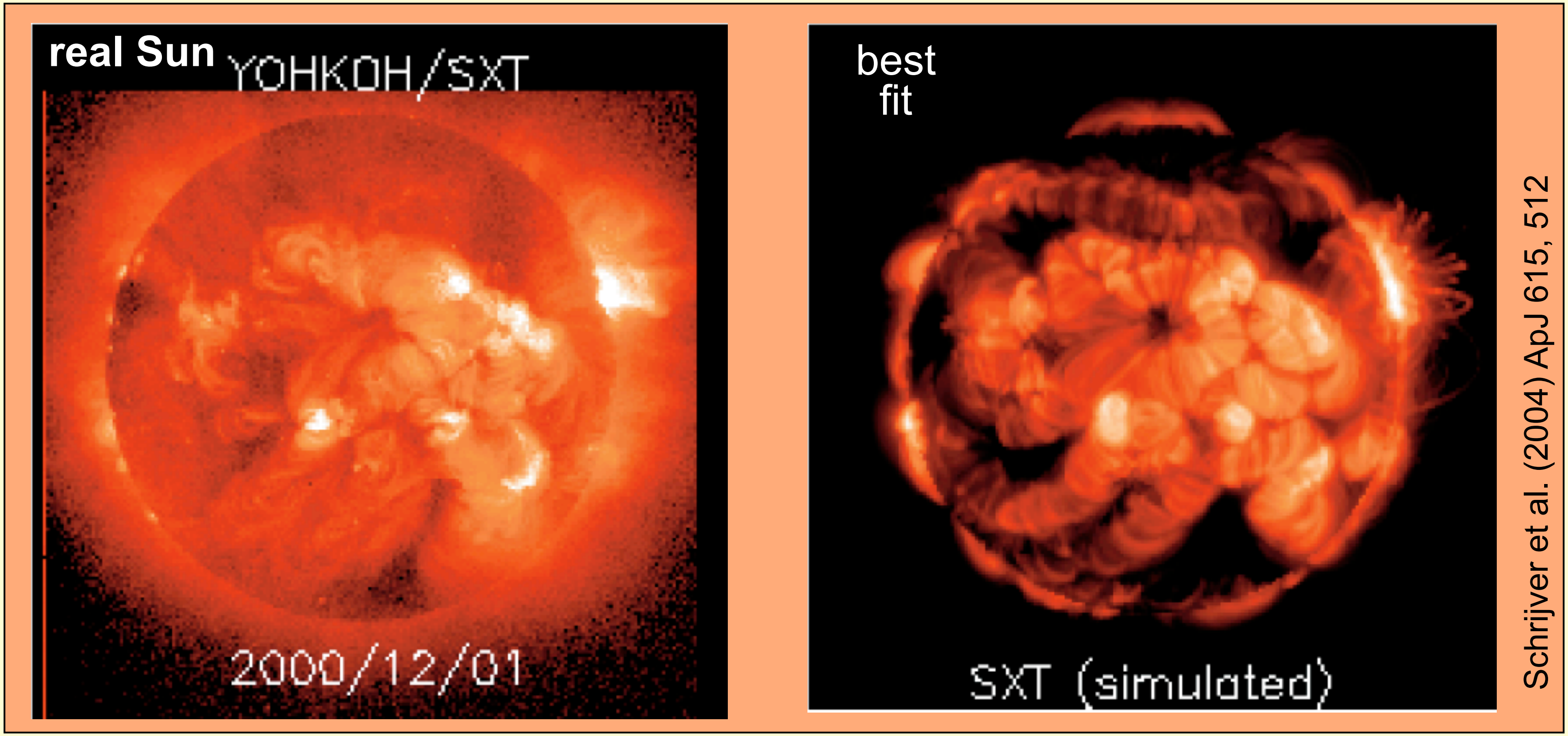
energy flux into loop:

$$F_H = \alpha\, B_{\text{base}}^{\beta}\, L_{\text{half}}^{\lambda}\, f(B_{\text{base}})$$

quenchning to account for sunspots being X-ray dark:

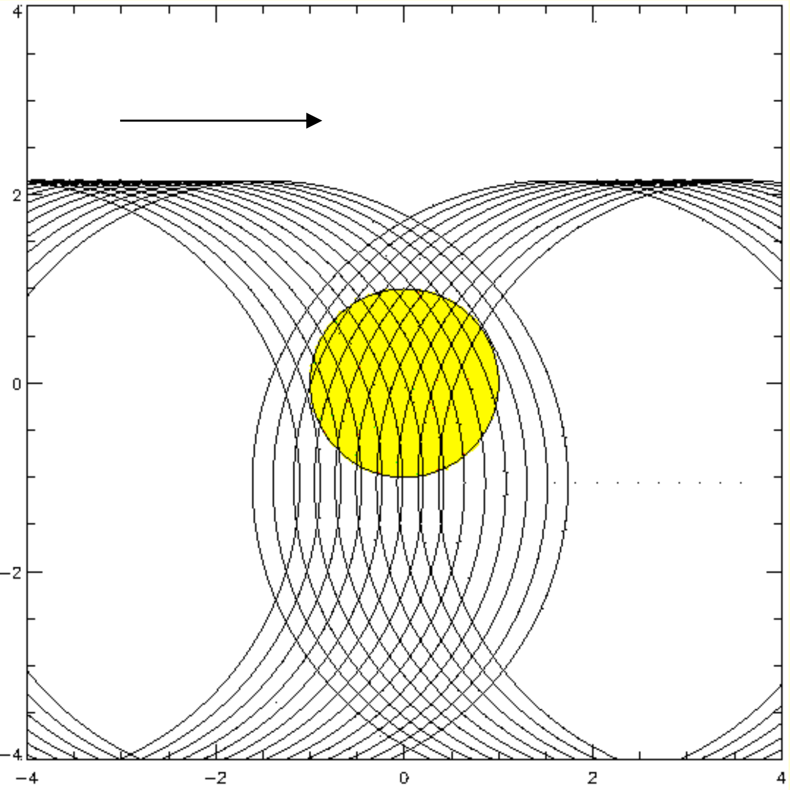
$$f(B) = \exp\left(-\frac{B^2}{500\,\mathrm{G}^2}\right)$$

free parameters:	β	λ
[best fit values]	[1.0 ± 0.5]	[-0.7 ± 0.3]



Schrijver et al. (2004) ApJ 615, 512

Surface structures of an X-ray corona

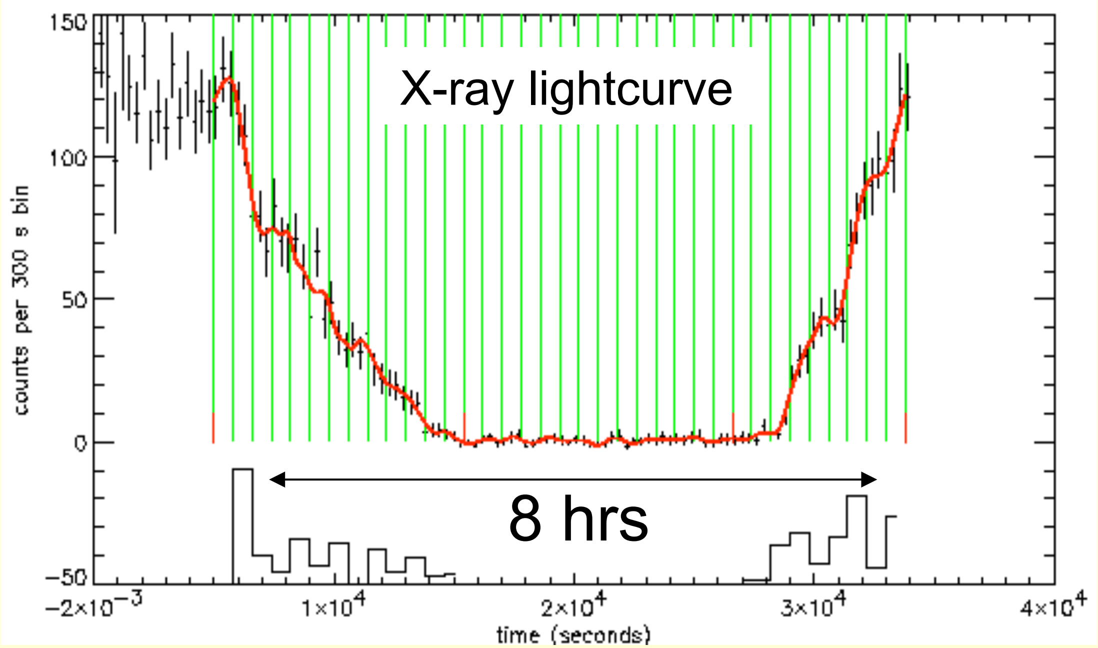


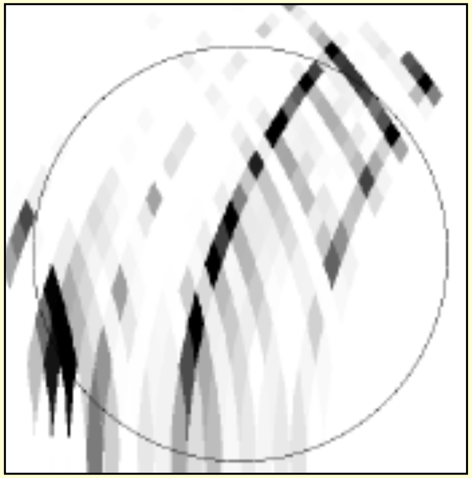
A total eclipse
of a "young Sun" (G5V):

α Coronae Borealis

X-ray bright secondary: G5V R_G: 0.90 $R_\odot$
X-ray dark primary: A0 V R_A: 2.89 $R_\odot$

period: 17.35 days

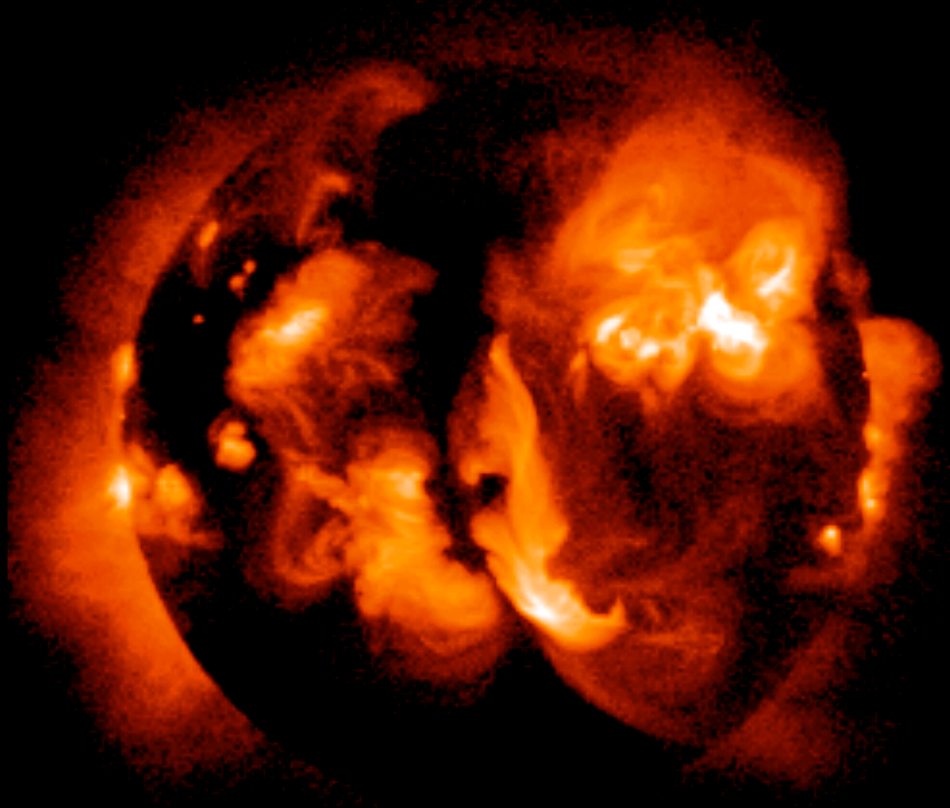




Güdel et al. (2003)
A&A 403, 155

active star

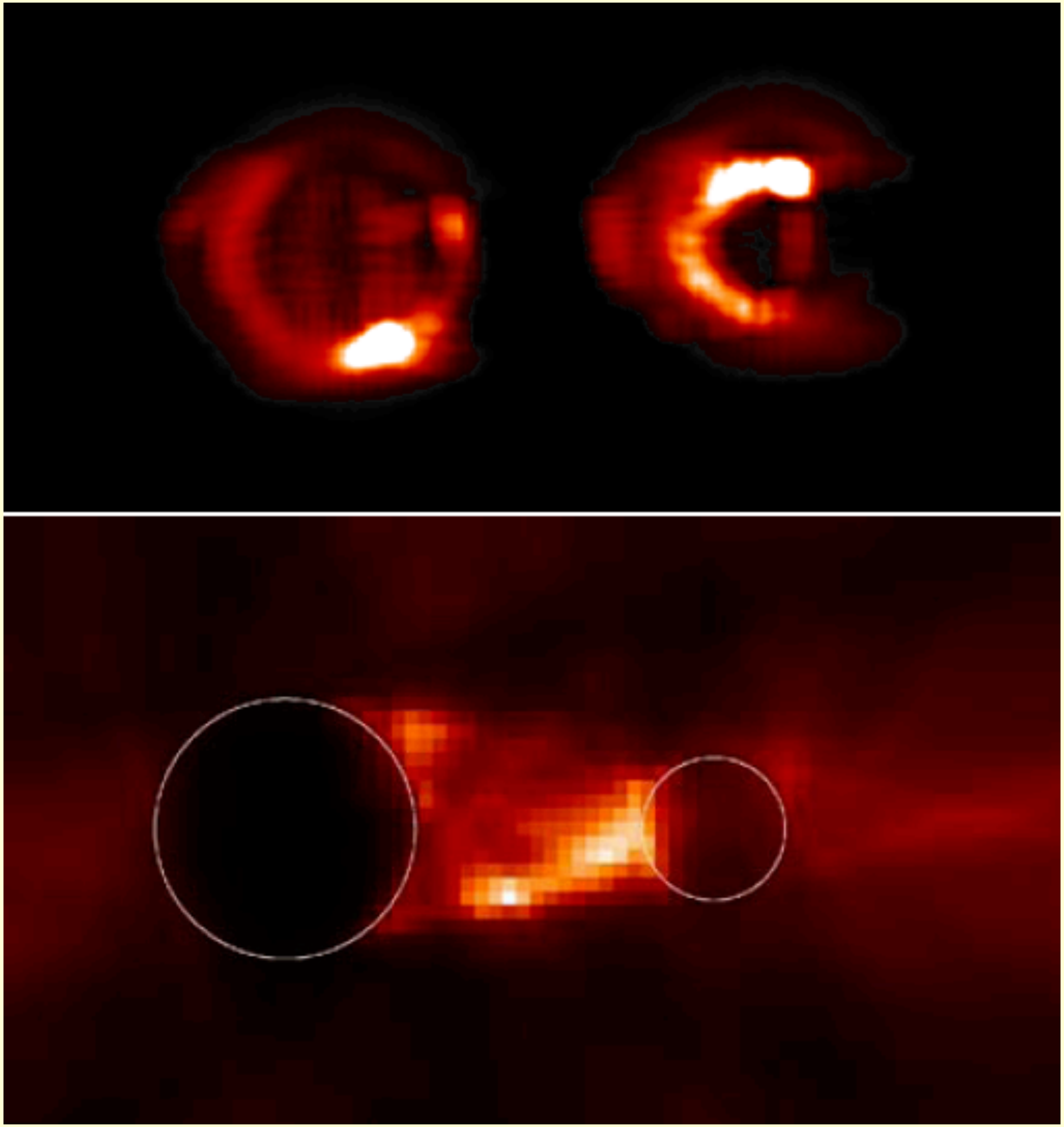
(α Coronae Borealis; G5 V; Güdel et al. 2003)



quiet star

(Sun; G2 V; Yohkoh)

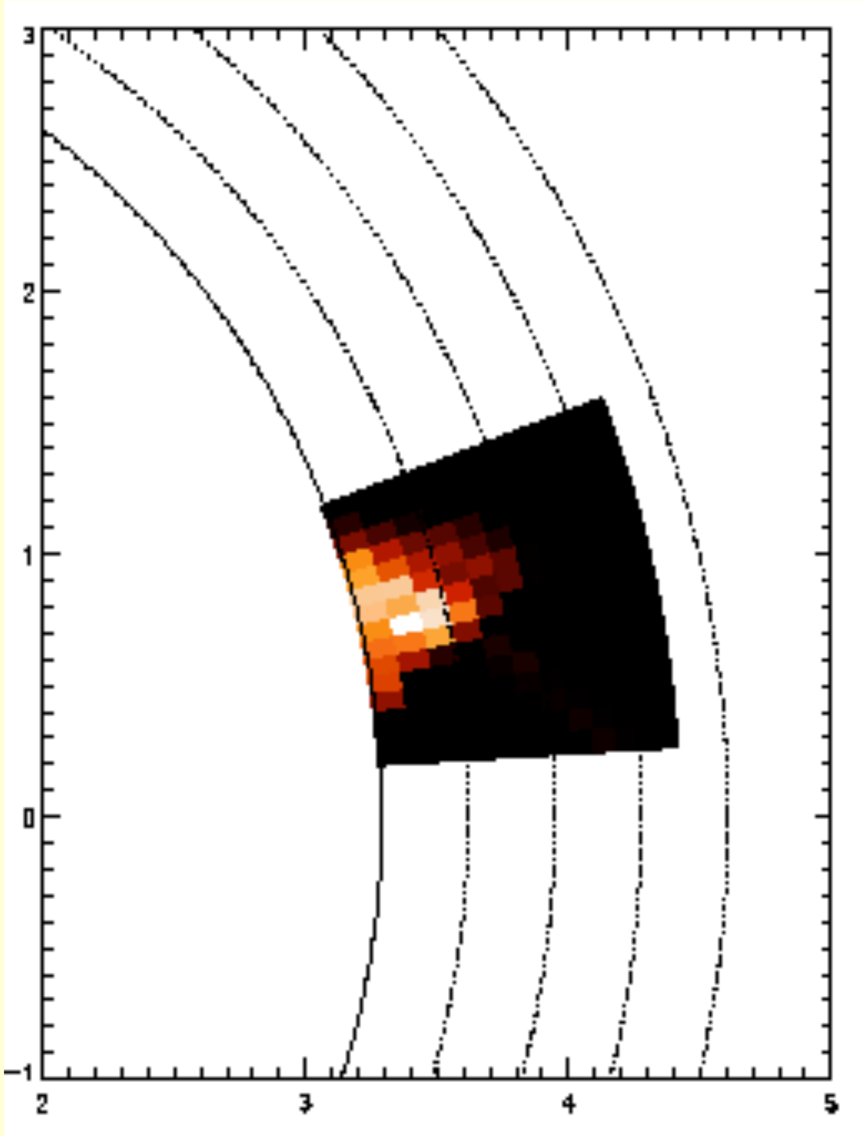
Eclipsing binaries



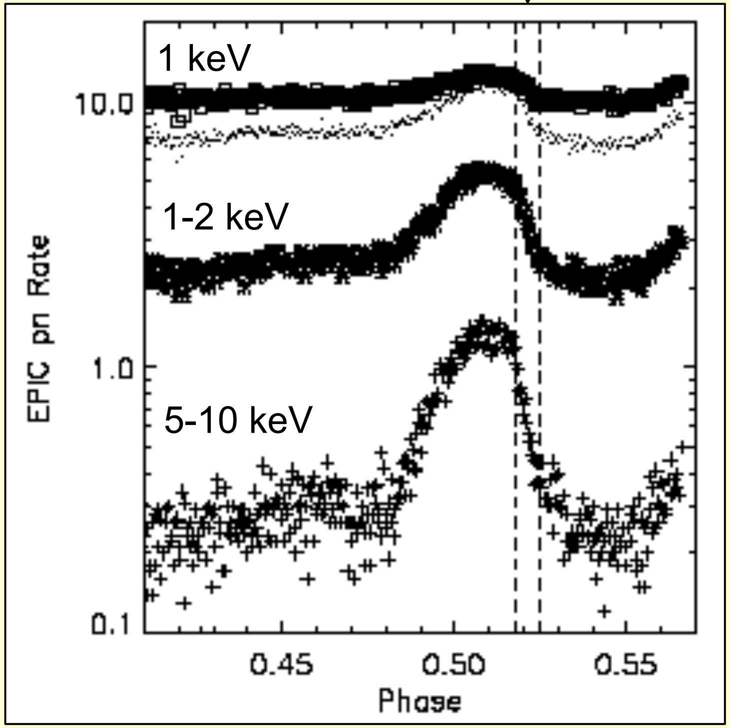
(from review of Güdel 2004, A&ARv 12, 71)

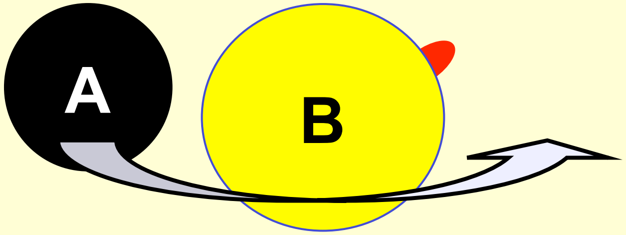
Flare on Algol B

Eclipsing binary: Algol A (B8 V) X-ray dark
Algol B (K2 III) X-ray bright



Eclipse results in asymmetric light curve

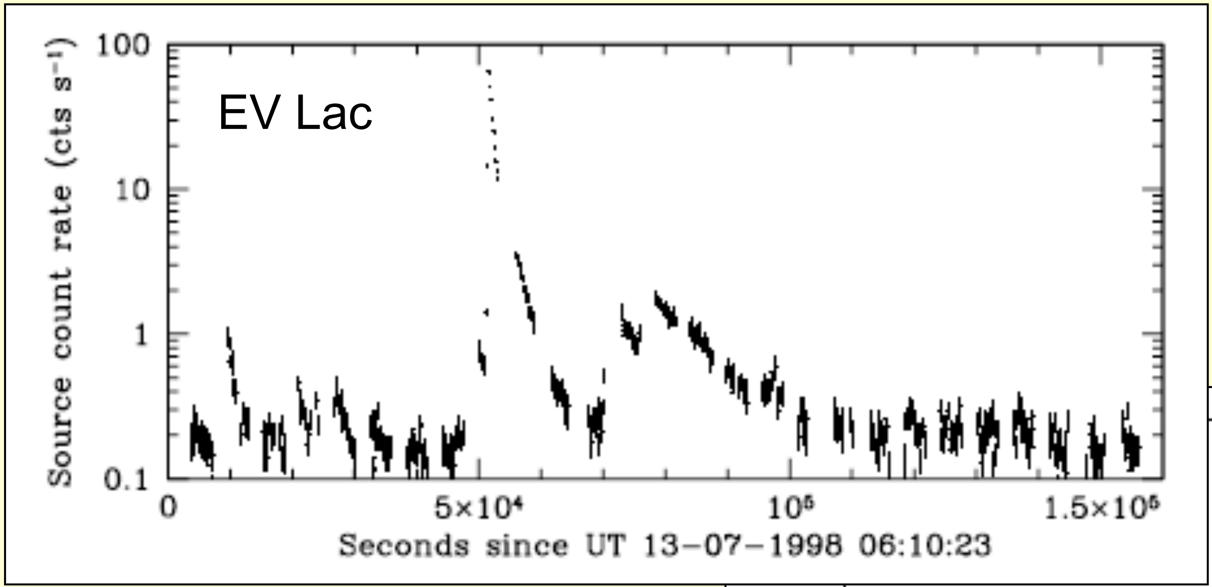




XMM / Newton

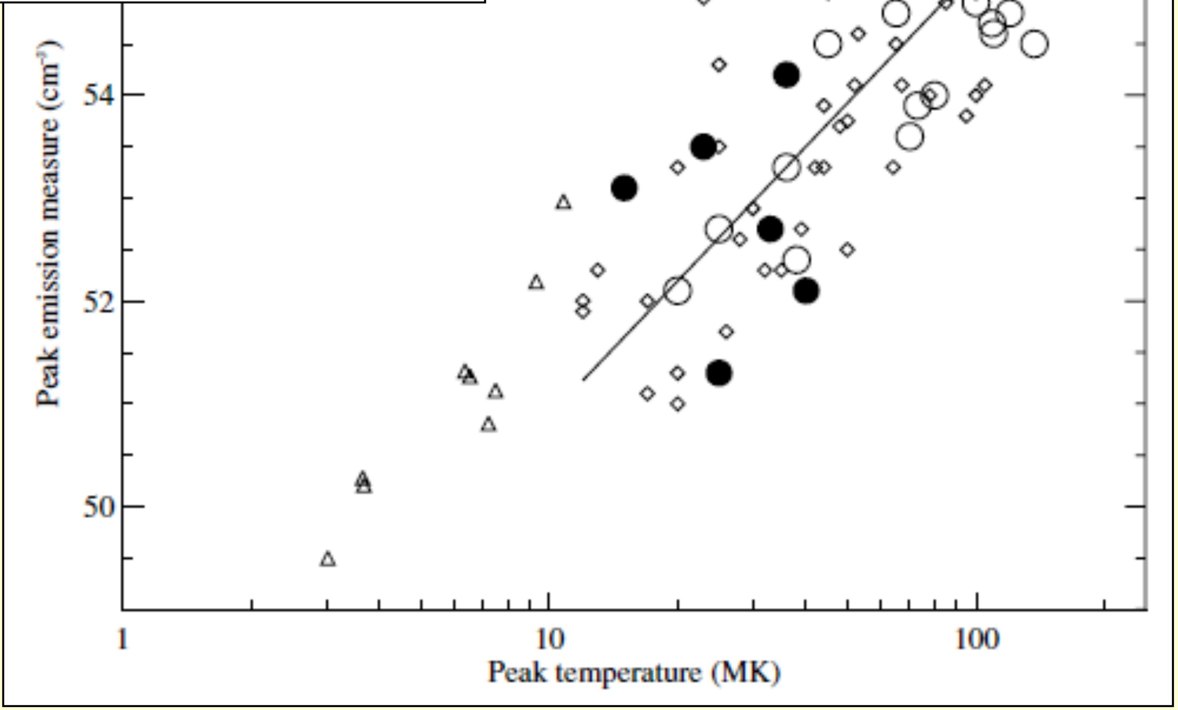
Schmitt, Ness, and Franco (2003) A&A 412, 849

Flares and temperatures



individually resolved
stellar flare(s)

Güdel 2004, A&ARv 12, 71



statistical relation
for stellar flares:

temperature and
emission measure

$EM \sim T^{4.3}$

What are the dominant structures in X-rays?

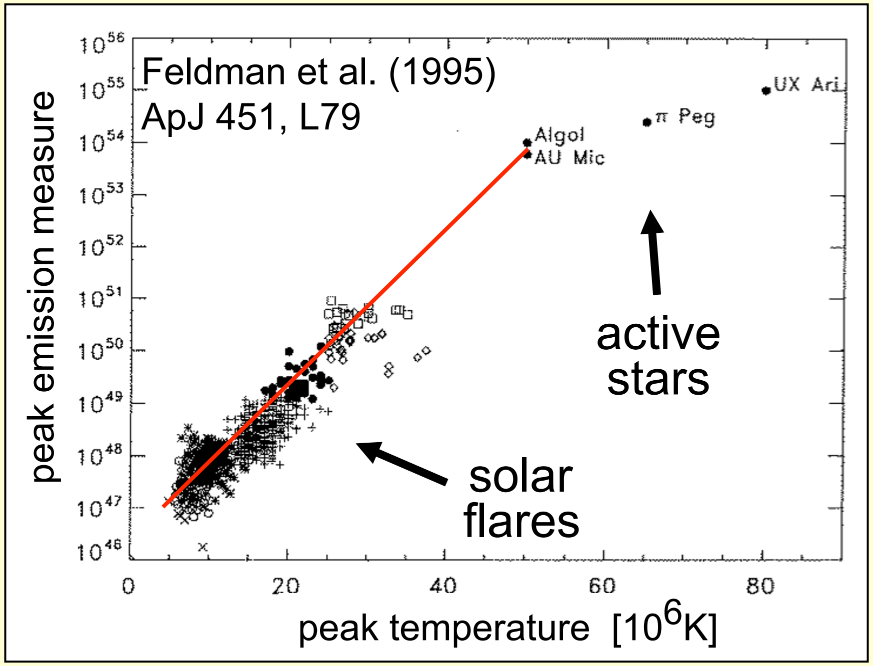
Where does the X-ray emission
come from in active stars?

higher "filling-factor" than Sun?

- ⇨ not enough space on the surface
- ⇨ and: also stellar X-rays are structured

stellar corona are not only brighter,
they have also

- ⇨ high densities
- ⇨ high temperatures


Feldman et al. (1995)
ApJ 451, L79

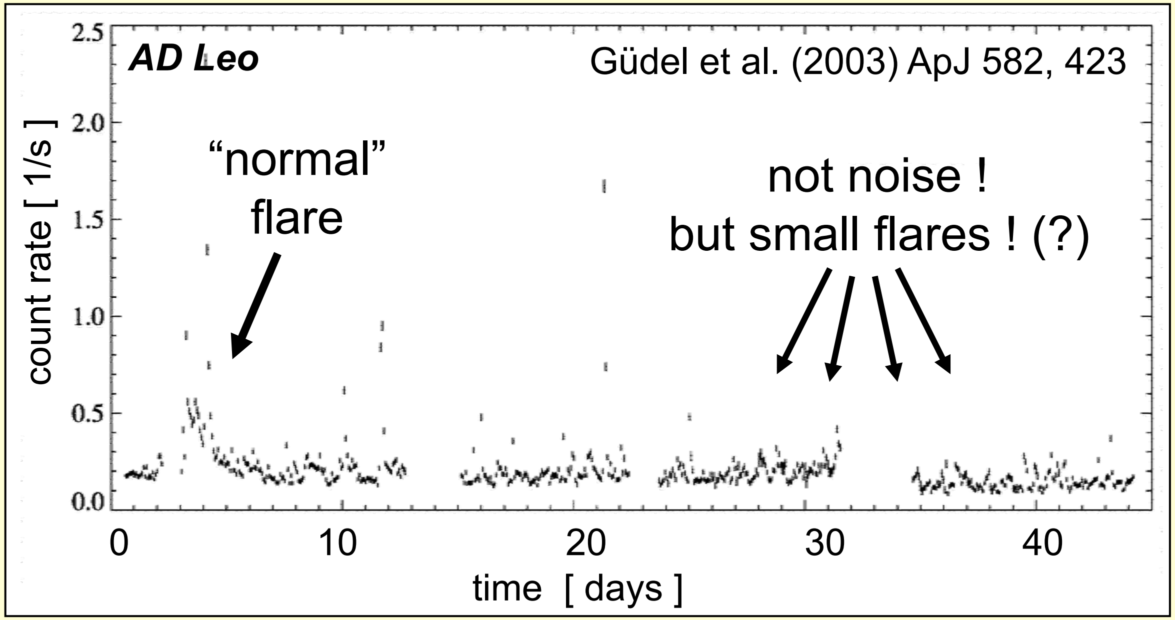
active stars

solar flares

Could it be flares?

Güdel (2003):

"A stochastic flare model
produces emission measure
distributions similar
to observed DEMs, and
predicts densities as observed
in 'quiescent' sources."


Güdel et al. (2003) ApJ 582, 423

"normal" flare

not noise !
but small flares ! (?)

Flares vs. background …

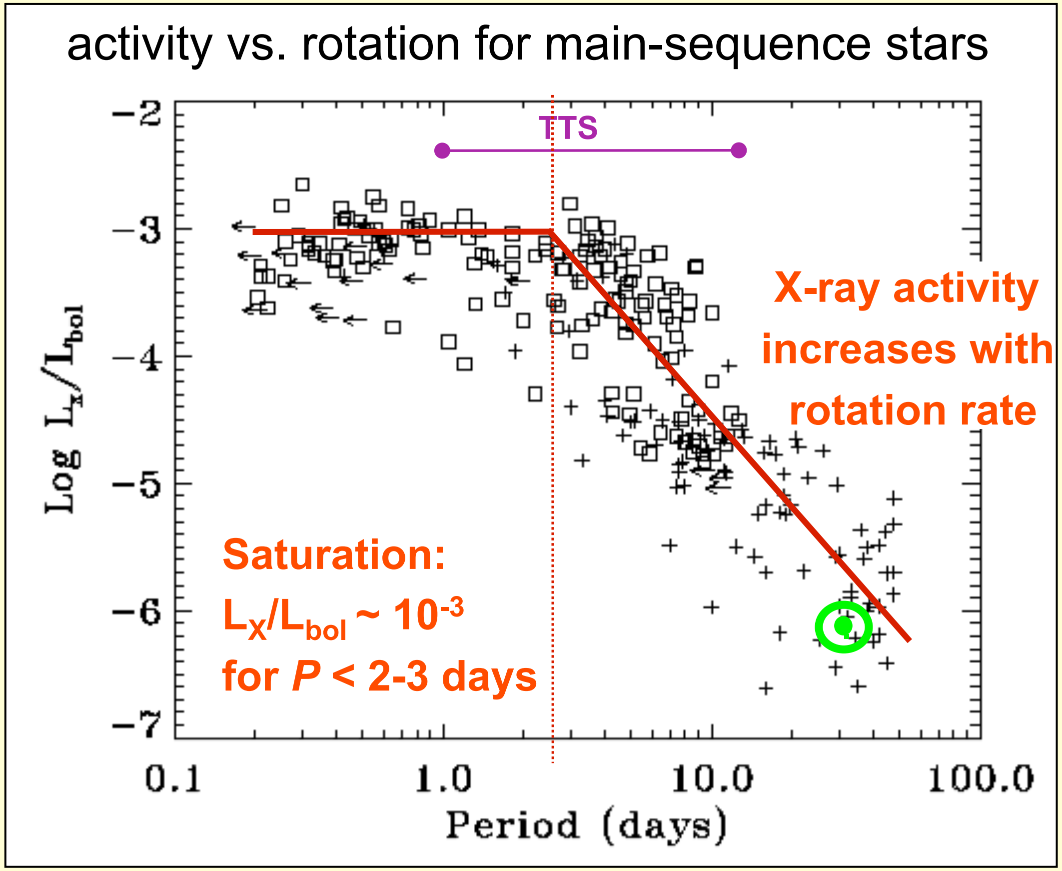
- activity increases with rotation (due to dynamo action)
  saturation for rapid rotation

  \>> scaled-up solar-like magnetic activity ?

- interpretation of major contribution to X-rays depends on energy distribution of flares

  $$dN/dE \propto E^{-\alpha}$$

  $\alpha > 2$: flare dominated
  $\alpha < 2$: flares not sufficient


activity vs. rotation for main-sequence stars

TTS

X-ray activity increases with rotation rate

Saturation:
$L_X/L_{bol} \sim 10^{-3}$
for P < 2-3 days

Pizzolato et al. (2003) A&A 397, 147

- thinkable scenarios:

flare-scenario

- same "quiet" corona as Sun
- extra magnetic energy goes into flares of all sizes

\>> light curve only due to flares

background scenario

- increased magnetic activity leads to higher densities and temperatures of the quiet corona
- plus some more stronger flares

\>> light curve quiet background plus flares!

Flares vs. background …

➨ ***new models for solar activity***

what happens to

> the quiet corona and
> solar flares

when increasing the
emerging magnetic flux?

Well, first we have to understand these phenomena on the Sun before thinking on stars!

flare-scenario

- same “quiet” corona as Sun
- extra magnetic energy goes into flares of all sizes

\>> light curve only due to flares

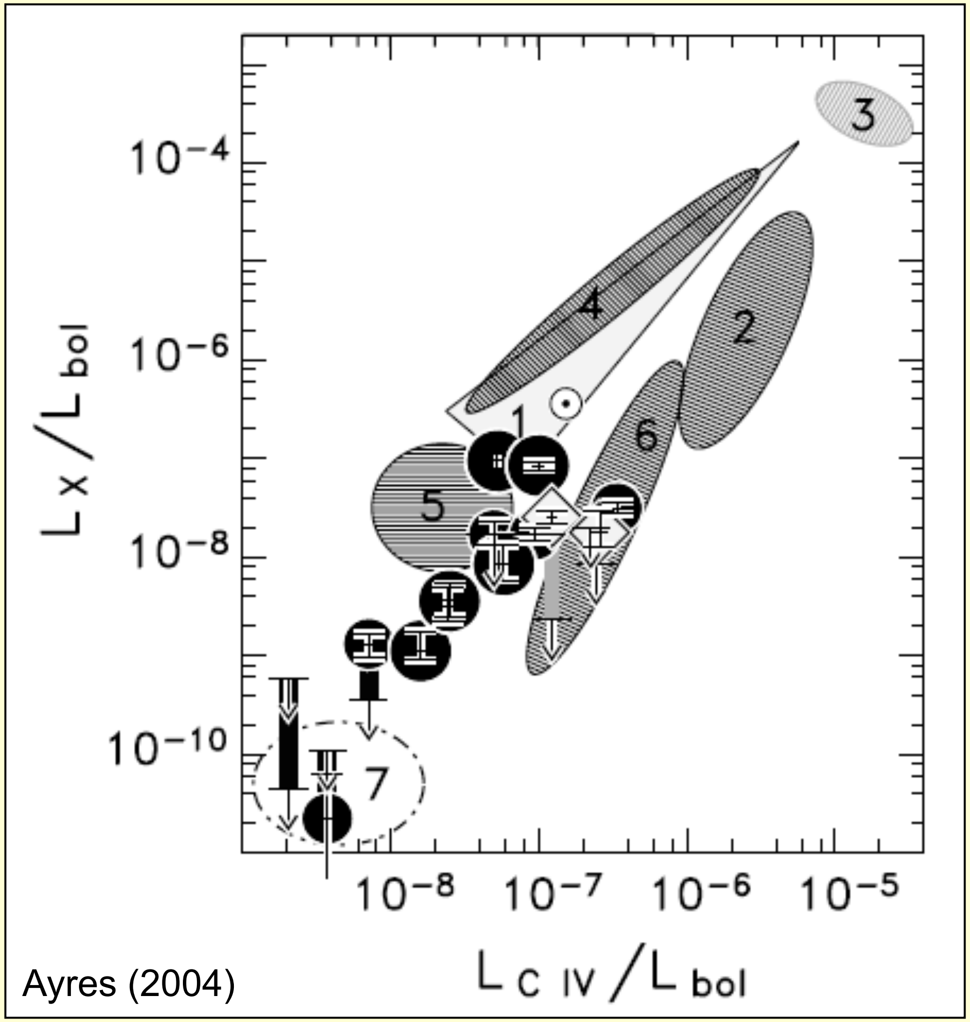
background scenario

- increased magnetic activity leads to higher densities and temperatures of the quiet corona
- plus some more stronger flares

\>> light curve quiet background plus flares!

Flux-flux relations

$$\frac{L_X}{L_{\rm bol}} \approx \left(\frac{L_{\rm C\,IV}}{L_{\rm bol}}\right)^{1.5} \; ; \qquad \frac{L_X}{L_{\rm bol}} \approx \left(\frac{L_{\rm Mg\,II}}{L_{\rm bol}}\right)^{3}$$



Ayres (2004)

- ► non-linear relation between chromosphere – TR – corona
- ► physics unclear
  - – chromospheric radiative processes?
  - – signature of heating process?
- ► “basal flux” (Schrijver 1987)
  - – constant “background” of chromospheric (TR) emission

scenario:

minimum chromospheric radiation in absence of magnetic field?

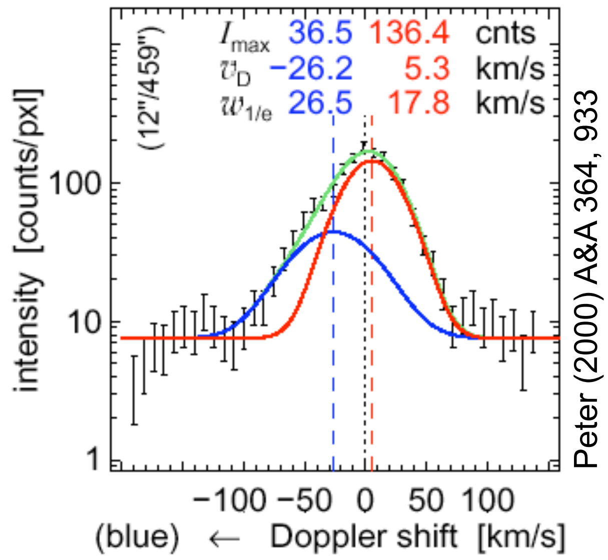
X-ray emission: purely magnetically heated

chromospheric emission: magnetically plus *acoustic* heating

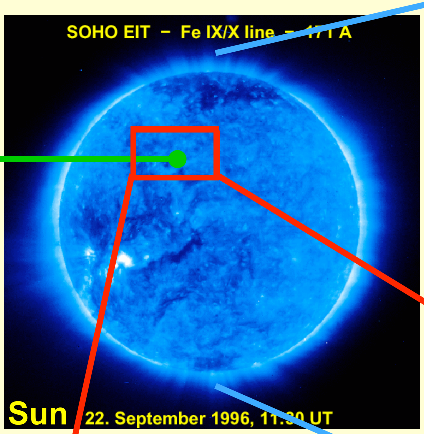
at low magnetic activity vanishes but acoustic heating still present

From the stars to the Sun: EUV profiles

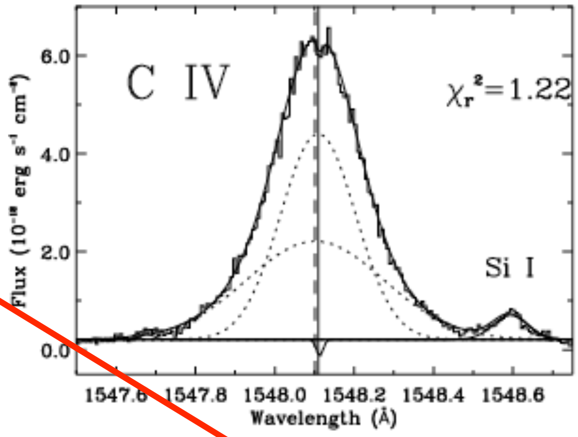
Sun: 1” x 1” network



Peter (2000) A&A 364, 933

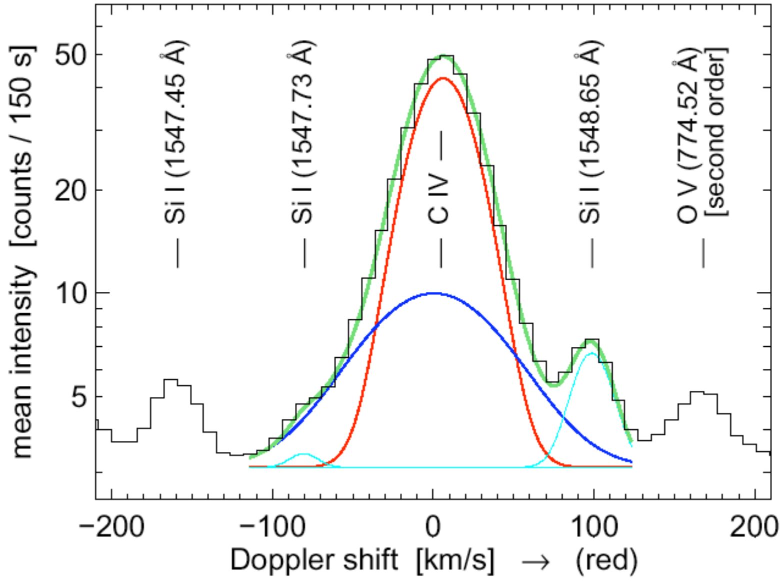


“full Sun”: αCen A (G2 V)



Pagano et al. (2004) A&A 415, 331

Sun (G2 V): average quiet Sun



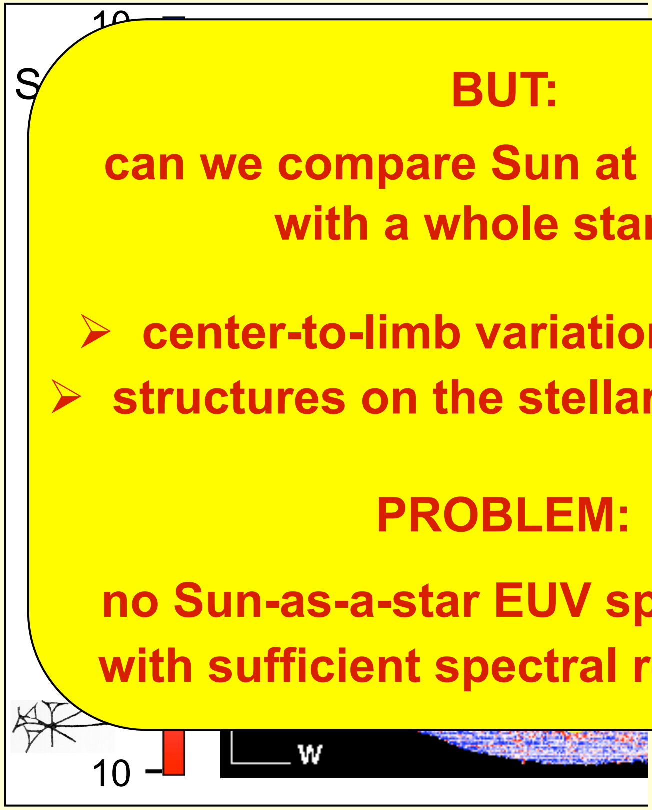
Peter (2000) A&A 364, 933

subtle but significant differences!

non–Gaussian line profiles:

- mixture of surface structures?
- center to limb effect?
- signature of heating process?

Doppler shifts: spatially resolved vs. full disk



BUT:

can we compare Sun at disc center with a whole star ??

- **center-to-limb variations of I, w, v_D**
- **structures on the stellar disk, e.g. AR**

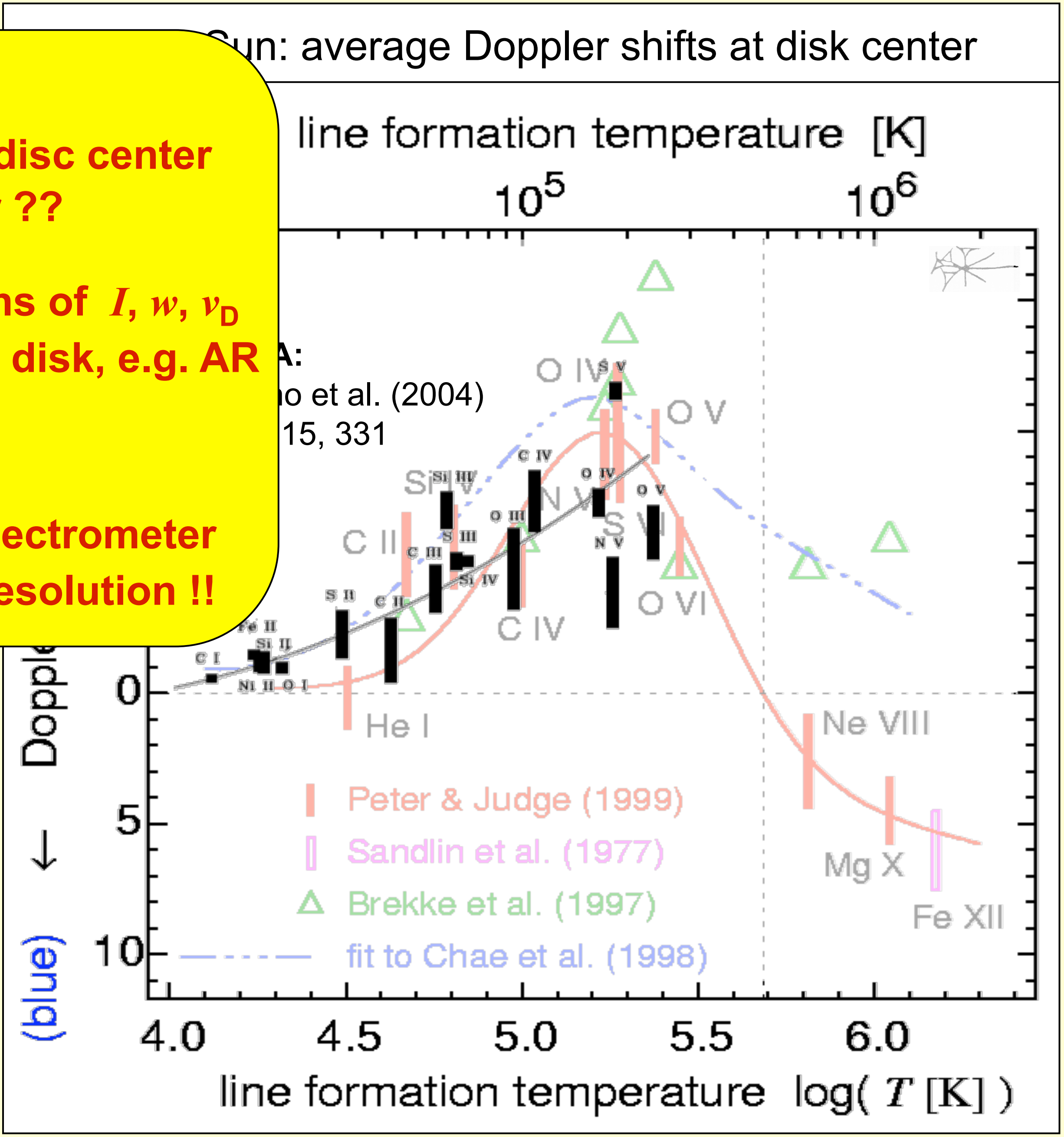
PROBLEM:

no Sun-as-a-star EUV spectrometer with sufficient spectral resolution !!

How to compare Sun and stars?

e.g.: net line shift

- amazing match between Sun and aCen A
- **BUT: – Sun at disc center – full stellar disk !!**

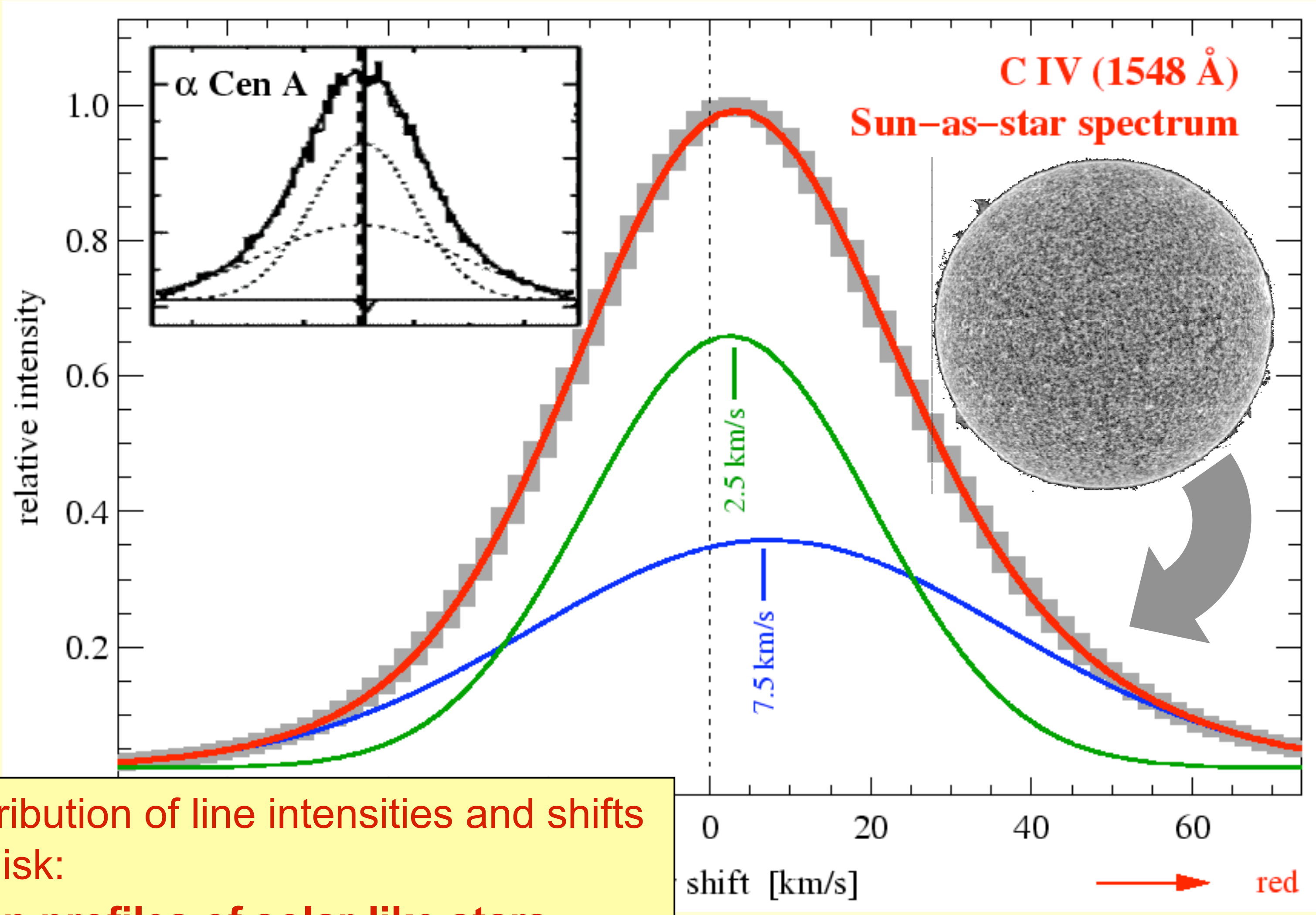


First EUV Sun-as-a-star spectrum

Composing the integral (total) solar spectrum from a SUMER full-disk raster map

full-Sun spectrum similar to α Cen A !

- but net redshift reduced by factor 1/3!



Peter (2006), A&A 449, 759

modeling distribution of line intensities and shifts on the solar disk:

non-Gaussian profiles of solar-like stars are due to distribution of surface structures

and not signature of heating process

Problem so far:
no full-Sun EUV spectrometer
with high spectral resolution!

Signatures of small-scale activity?

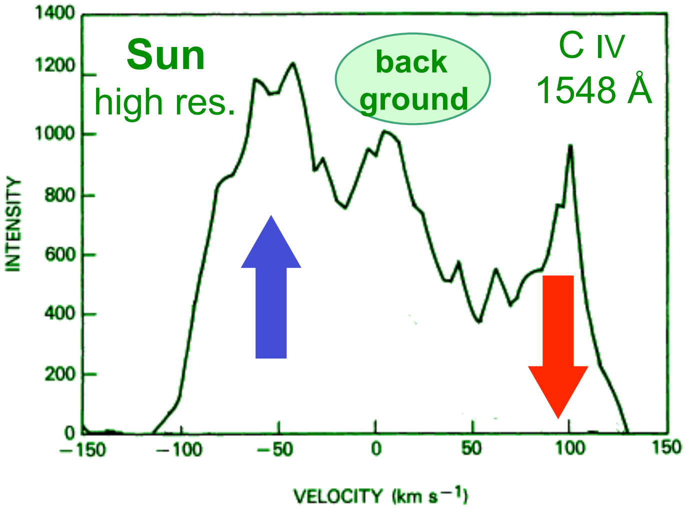
- spectra usually well described by double Gaussians !

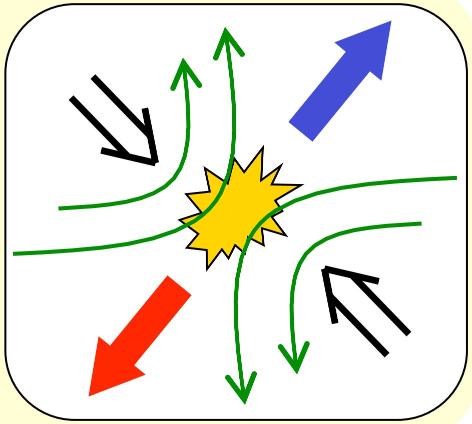
  >> what is the nature of these two components?

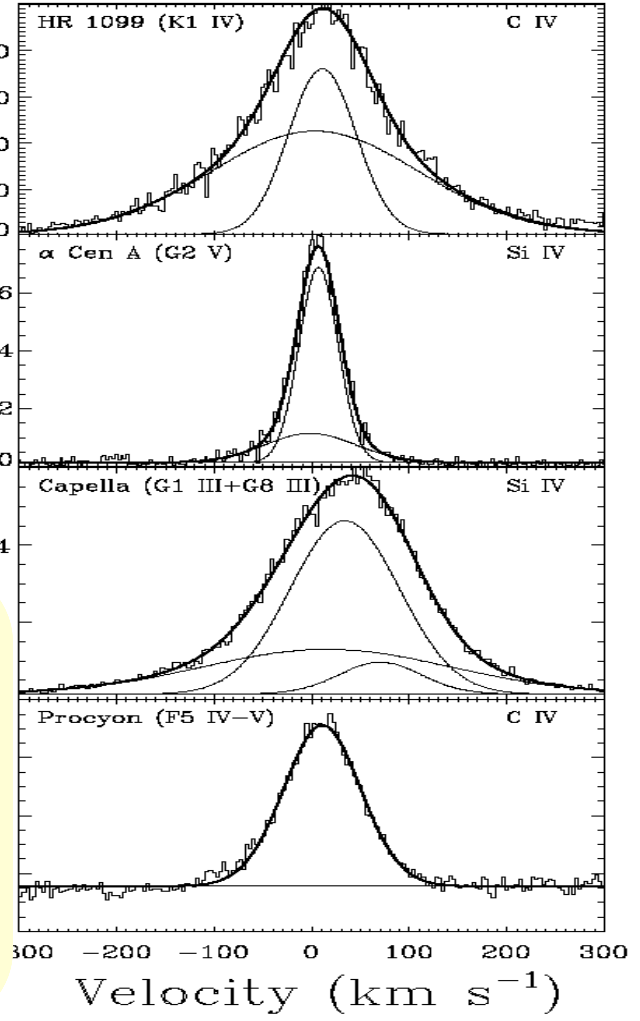
One possible interpretation:

- small scale activity (**explosive events**)
  causes flows ~v_A
  excess emission in line wings

solar-like → active stars:
asymmetric spectra of lines at ~10^5 K







Wood et al. (1997) ApJ 478, 745

Luminous cool giants: wind detection ?

- asymmetric spectra of lines at ~10^5 K (e.g. C III 977 Å, O VI 1032 Å)
- spectra usually well described by double Gaussians !

  >> what is the nature of these two components?

One possible interpretation:

(Dupree et al. 2005, ApJ 622, 629)

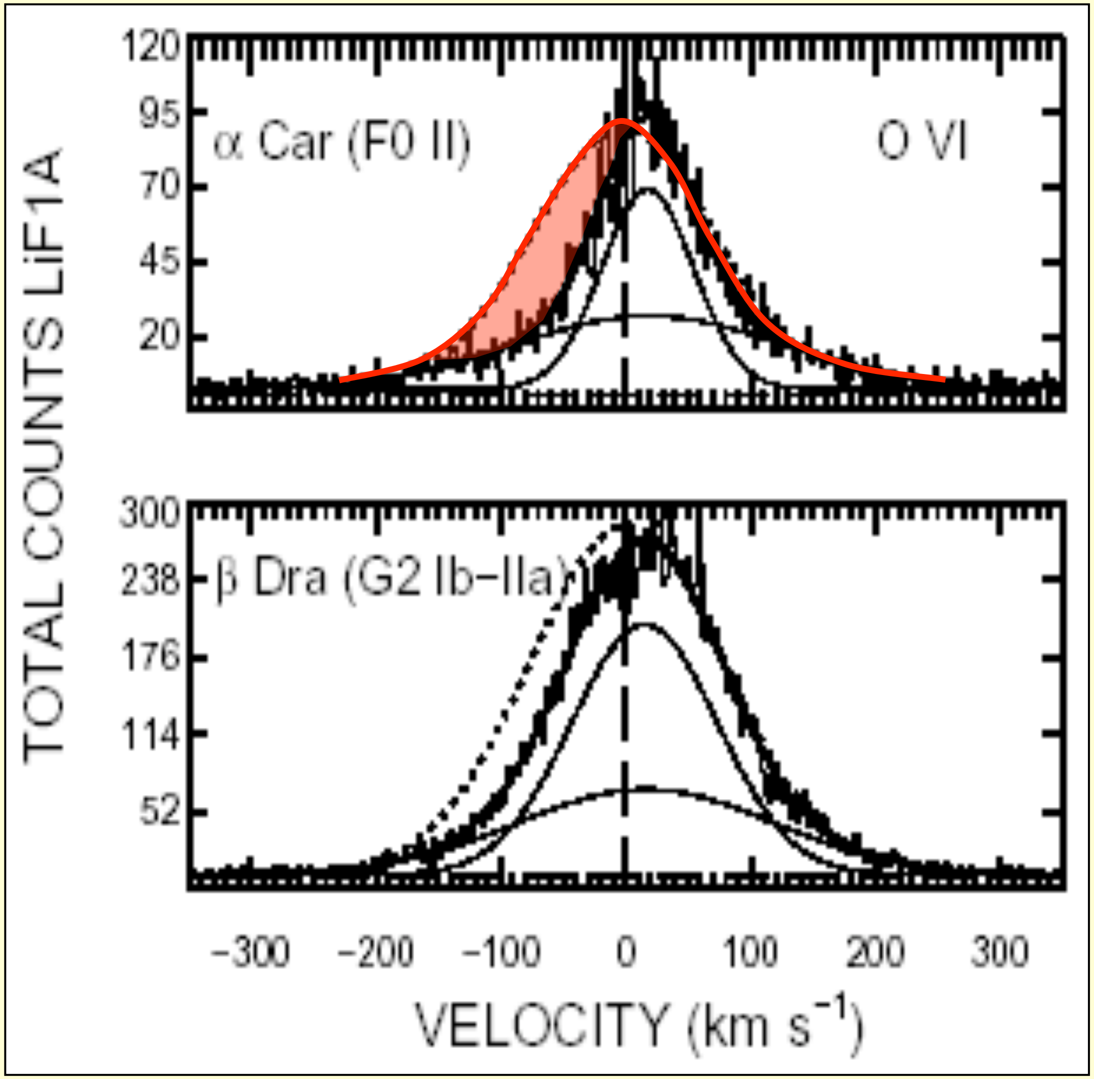
- single Gaussian fit only to red part of the spectrum

  >> excess absorption in blue wing:

  mass outflow ?

  ➡ **does it work ?**

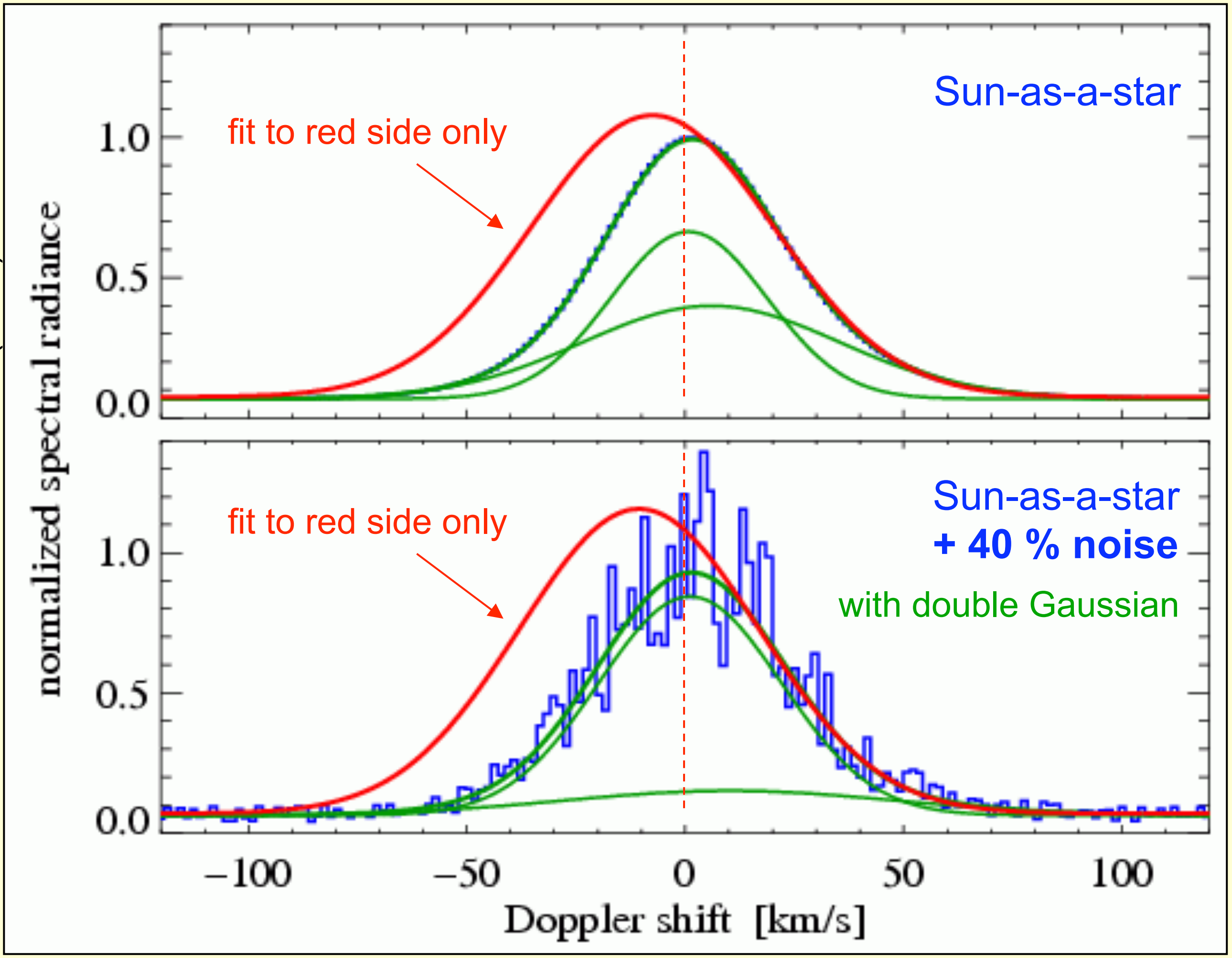
  ➡ **is it unique ?**



Dupree et al. (2005) ApJ 622, 629

FUSE spectra

The Sun "seen as a cool giant"



Peter (2006) A&A 449, 759

- "*cool giant wind detection procedure*" used by Dupree et al (2005) applied to the Sun-as-a-star spectrum of C IV (1548 Å)
- **full-Sun looks similar to cool giants !!**
- **line asymmetry of cool giants signature of stellar surface structures ?**
  - ➡ e.g. large convection patterns on giants
    - \>> as expected by Schwarzschild (1975) ApJ 195, 137
    - \>> and simulated by Freytag et al. (2002) AN 323, 213

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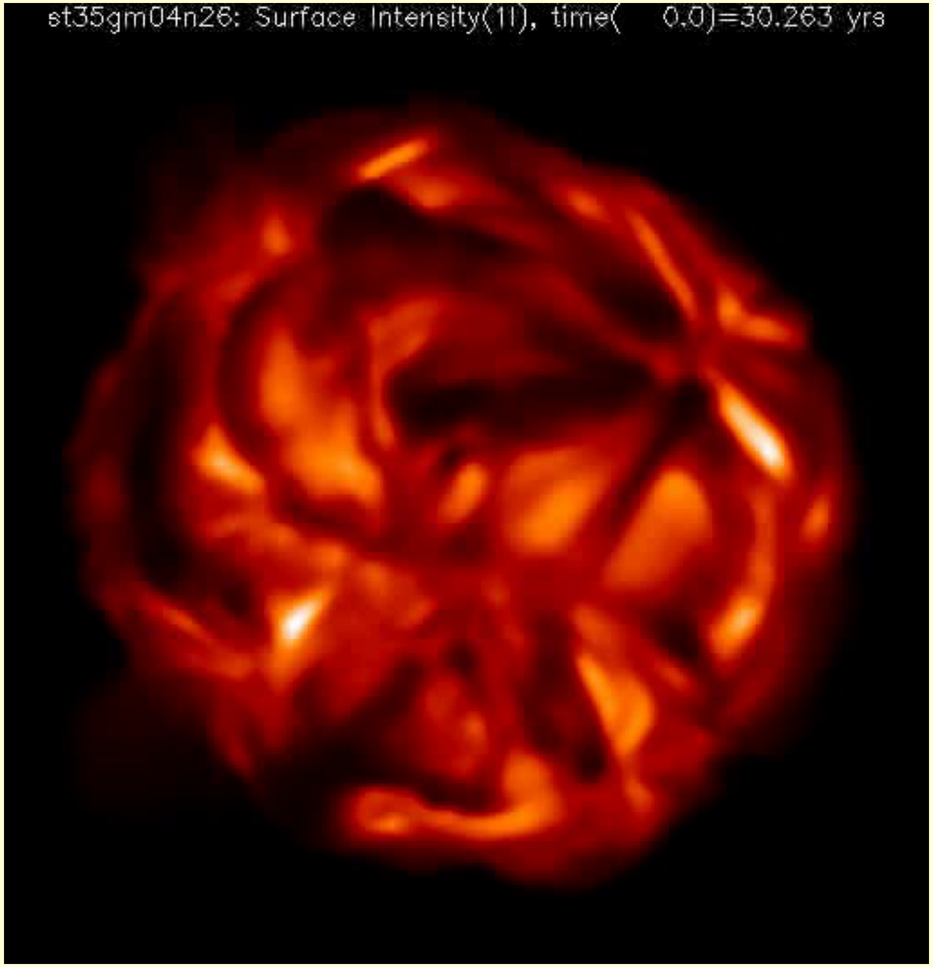

3D model of convecion in a giant star – Betelgeuse
Freytag et al. (2002) AN 323, 213

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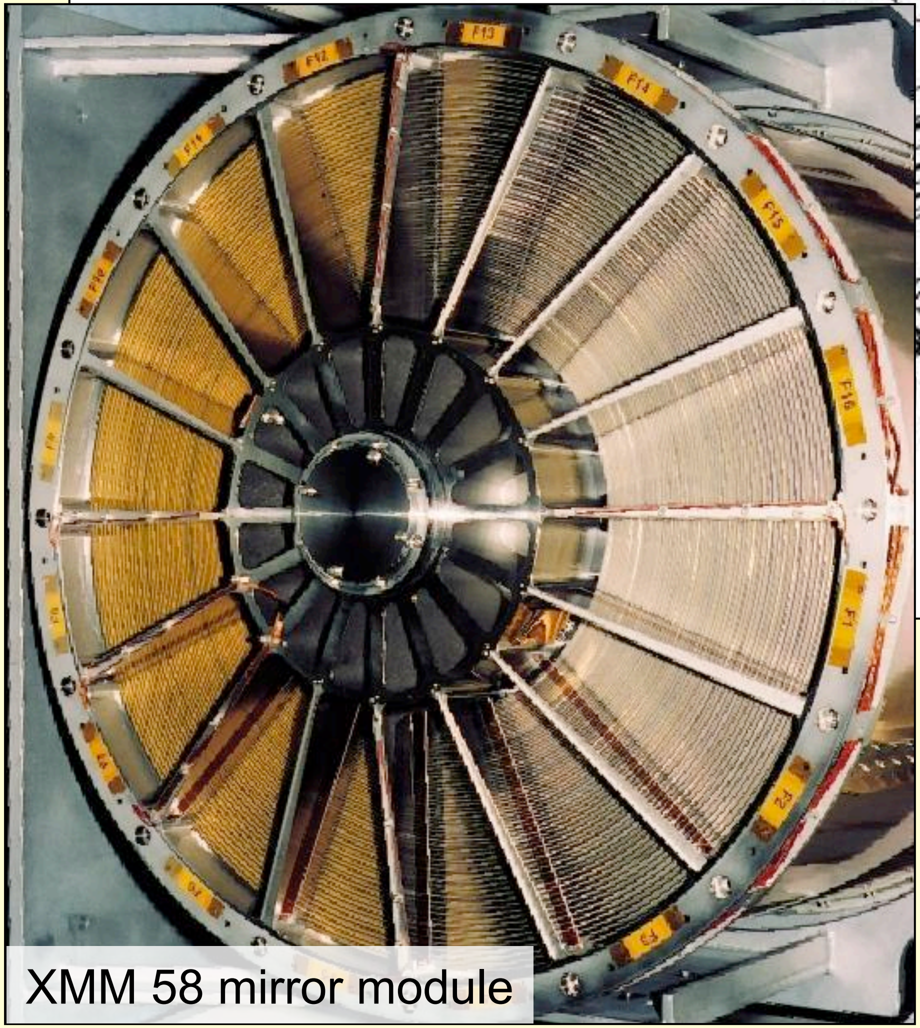
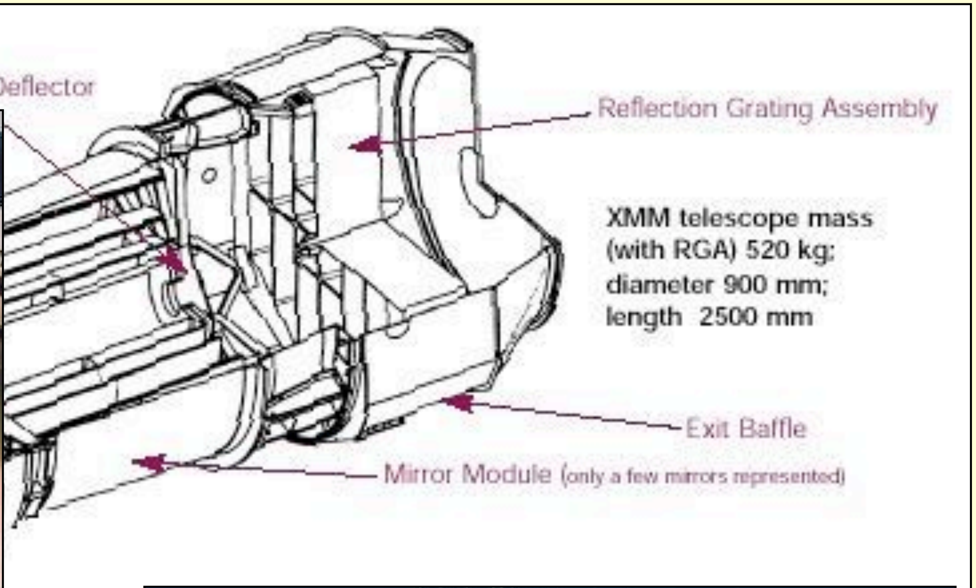
XMM / Newton X-ray observatory



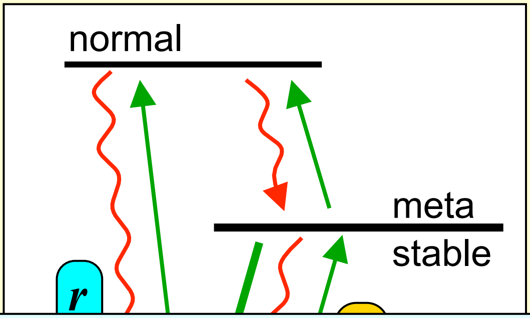
XMM 58 mirror module

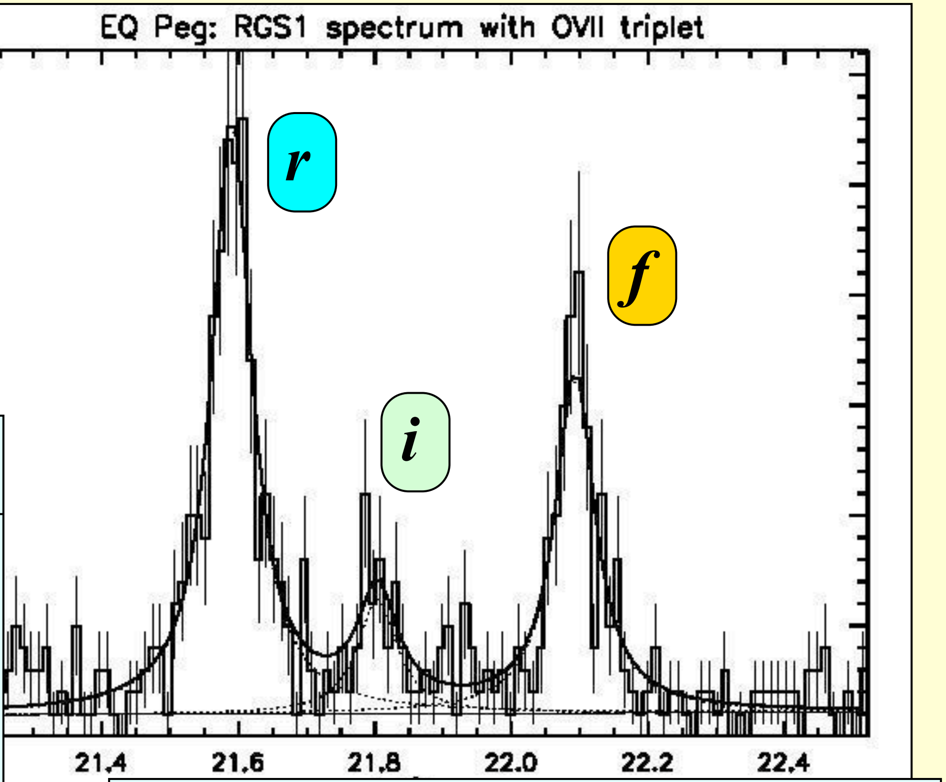


XMM telescope mass
(with RGA) 520 kg;
diameter 900 mm;
length 2500 mm

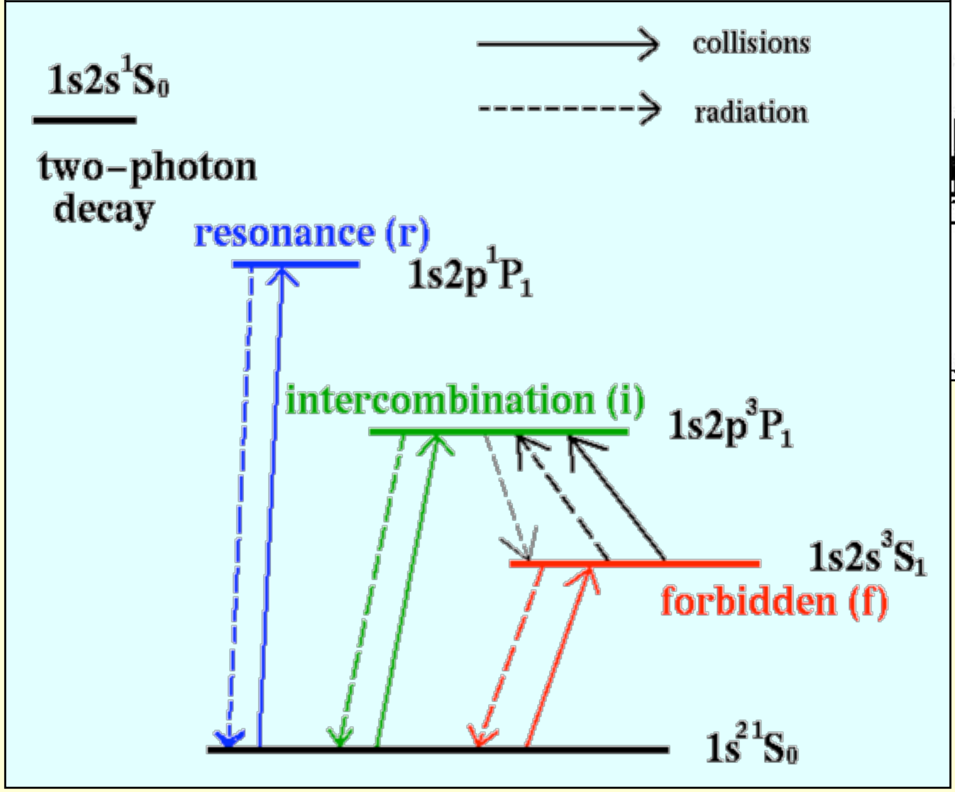
X-ray density diagnostics: He-like ions

principle: a simple 3 level atom



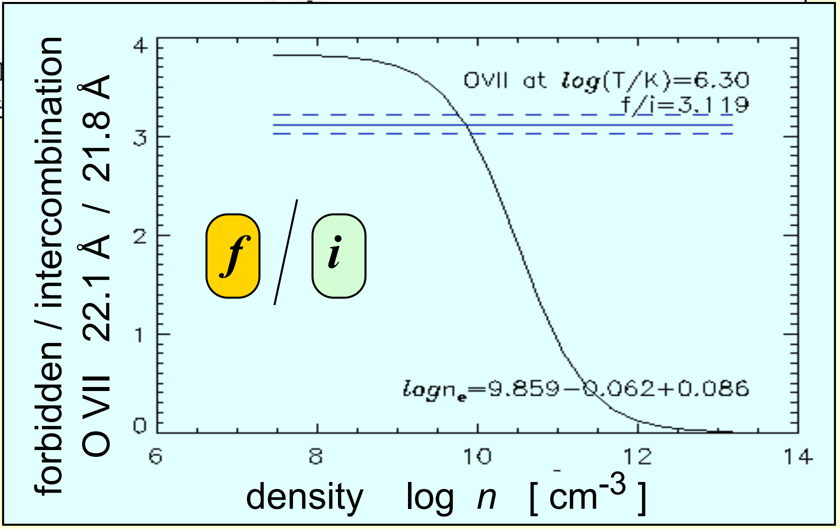


a more complicated case: He-like ions



XMM-

Hamburger St



Differential emission measure – DEM

$$F = \int h\nu \, A_{21} \, n_2 \, \mathrm{d}h$$

$$G(T, \cancel{n_e}) = h\nu \, A_{21} \cdot \frac{n_2}{n_e \, n_{\mathrm{ion}}} \cdot \frac{n_{\mathrm{ion}}}{n_{\mathrm{el}}} \cdot \frac{n_{\mathrm{el}}}{n_{\mathrm{H}}} \cdot \frac{n_{\mathrm{H}}}{n_e}$$

excitation

ionization equilibrium

abundance

≈ 0.8 for full ionization

$$F = \int G(T, \cancel{n_e}) \, n_e^2 \, \mathrm{d}h$$

$$\boxed{DEM = n_e^2 \left(\frac{\mathrm{d}T}{\mathrm{d}h} \right)^{-1}}$$

$$F = \int G(T, \cancel{n_e}) \, DEM \, \mathrm{d}T$$

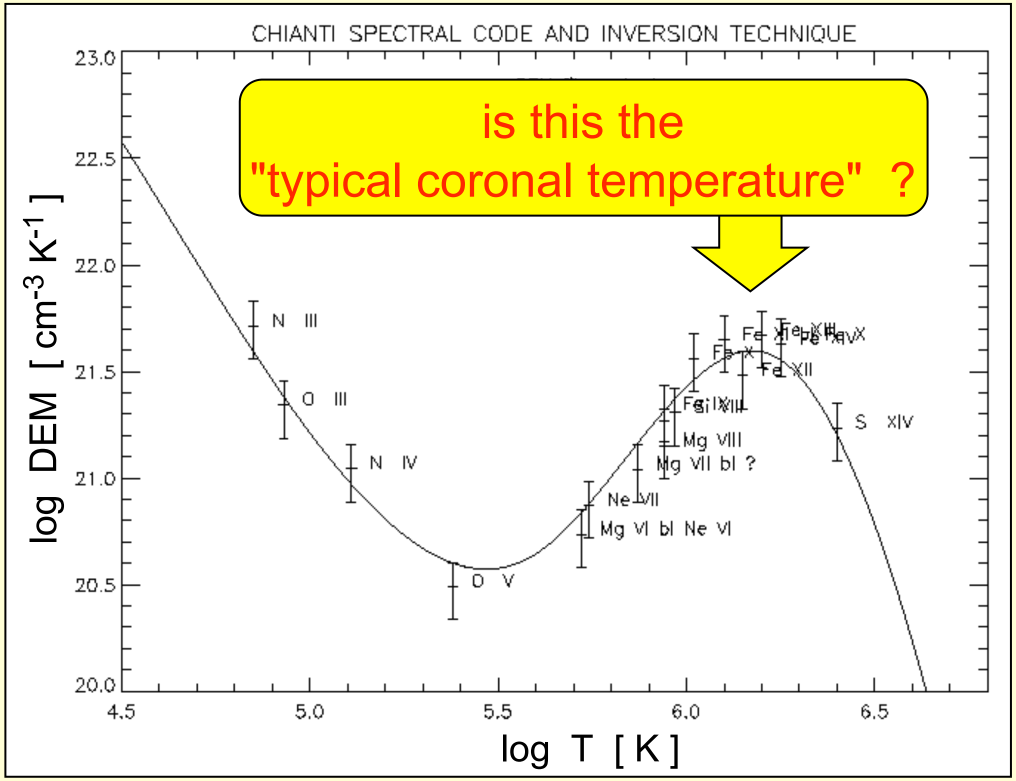
- $G(T)$: atomic physics
- DEM: thermodynamics (n,T)

  ➡ same for all lines!!

given a set of observed emissions F for lines with known $G(T)$:

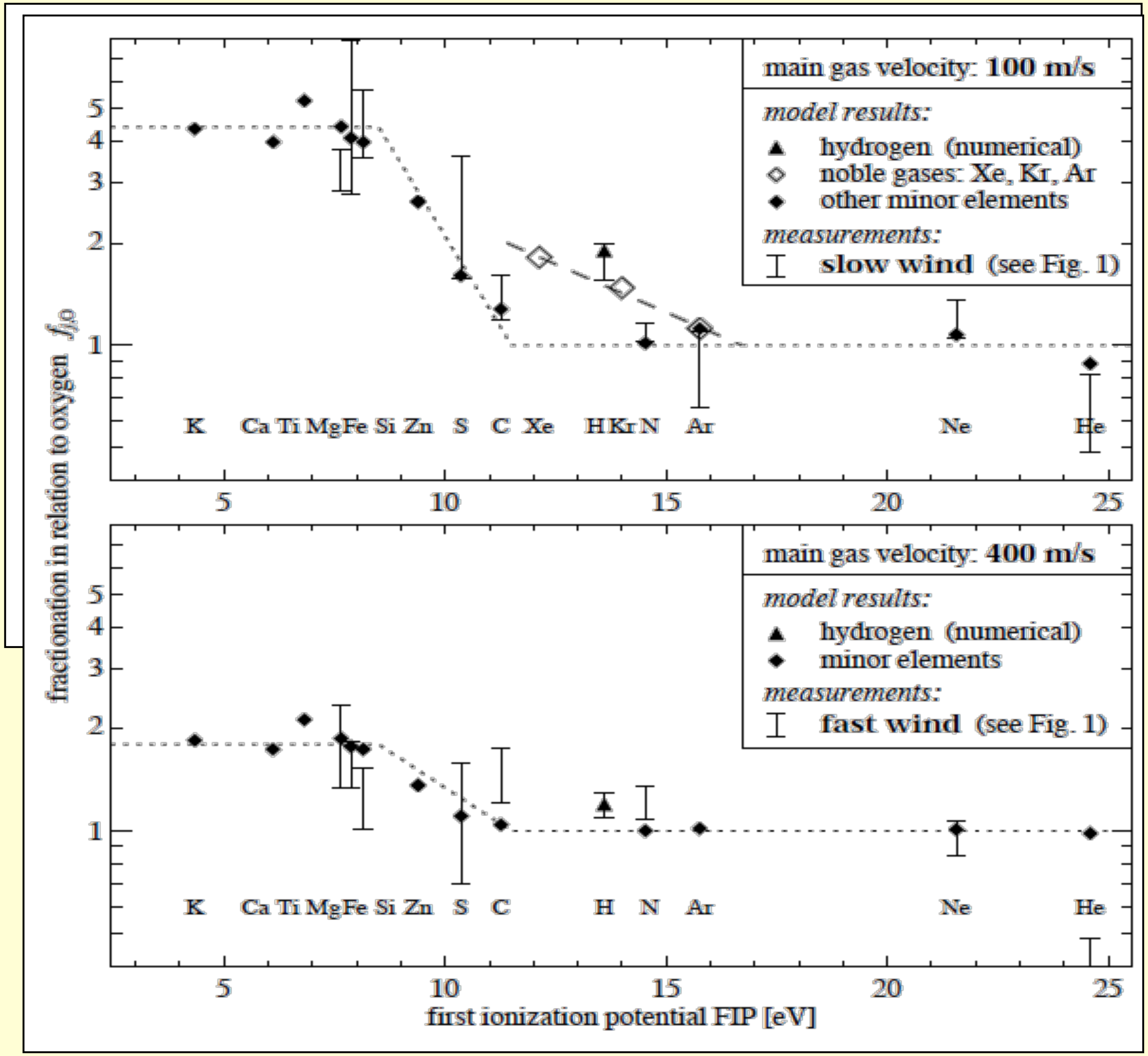
➡ density-temperature structure $DEM(T)$

iterative procedure; ill-posed problem



is this the "typical coronal temperature" ?

Solar FIP Effect



model:

ionization-diffusion

– once particles of minor species are ionized they are carried out with solar wind

– diffusion of neutral through p-background supplies new minors

– faster velocity of background suppresses FIP effect

(Peter & Marsch 1998)

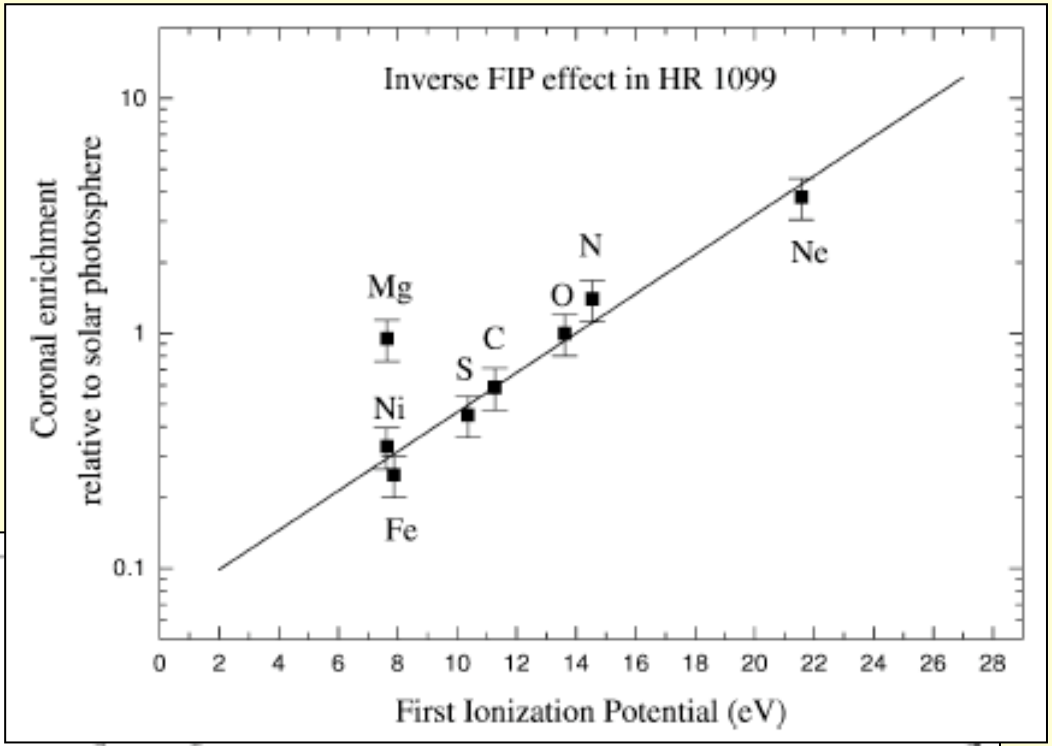
$$\lim_{U_H \to 0} f_{j,k} = \frac{w_j}{w_k} = \left(\frac{r_{kH}}{r_{jH}}\right) \sqrt{\frac{\tau_k}{\tau_j}} \left(\frac{A_j + 1}{A_j} \, \frac{A_k}{A_k + 1}\right)^{1/4}$$

(Inverse) FIP effect

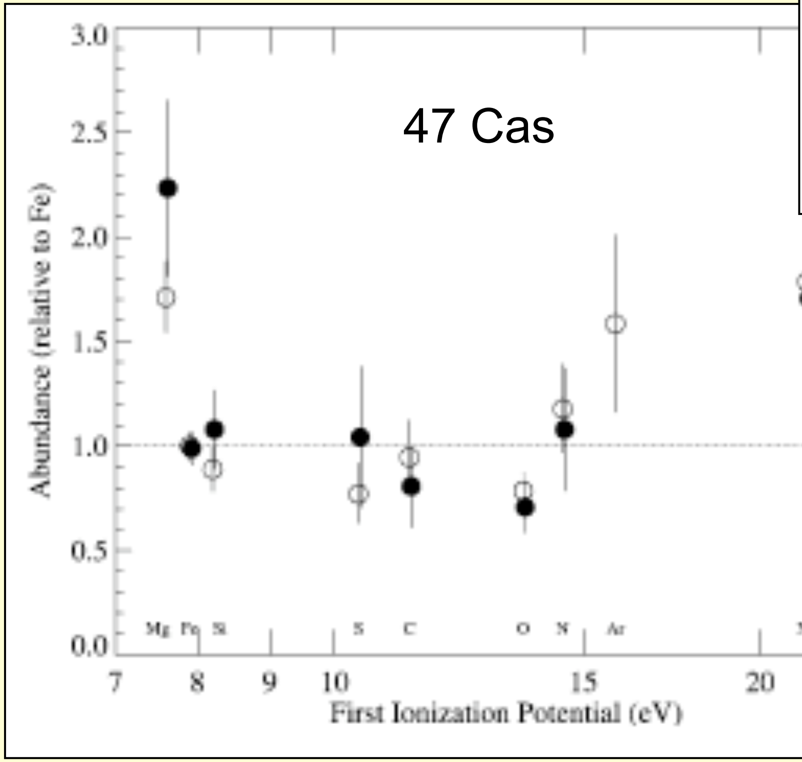
can show a FIP effect
or an inverse FIP effect

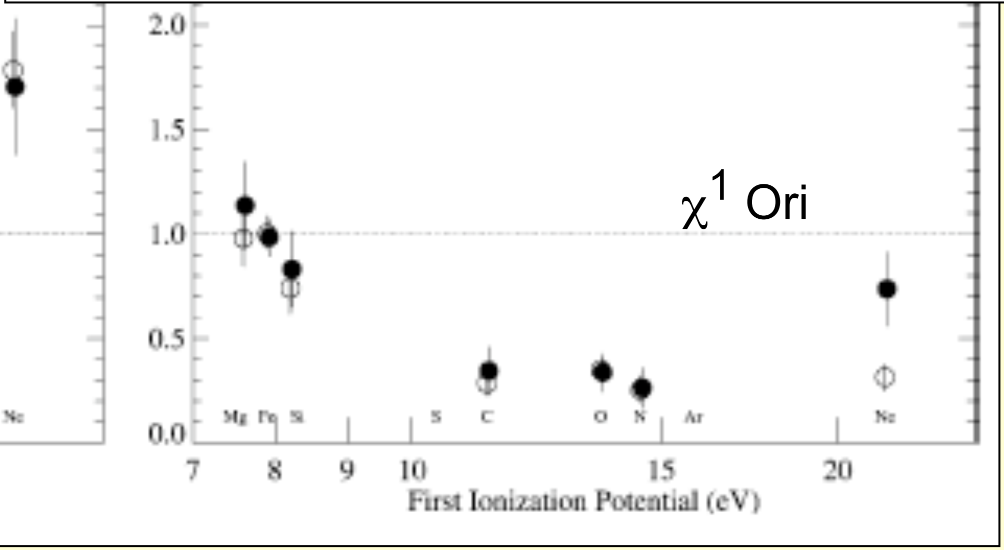
– nature of FIP effect still unclear

– relation of FIP / inverse FIP
to stellar parameters unclear



Brinkmann et al (2001)





Telleschi et al (2004)

Summary / lessons learnt

- stellar surface structures through Doppler imaging
- stellar coronae through less reliable techniques, e.g. eclipse mapping

- stellar corona are concentrated in small active regions (➡ filling factor?)
- are stellar coronae dominated by flares ?
- coronal activity related to rotation / age / dynamo action

- interpretation of stellar coronal spectra often difficult
  → lack of information on spatial structures (and temporal evolution)

- density and temperature diagnostics based on ill-posed inversion problems
  → how to constrain these inversions

- (forward) stellar coronal models can help to interpret stellar structures
  → can we reliably infer average temperatures, densities, abundances ?
  → what do these "average" quantities mean ?