Stellar coronae and the Sun

Hardi Peter
Kiepenheuer-Institut
für Sonnenphysik
Freiburg

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

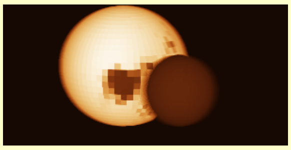
KIS

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

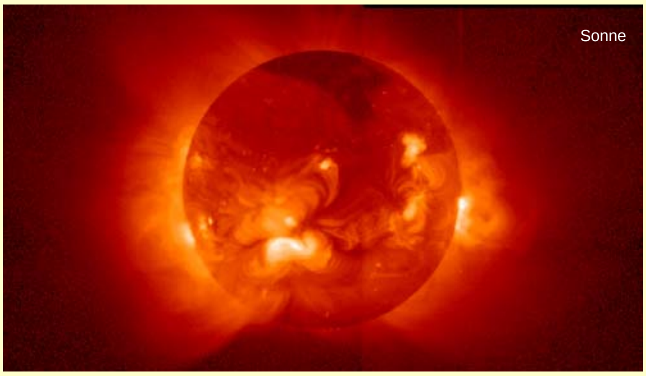
Tom Ayres (2004)

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

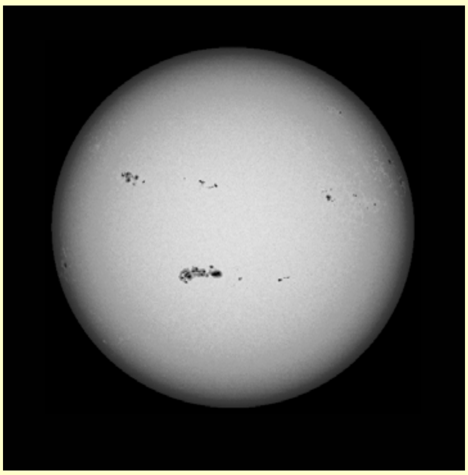


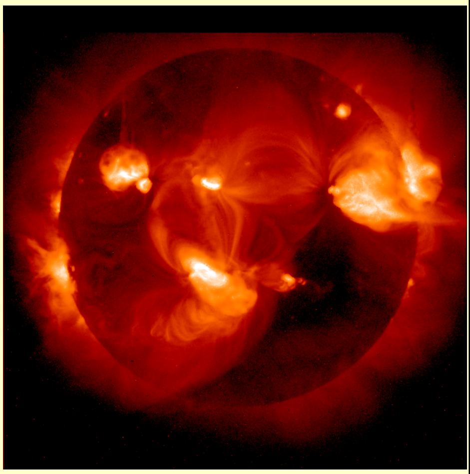
XY Ursa Major
(A. Collier Cameron)



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

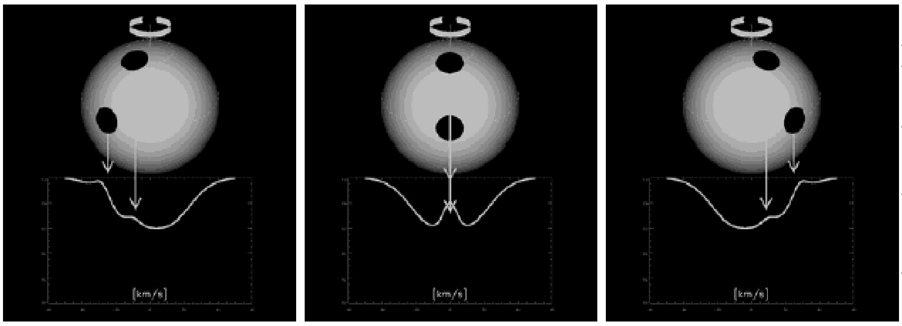
Comparing photosphere and corona: the Sun





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

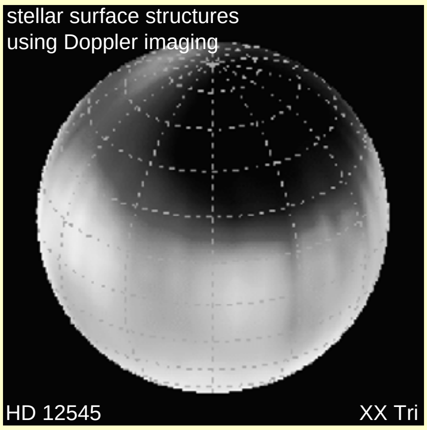
time series of spectra

⇩

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 ??

Stellar coronal observations in the radio

angular resolution of a telescope:

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

Very Long Baseline Interferometry“

D = diameter of Earth

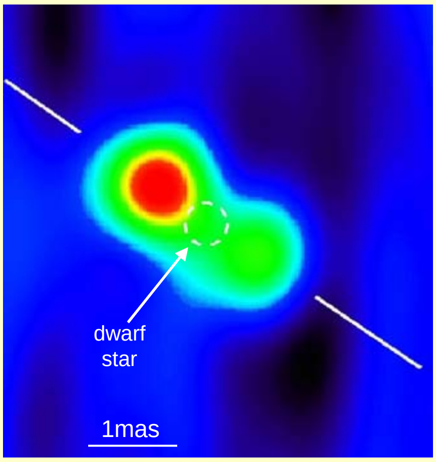
λ = 10 cm (typical radio)

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

radio corona:

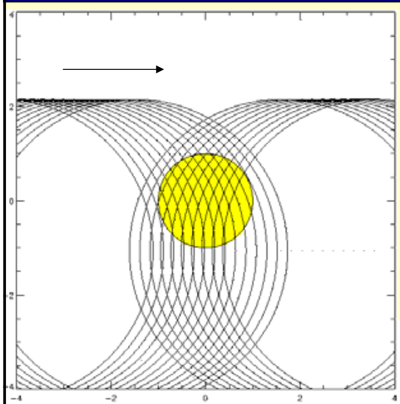
radio emission of electrons circling around magnetic field

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



UV Cet (Benz et al. 1998)

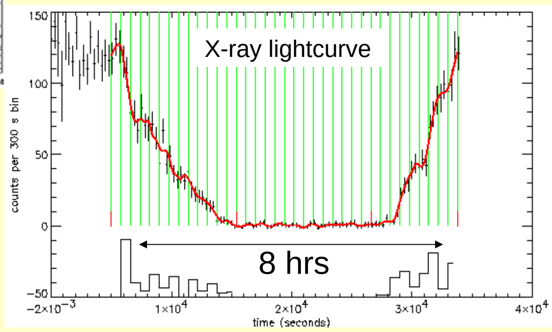
Surface structures of an X-ray corona

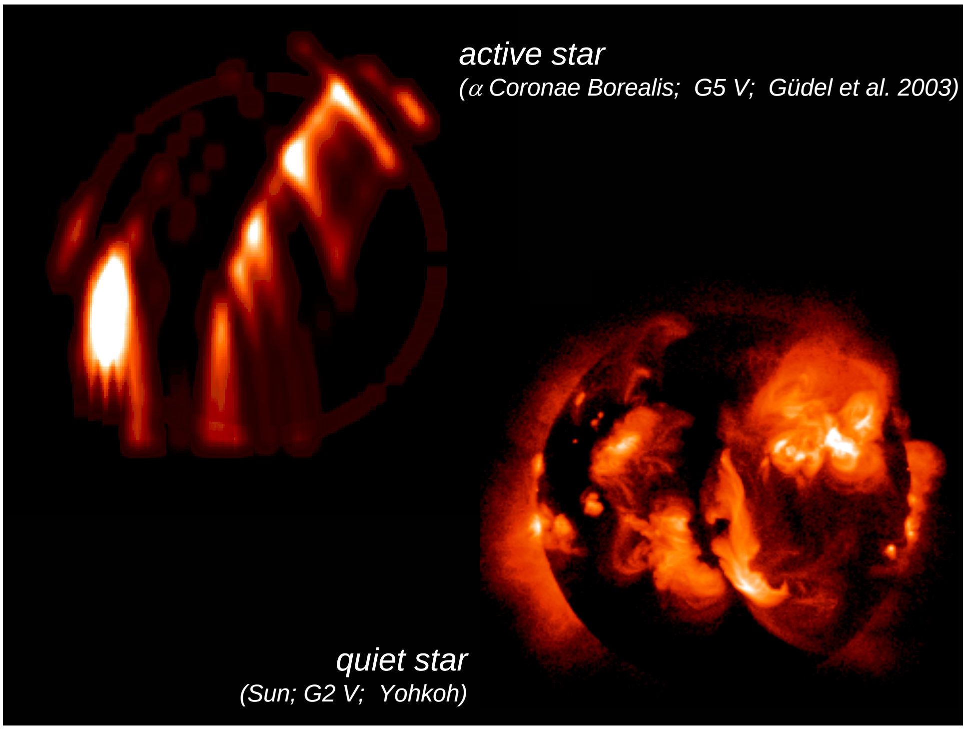


Güdel et al. (2003)
A&A 403, 155

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

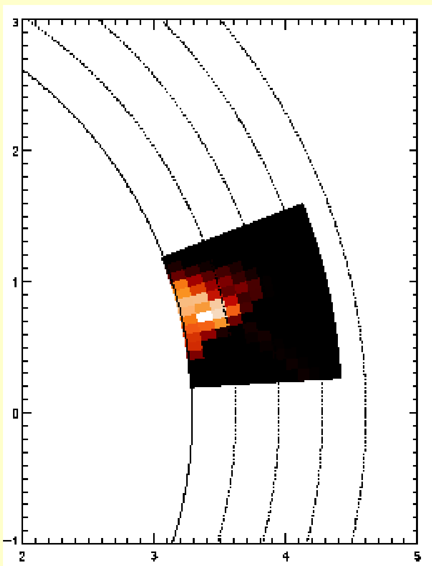




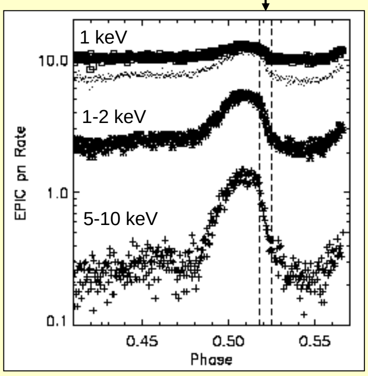
Flare on Algol B

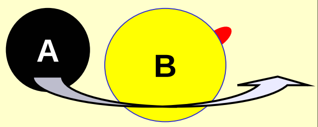
Eclipsing binary: Algol A (B8 V) X-ray dark
Algol B (K2 III) X-ray bright

Eclipse results in asymmetric light curve



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





XMM / Newton

What are the dominant structures in X-rays?

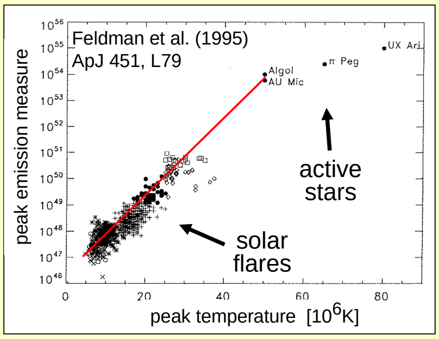
Where does the X-ray emission come from in active stars?

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

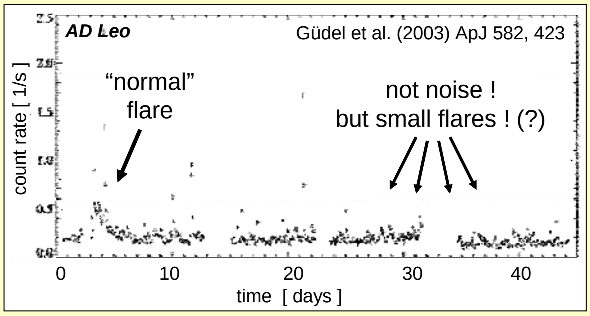
⇨ high densities
⇨ high temperatures



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."



Flares vs. background …

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

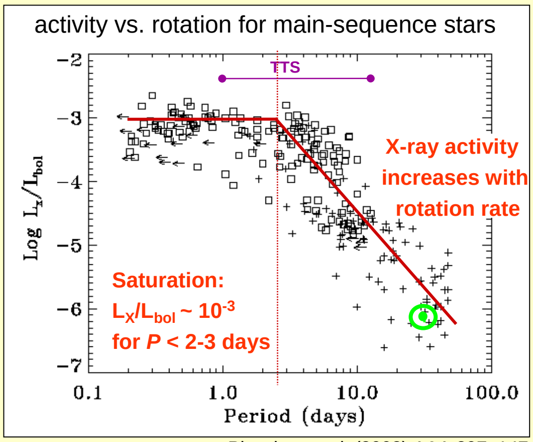
  >> scaled-up solar-like magnetic activity ?

- 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

- thinkable scenarios:



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

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!

Appearance of corona in a multi-loop simulation

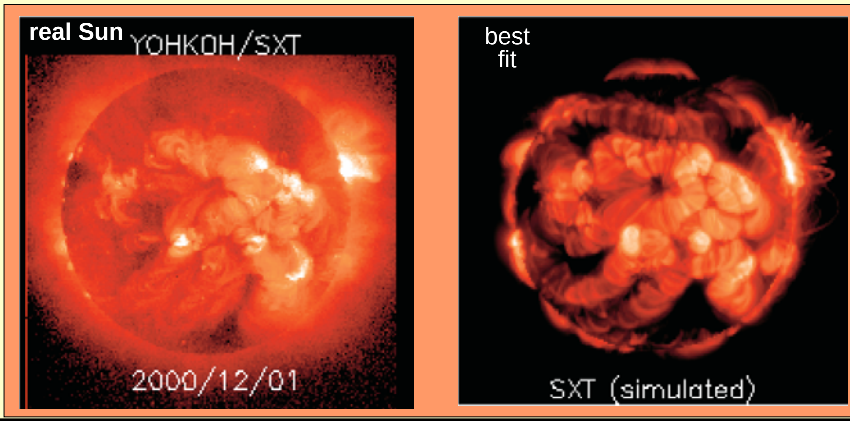
potential field extrapolation → simple 1D static loop models to many field lines

energy flux into loop: $F_H = \alpha \, B_{\mathrm{base}}^{\beta} \, L_{\mathrm{half}}^{\lambda} \, f(B_{\mathrm{base}})$

quenchning to account for sunspots being X-ray dark:

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

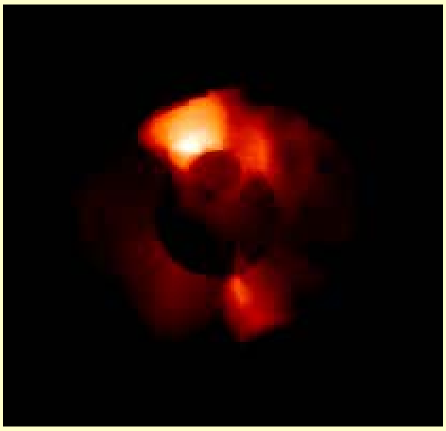
free parameters:	β	λ
[best fit values]	[1.0 ± 0.5]	[-0.7 ± 0.3]



Schrijver et al. (2004) ApJ 615, 512

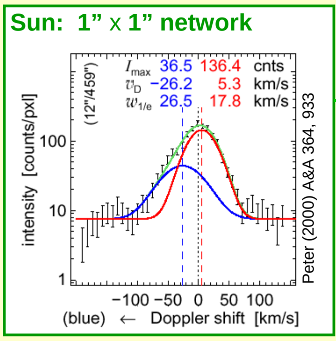
3D stellar corona: Doppler-Zeeman-Imaging

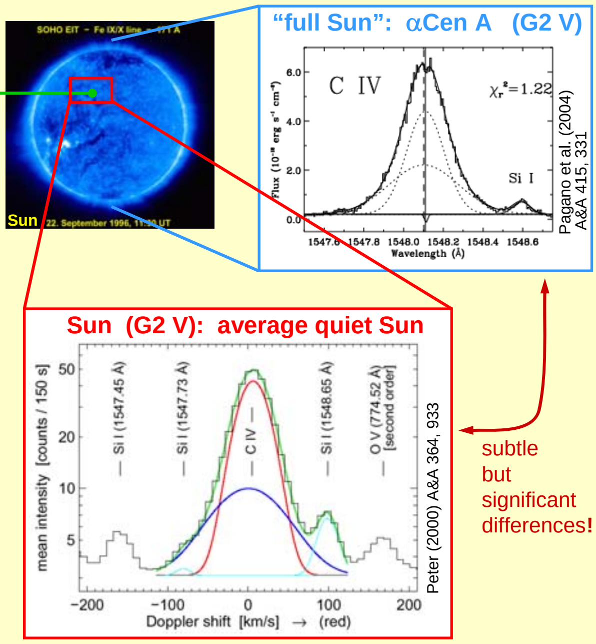
- **AB Doradus**
  cool active star (K2V)
  $T_{\mathrm{eff}} \approx$ 4000K
  half as luminous as our Sun (0.4 $L_{\odot}$)
  fats rotator (50 $\Omega_{\odot}$)
  distance ≈ 49 light years
  observations: 7.–12. 12. 1995
- structures on the surface in intensity and magnetic field using Zeeman-Doppler-imaging (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)

From the stars to the Sun: EUV profiles

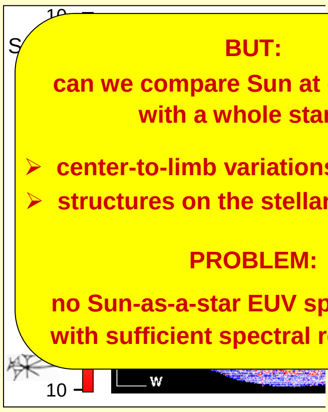




non–Gaussian line profiles:

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

Doppler shifts: spatially resolved vs. full disk

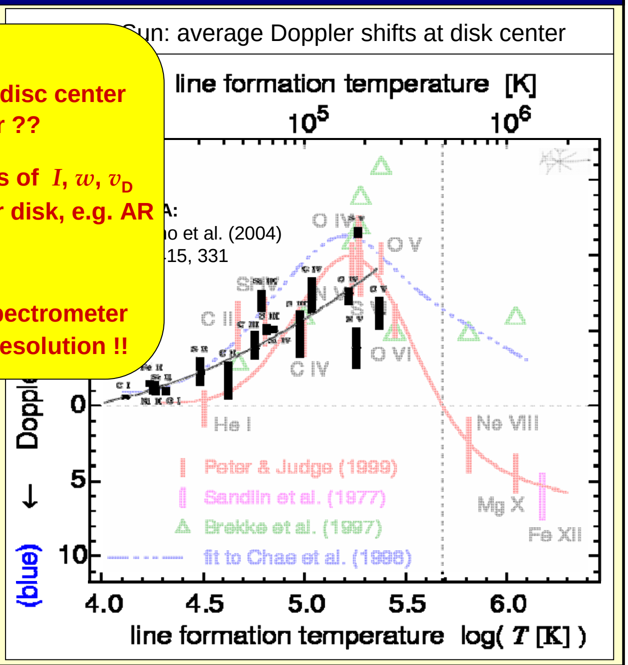


BUT:
can we compare Sun at disc center with a whole star ??

- **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 !!**

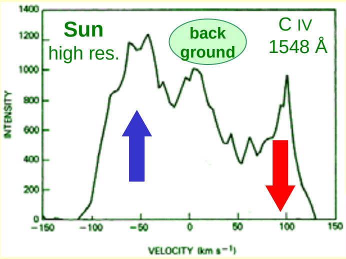
Signatures of small-scale activity?

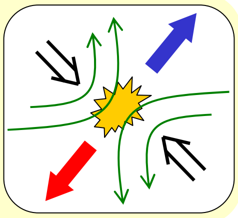
- spectra usually well described by double Gaussians !

  >> what is the nature of these two components?

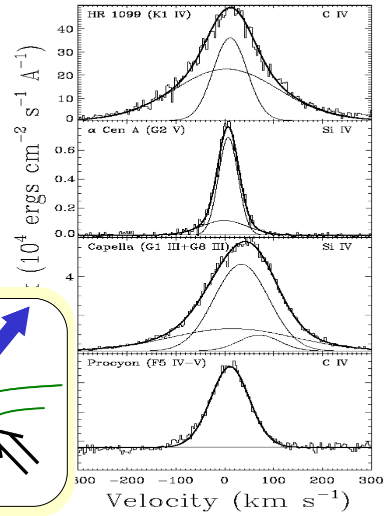
One possible interpretation:

- 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

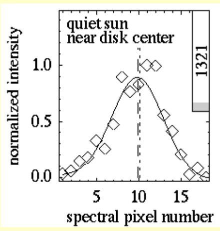
SUMER full disk scan: C IV (1548 Å)

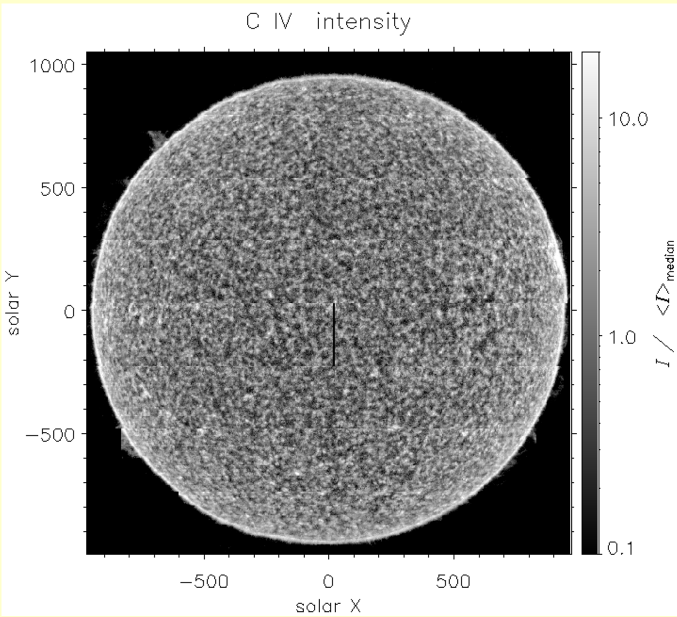
~ 10^6 spectra on the disk

construct a full disk spectrum from this raster

Problems:

- not a snapshot ~24 hours scan
- "stability" of the spectrograph





Thermal (in)stability of SUMER

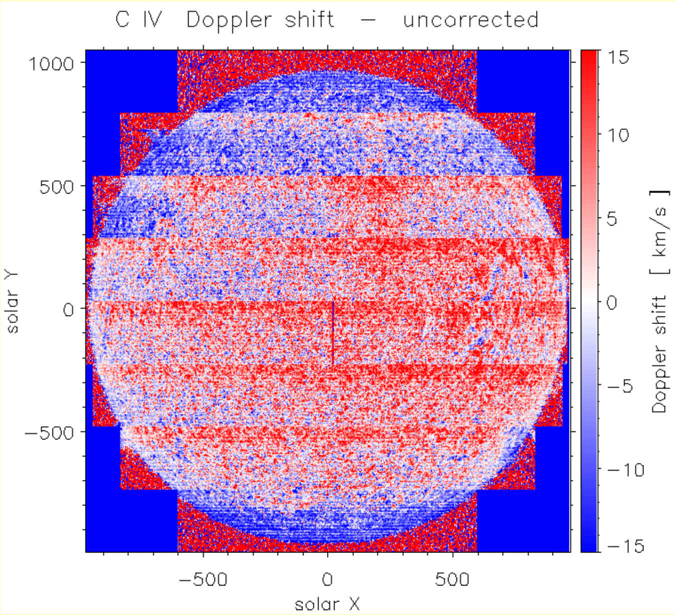
- the spectral line moves on the detector:

  quasi-periodic

  ±1 pixel (10 km/s)

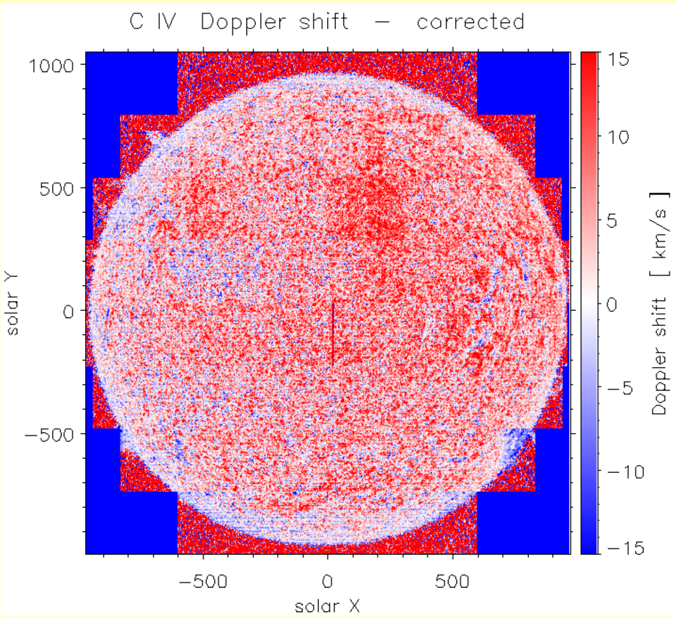
  (period ~2 hours)

- wavelength accuracy limited by thermal stability



Constructing the full disk spectrum

- do a Gaussian fit to each spectrum
- correct Doppler shifts for quasi-periodic variation
- use intensity, width and corrected shift to calculate "corrected spectra"
- sum these spectra to get sun-as-star spectrum

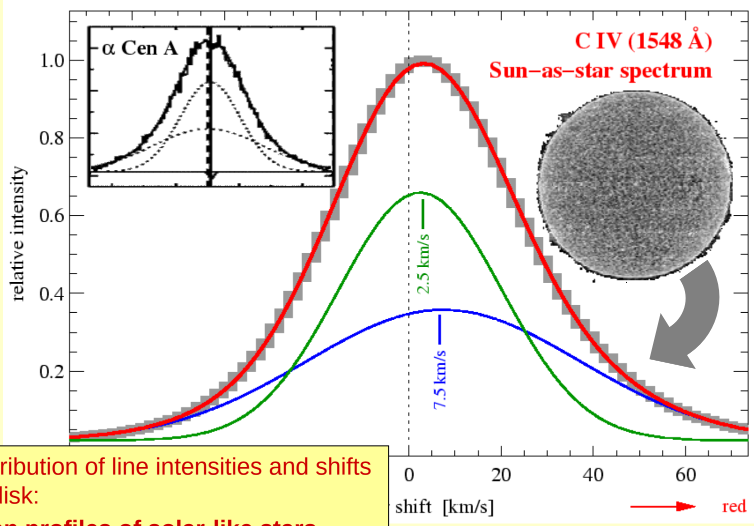


First EUV Sun-as-a-star spectrum

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 in press

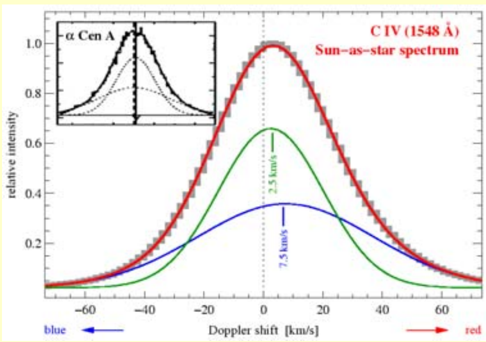
modeling distribution of line intensities and shifts on the solar disk:
non-Gaussian profiles of solar-like stars are due to distribution of surface structures
and not signature of heating process

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

Comparing the Sun to αCen A

What do we learn from the full-Sun spectrum?

- broad component:
  signature of cell-network structure
  [few information on heating process]
- narrow component:
  shift indicative for magnetic flux
  in chromospheric network
  vis. magnetic activity



Consequences for Sun vs. αCen A:

- Sun and αCen have similar structure of super-granulation / chromospheric network
- αCen A has much higher redshift
  - ➡ is there more energy density in the super-granulation ?
    αCen A has ~25% lower surface gravity (Morel et al. 2000, A&A 363, 675)
  - ➡ is αCen A much more active than quiet Sun?
    However: no EUV cycle on αCen A on time scale comparable to Sun
    (Ayres et al 1995, ApJS 96 223)
    - ➡ **less active regions on αCen A but a stronger network?**

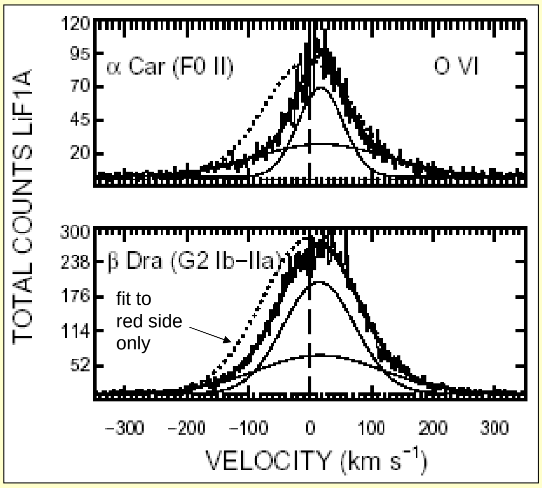
Luminous cool giants: wind detection ?

- 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)

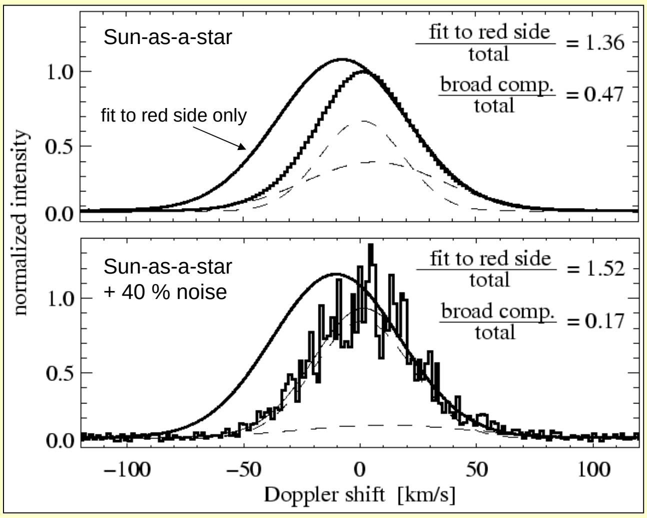
- single Gaussian fit only to red part of the spectrum
  >> excess absorption in blue wing:
  mass outflow ?
  ➡ **does it work physically ?**
  ➡ **is it unique ?**



Dupree et al. (2005) ApJ 622, 629

The Sun "seen as a cool giant"

- "*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

Inferring the structure of stellar coronae

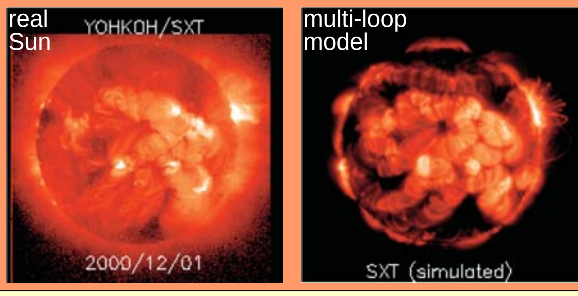
Multi-loop model:

construct the corona as a superposition of many loops

currently: static loops e.g.:

– 0D (constant *T*,*p*)
– constant *p*
– 1D static approximation

appearance of corona in a multi-loop simulation



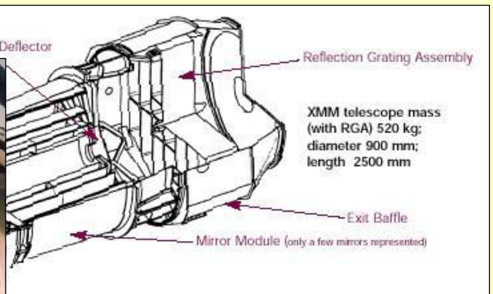
Schrijver et al. (2004) ApJ 615, 512

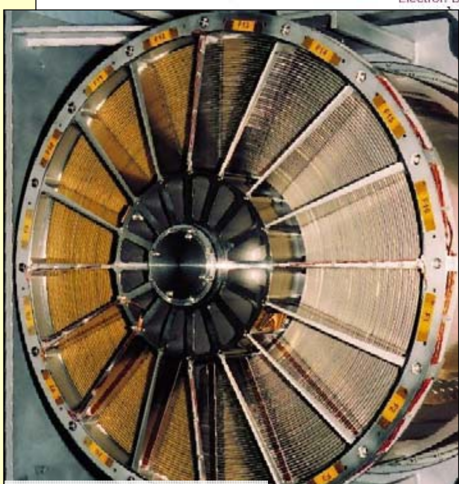
Example: use 1D models with different heating functions $E_H \sim B^{\alpha}$ ➡ α

Different approach – spectroscopy:

- use stellar spectra and derive average coronal properties through an inversion
  ➡ *T*, *p*, *L* (e.g. Ness et al. 2004,……)
- how reliable are such inversions ?
- what is the inferred "average" property ?

XMM / Newton X-ray observatory



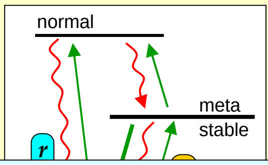


XMM 58 mirror module

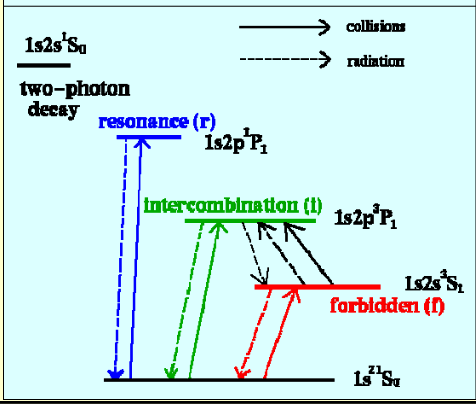
XMM-NEWTON esa

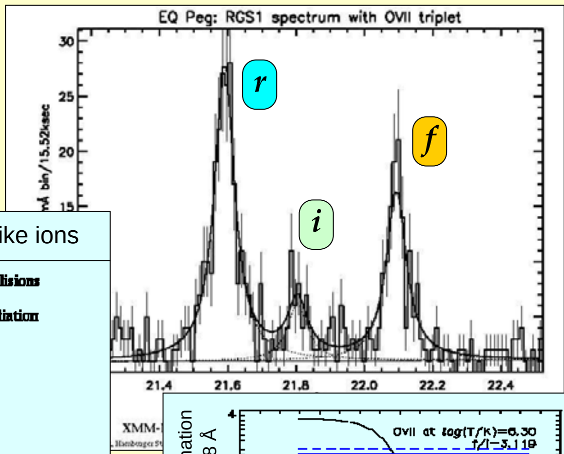
X-ray density diagnostics: He-like ions

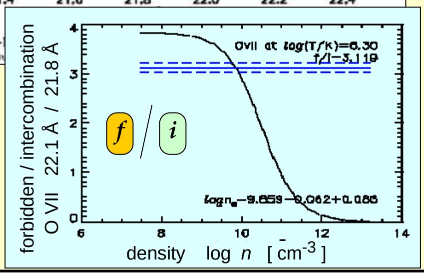
principle: a simple 3 level atom



a more complicated case: He-like ions







Differential emission measure – DEM

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

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

excitation — ionization equilibrium — abundance — ≈ 0.8 for full ionization

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

$$DEM = n_e^2 \left(\frac{dT}{dh}\right)^{-1}$$

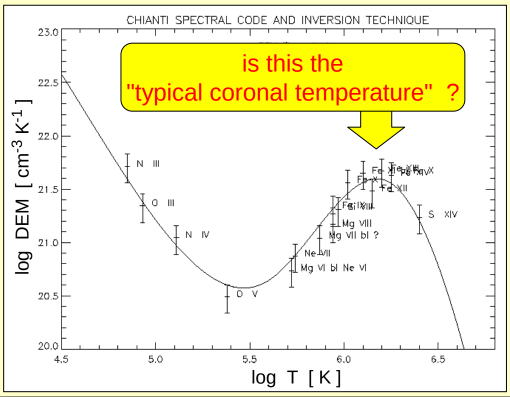
$$F = \int G(T,\cancel{n_e})\; DEM\; dT$$

- $G(T)$: atomic physics
- DEM: thermodynamics (n,T)
  - ➡ same for all lines!!

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

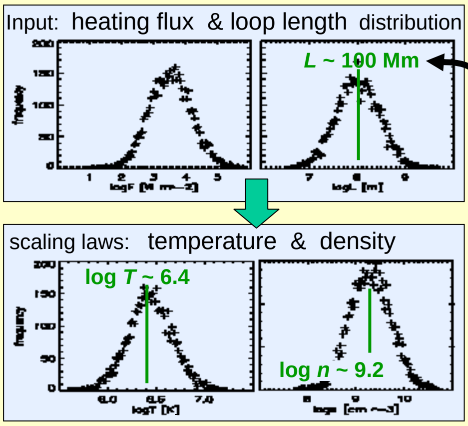
➡ density-temperature structure $DEM(T)$

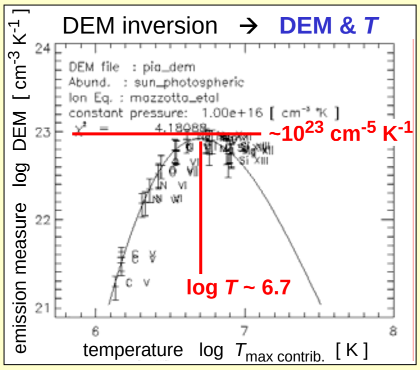
iterative procedure; ill-posed problem

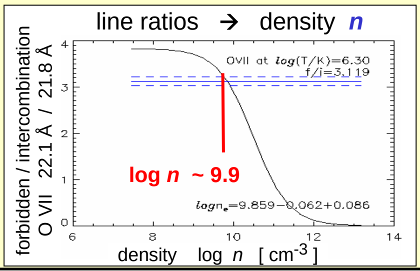


Testing stellar inversions: coronal scale height

Zacharias, Peter & Ness (in progress)







$$EM_V = \int n^2\, dV = A_\star \int n^2 \frac{dh}{dT} dT = DEM\ A_\star\ T_{max}$$

emitting volume $V = EM_V / n^2$

scale height $\mathbf{L = V / A_\star = DEM\ T_{max} / n^2 \approx 80\ Mm}$

"Forward inversions": results & future

An inversion

- overestimates the "typical" temperature
- overestimates the "typical" density
- gets right order of coronal extension (!)

To be done:

- model multi-loop coronae with more realistic static loops:
  T(s), p(s) given through analytical approximations (Aschwanden & Schrijver 2002, ApJS)
- test static loops using dynamically evolving loops
  ➡ compare analytic approximation to up-to-date loop models e.g. with E_H~sin(ωt)
- do analytical multi-loop model for a full 3D MHD coronal model
  ➡ **is the multi-loop approach meaningful?**

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 ?

- stellar EUV emission line profiles are *not* symmetric
  (probably also in X-rays, but there we do not have the sufficient resolution…)

- are asymmetries due to
  - heating process itself ?
  - small scale transient events: nano-/micro-/etc flares ?
  - absorption effects due to wind ?
  - stellar surface structures ?

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