X-ray Observations of Stars

Rachel Osten

University of Maryland,

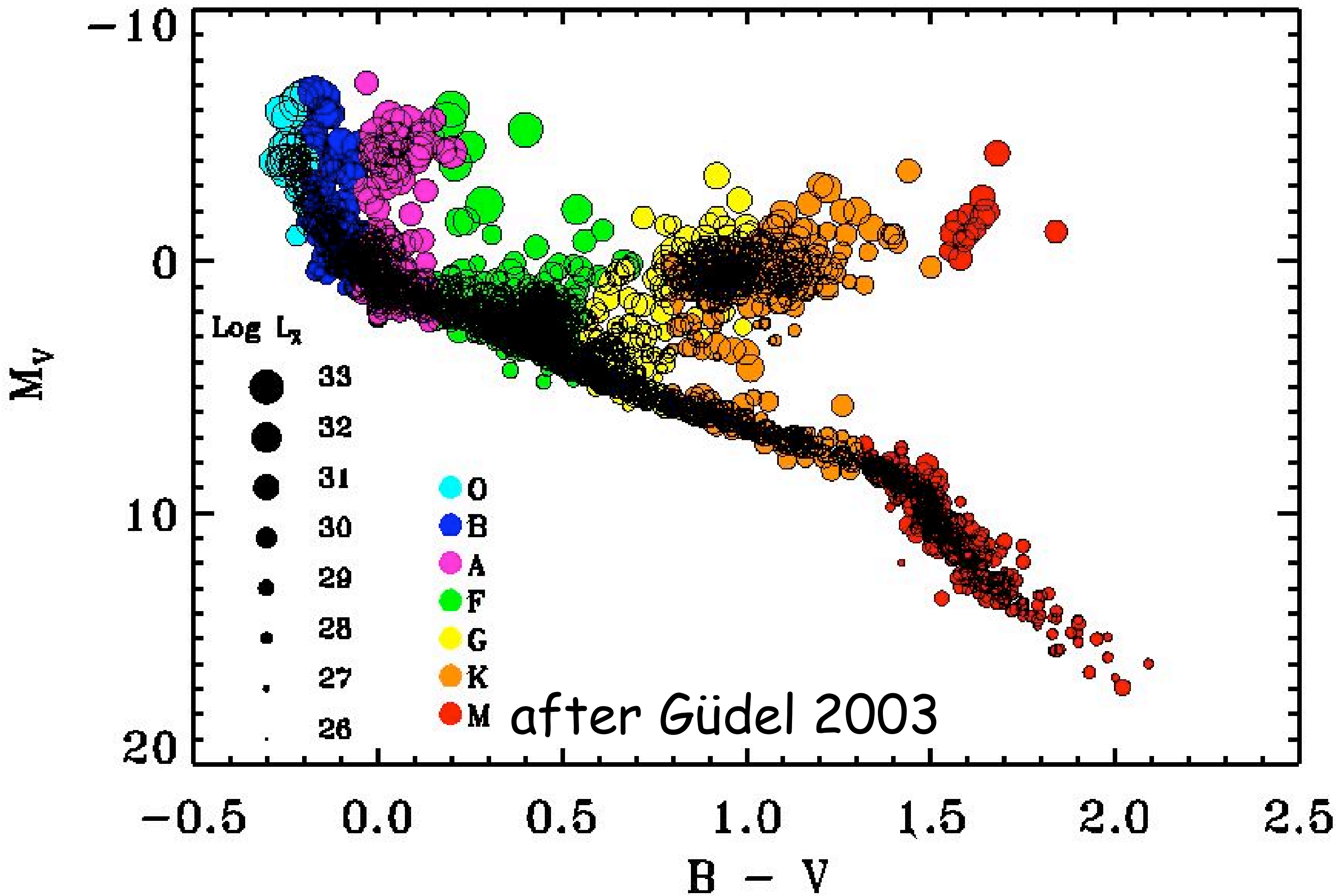
NASA/GSFC

(The highest spatial resolution X-ray observation of a star!)

Outline

- X-ray HR diagram
- The 3 R's
- Hot stars: science topics
- Cool stars: science topics

X-ray HR diagram



Resolution, resolution, resolution

Spectral

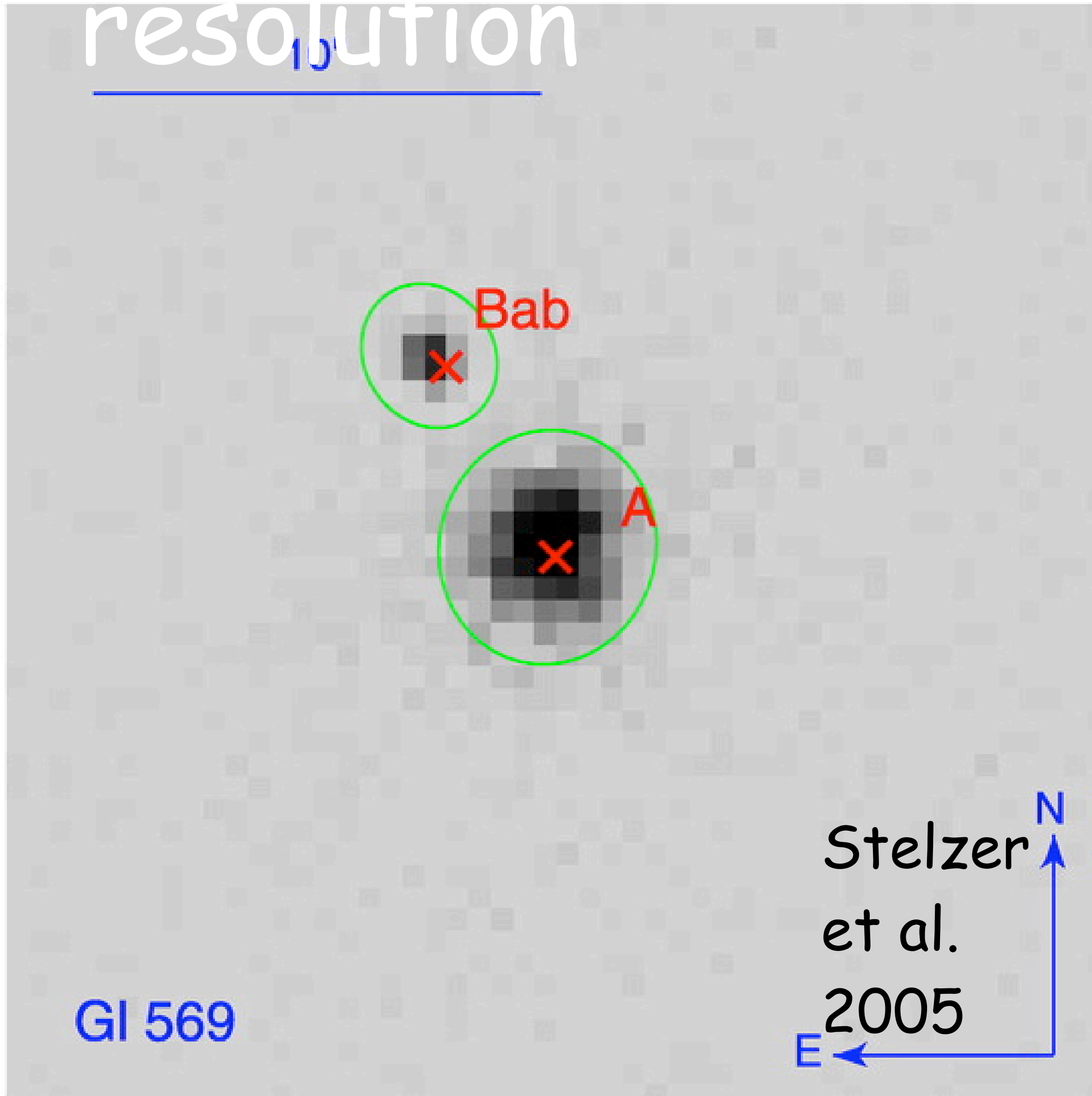
Spatial

Time

Resolution, resolution, resolution

ACIS image of Gl569, resolving the brown dwarf binary (Bab) from the M star primary

Spatial

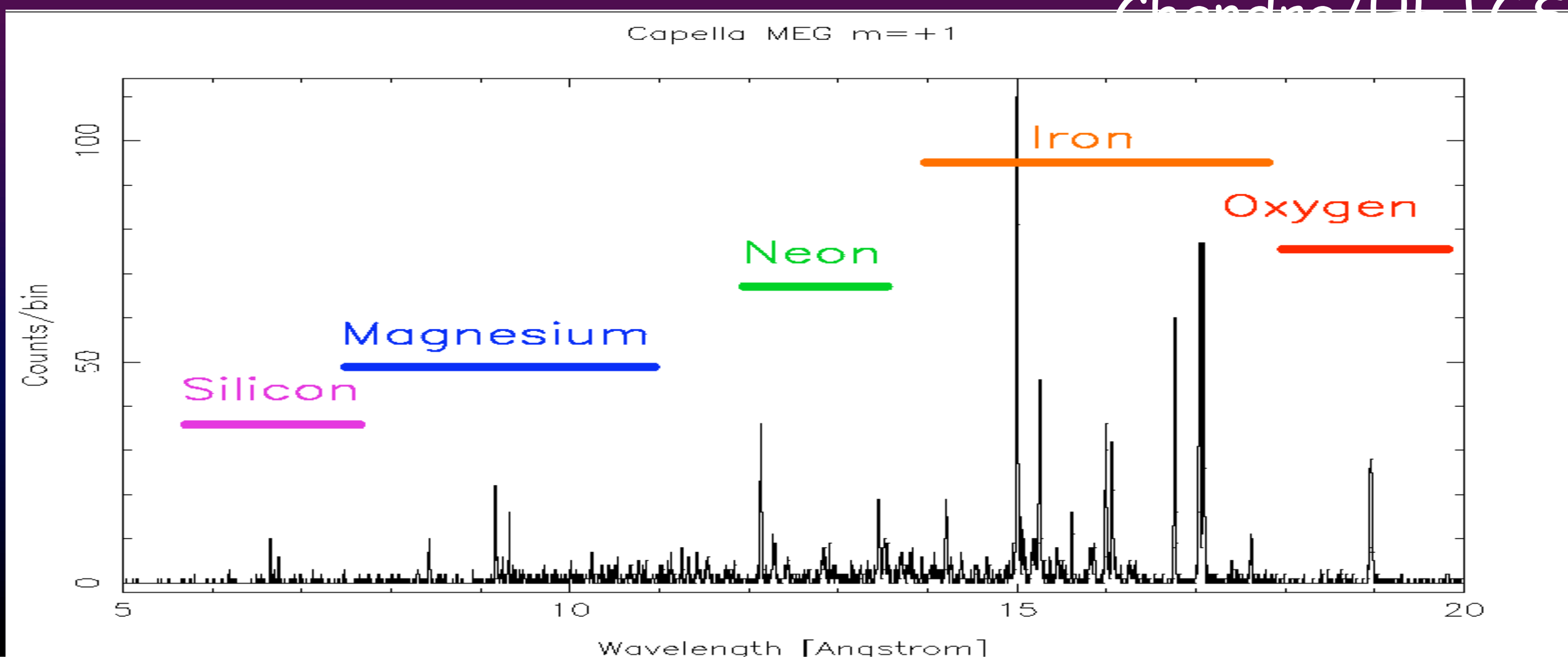


Stelzer et al. 2005

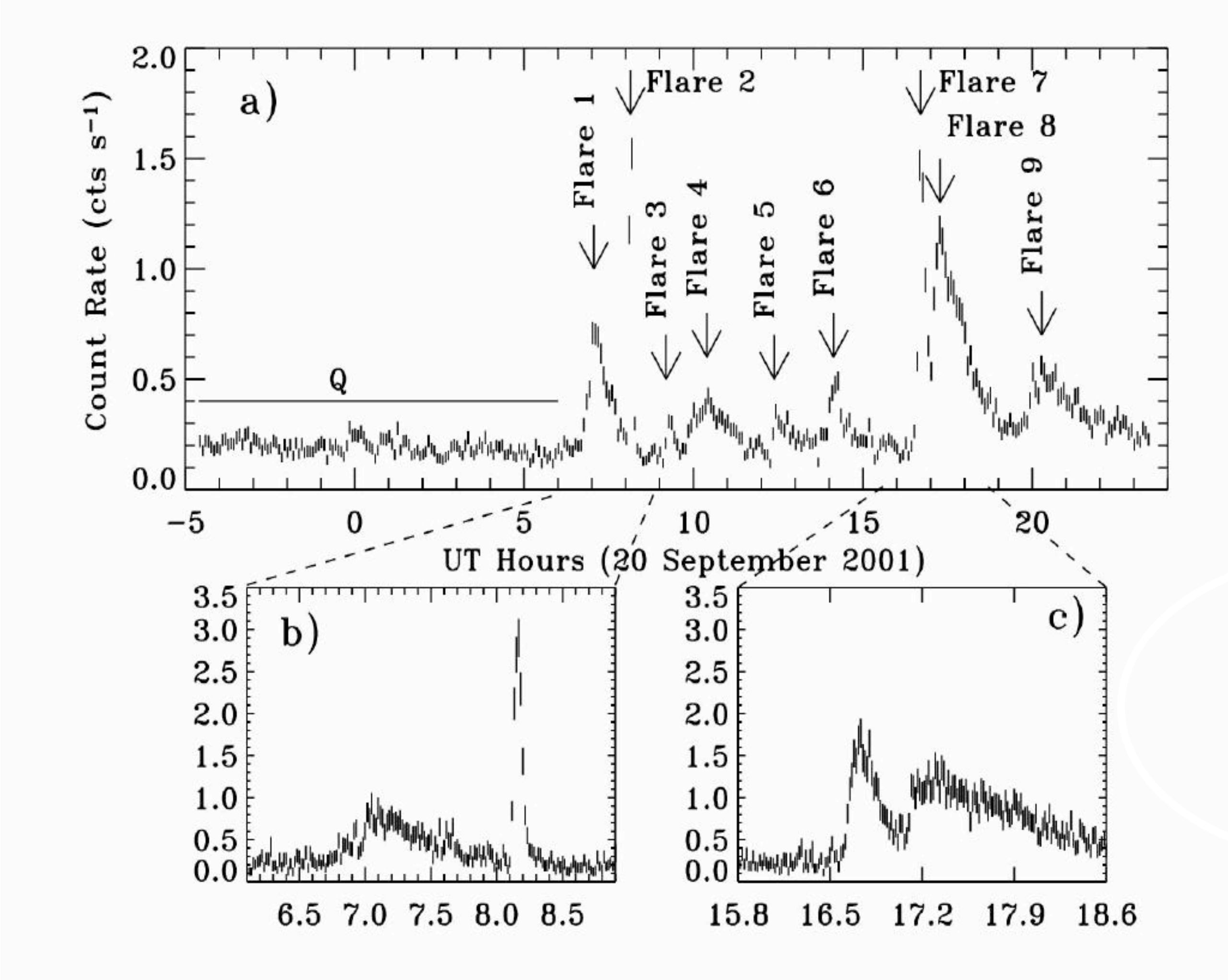
Resolution, resolution, resolution

Spectral

First light spectrum of Capella with Chandra/HETGS



Resolution, resolution, resolution



Chandra/HETGS light curve of flaring activity in the M dwarf EV Lac (Osten et al. 2005)

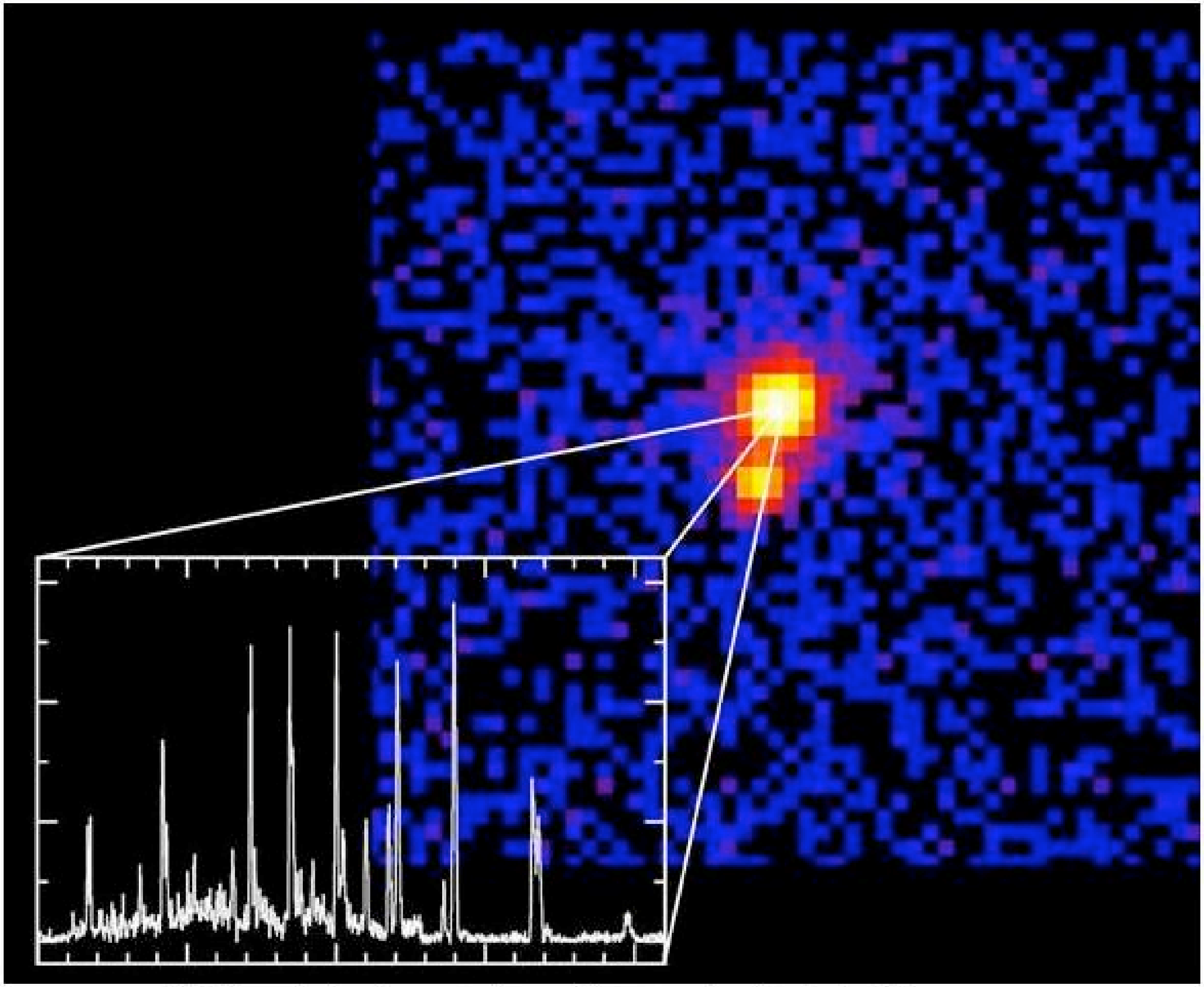
Time

Massive Stars (>10M_{sun}) & X-ray Emission

- Radiative envelopes, no convection to surface (unlike solar-type stars)
- Hence, no dynamo generation of magnetic activity => no X-ray emission?
- Actually, no. . .

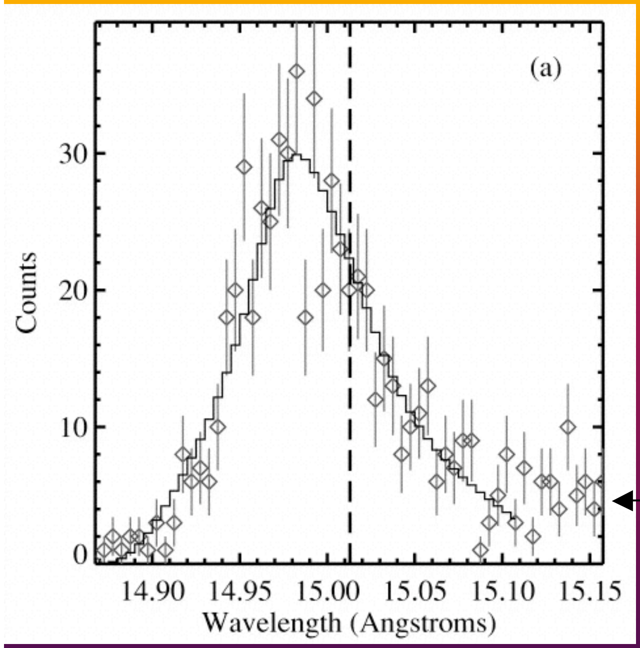
X-ray Spectrum of Zeta Ori (Cassinelli 2000)

Outflowing stellar winds convert a portion of their energy into X-ray emission through shocks

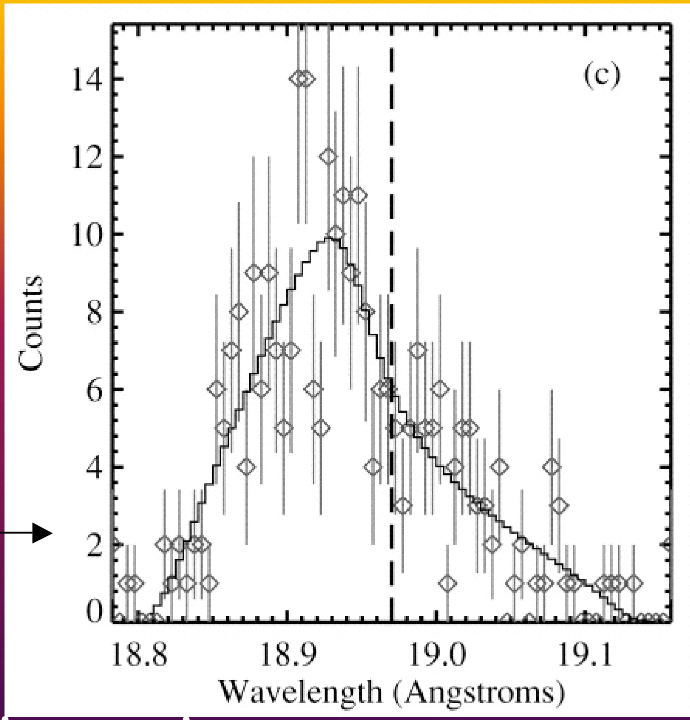


HETG emission line spectrum of the massive star Zeta Ori

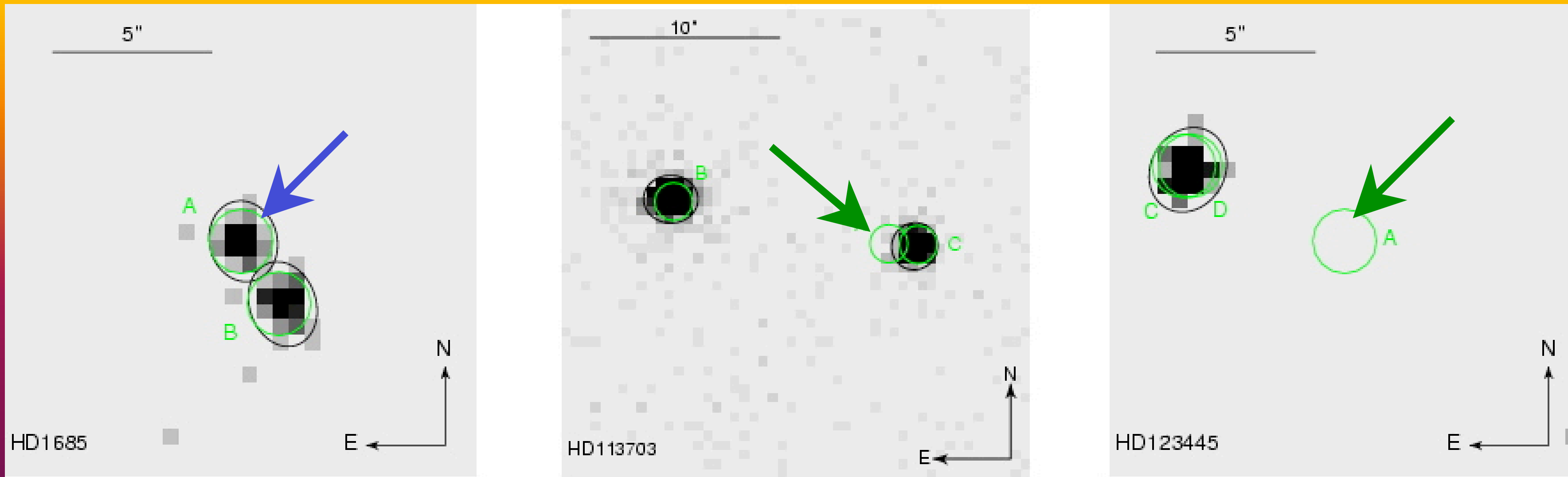
Wind Structure

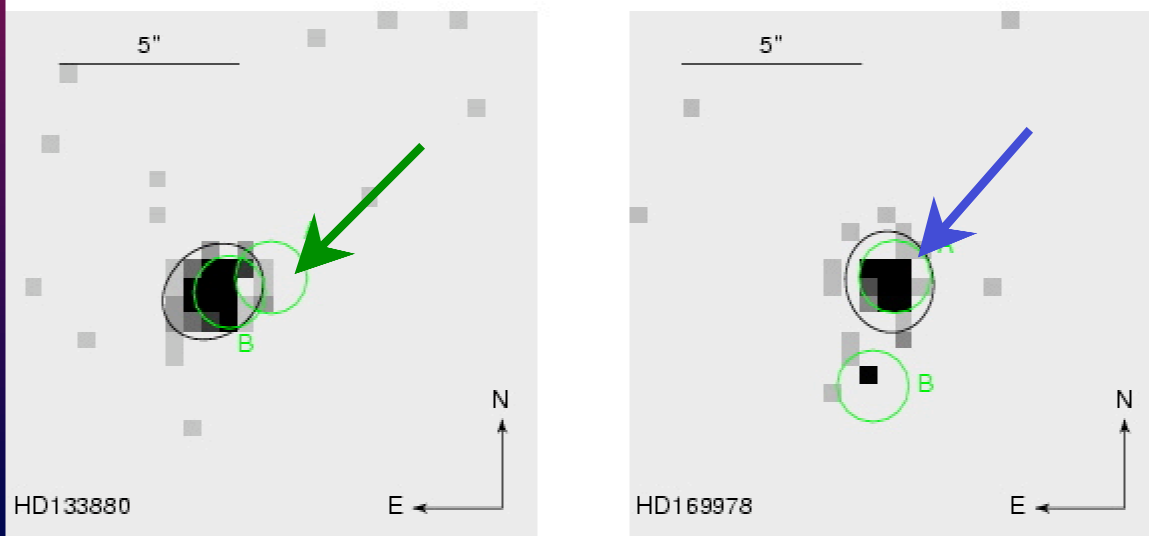


O supergiant Zeta Puppis; Kramer et al. 2003



- Lines are broader than spectral resolution, blueshifted
- Modelling line profiles gives understanding of wind structure & dynamics: clumpy? Mass-loss too high?
- Find hidden binaries via wind-wind collisions
- X-ray emission can have significant influence on CS environment of young stars through photoionization





B stars possess neither strong stellar winds nor significant surface magnetic fields, so should not be able to produce X-ray emission

Stelzer et al. 2003

Companion hypothesis works for a fraction of these objects. . .does it work for all of them?

Cool stars: big issues

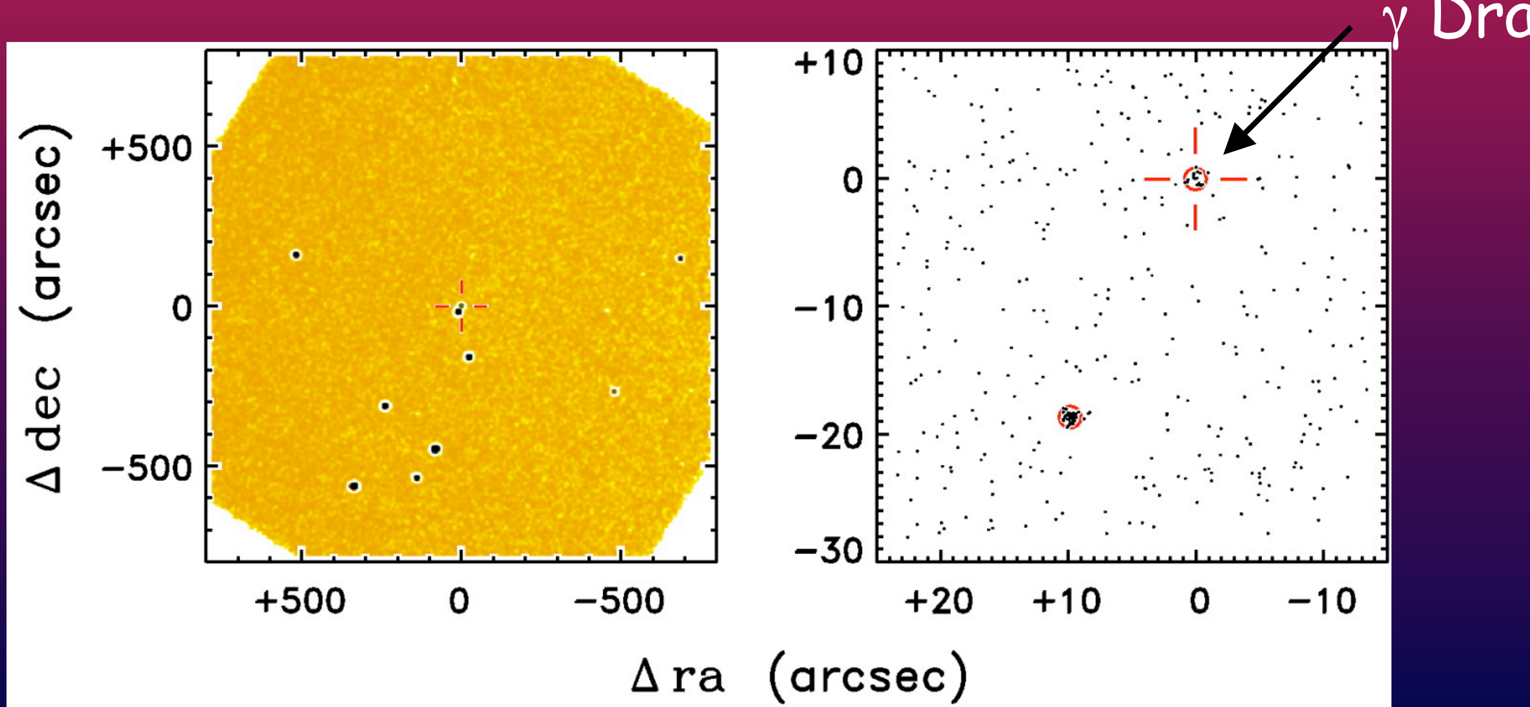
- Ultimate source of stellar coronal heating unknown; related to dynamo generation of magnetic fields
- Study manifestations of magnetic activity in stars w/different parameters (age, surface temperature, rotation, magnetic field topologies), determine how coronal heating observables change
- Compare with our closest star, the Sun

Cool stars: big issues

- Stars as light bulbs: Spatially identifying source of X-ray emission
- Stars as stars: Spectral diagnostics of dynamic, magnetically heated plasma
  - Temps/Differential Emission Measure
  - Coronal Abundances
  - Electron densities
  - Other diagnostics (Fe 6.4 keV, velocities, NT HXR emission)
  - Changes of these quantities

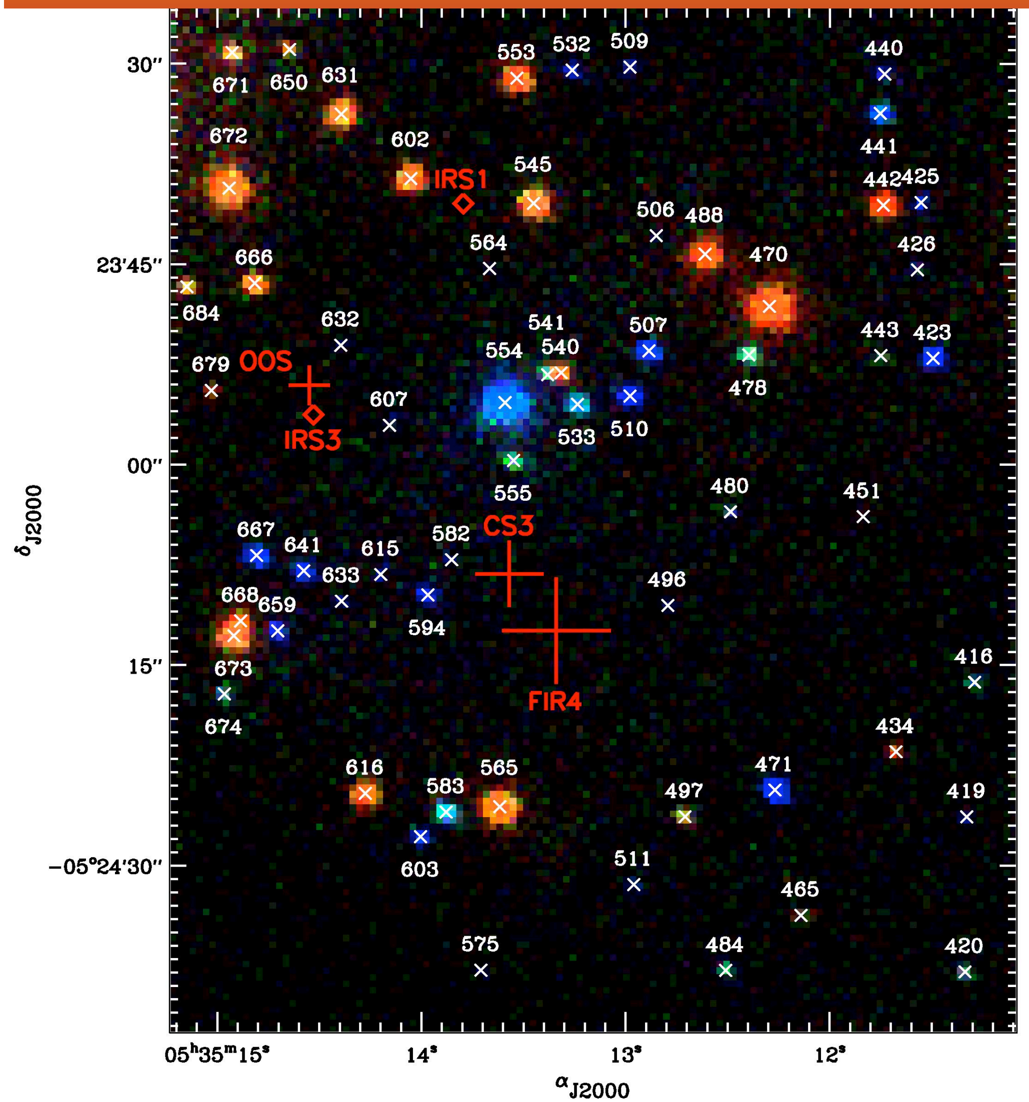
Spatially identifying source of X-ray emission

Hybrid giants & source of X-ray emission



Ayres et al. (2006): γ Dra, a windy hybrid coronal giant, has an X-ray brighter companion 21″ away (explaining some of the ROSAT flux), but has a feeble corona itself

Orion Nebula: Orion Molecular Core 1

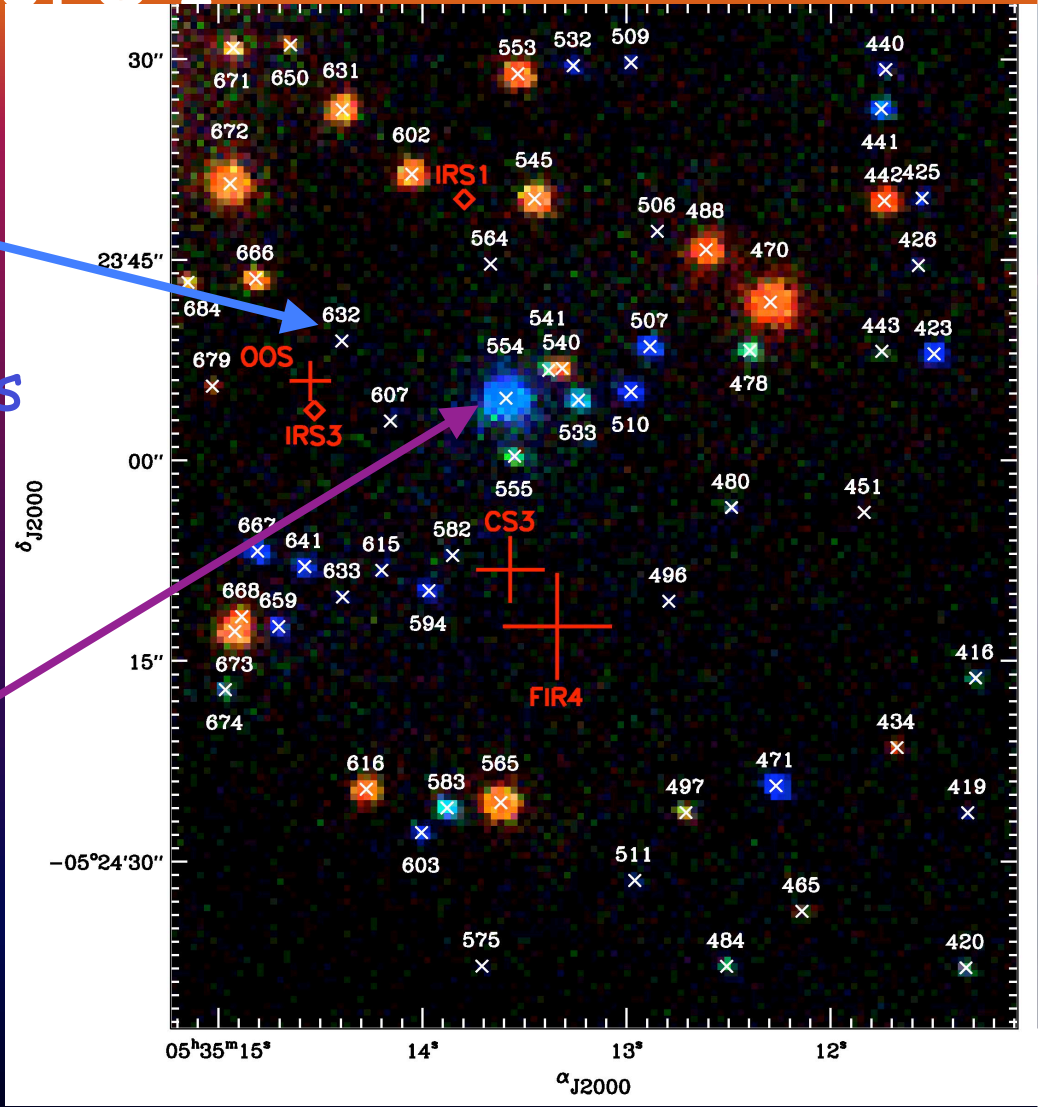


COUP; Feigelson et al. 2005

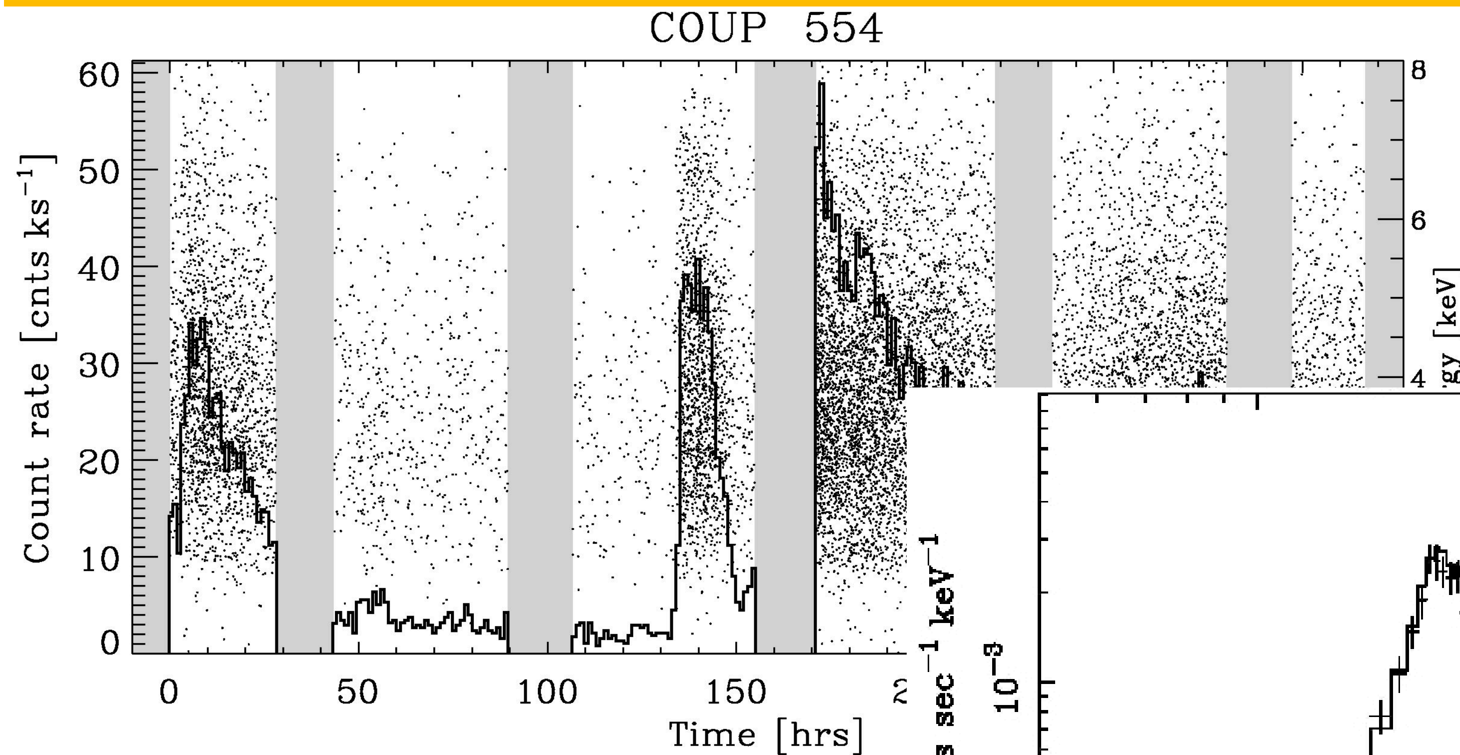
McCaughrean 2005

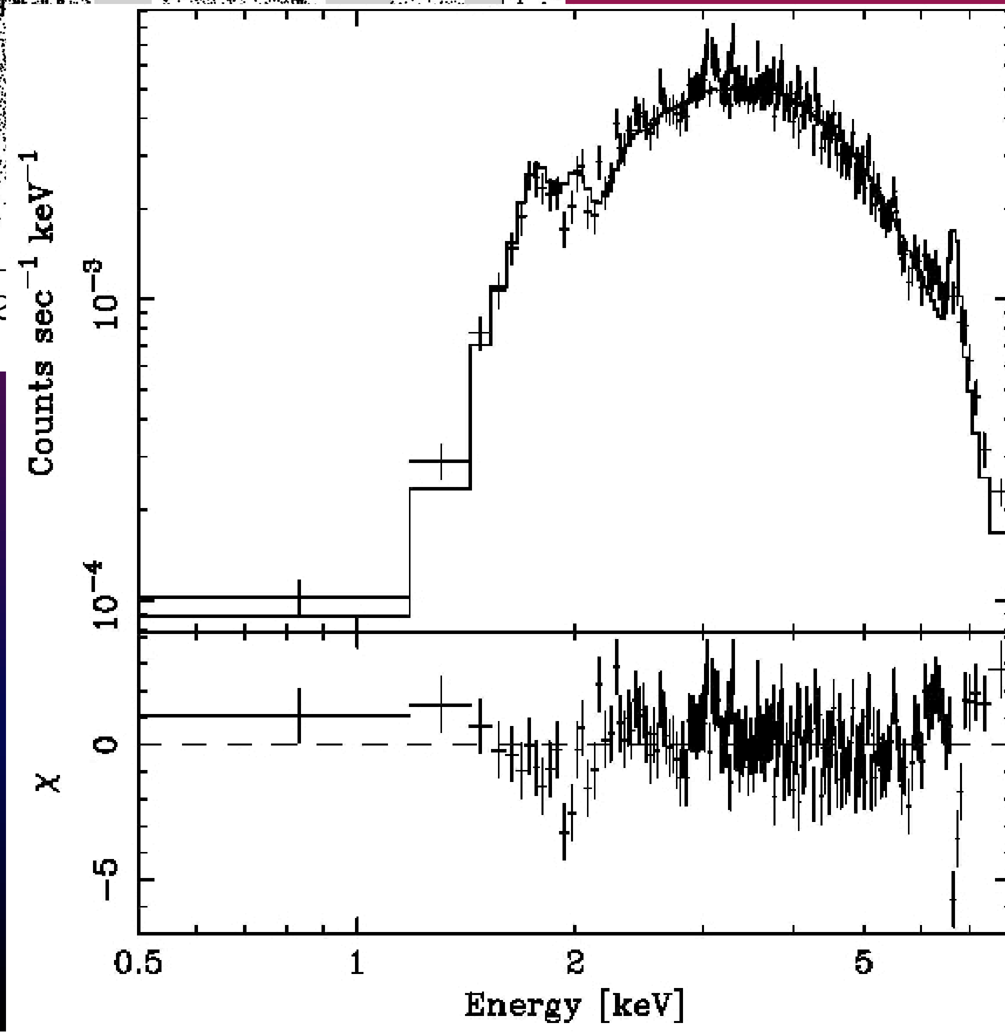
Orion Nebula: Orion Molecular Core 1

X-ray observations allow detection of young stars through large amounts of visual extinction (500 mags to star indicated in blue!)



Characteristics of coronal plasma in young stars: how to get from there (t~1 MY) to the Sun (5GY), effect on stellar environment





Spectral parameters:

T_{cor},

N_H

VEM

Related quantities:

L=size of coronal loops

Differential Emission Measure

Equation for plasma in coronal equilibrium (flux of one line): *j*-th level of the *m*-th ionization state of element

$$F_\lambda = \frac{1}{4\pi d^2}\int n_j A_{ji} dV \quad (\mathrm{photons\ \ cm^{-2}\ \ s^{-1}})$$

N_j=pop'n of *j*-th level of ion, A_{ji}=spont. emission prob. from level *j* to level *i*

$$n_j = \frac{n_J(X^{+m})}{n(X^{+m})}\frac{n(X^{+m})}{n(X)}\frac{n(X)}{n(H)}\frac{n(H)}{n_e}\, n_e$$

Re-write n_j as product of ratios

Level pop'n

Ion. fraction

Abundance

=0.83 in fully ionized plasma

$$F_\lambda = \frac{1}{4\pi d^2}\int \frac{n_J(X^{+m})}{n(X^{+m})}\frac{n(X^{+m})}{n(X)}\frac{n(X)}{n(H)}\frac{n(H)}{n_e}\frac{A_{ji}}{n_e}\, n_e^2 dV$$

Rewrite as

$$= \frac{1}{4\pi d^2}\int A_X P_\lambda(T) n_e^2\ dV$$

With A_X = abundance, $P_l(T)$ ="contribution function" or "emissivity" (but check definition; it can vary)

Differential Emission Measure

So, with the previous equation and a new definition,

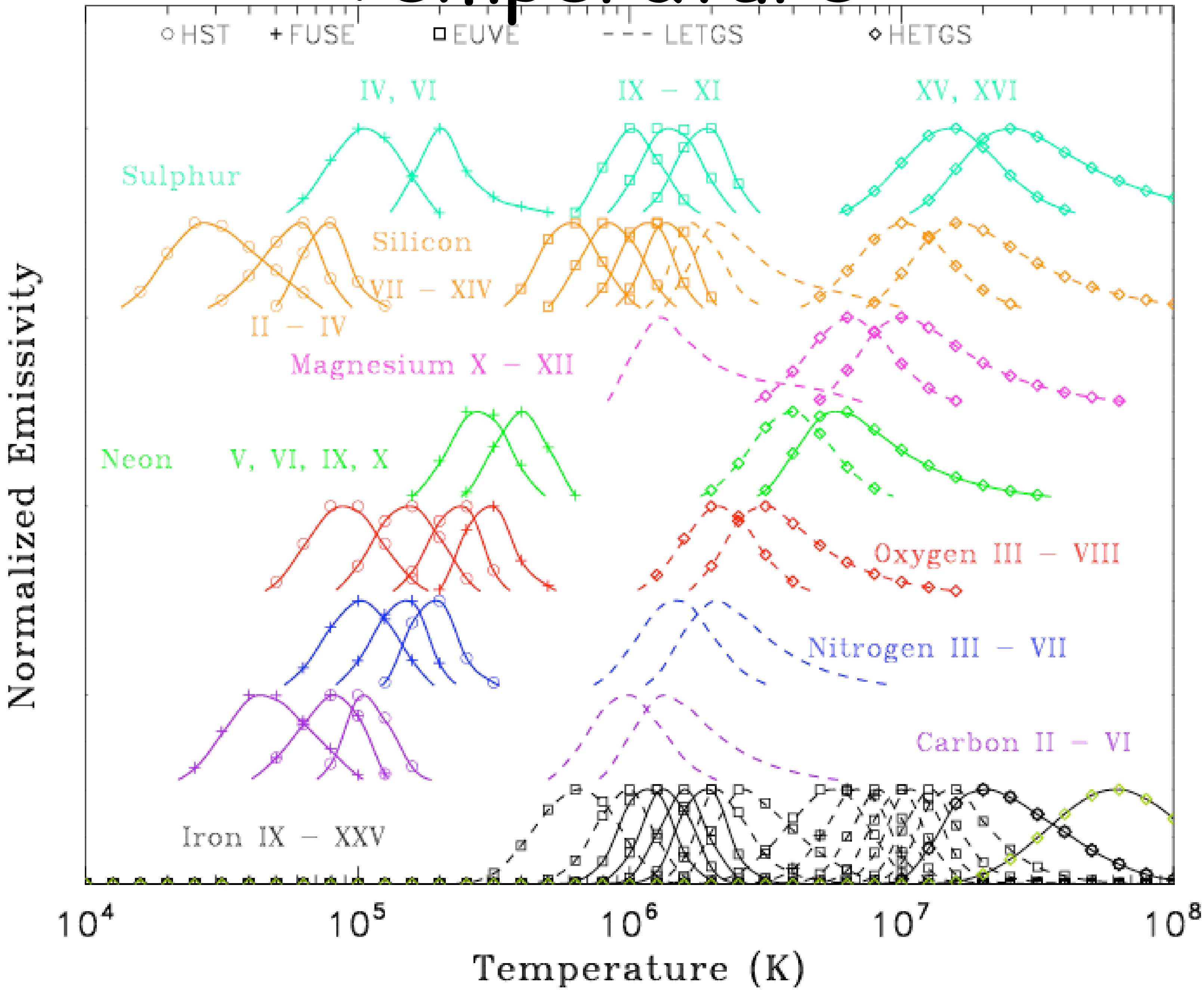
we get $$\phi(T) = \frac{n_e^2\, dV}{d\log T}$$

$$F_\lambda = \frac{1}{4\pi d^2} \int P_\lambda(T) A_X \phi(T) d\log T$$

Where f(T) is the *emission measure differential in temperature*, or differential emission measure (DEM), basically, **the amount of plasma at a given temperature**. Why is this important? The shape of the DEM can be used to infer coronal structure and test (some) coronal heating models.

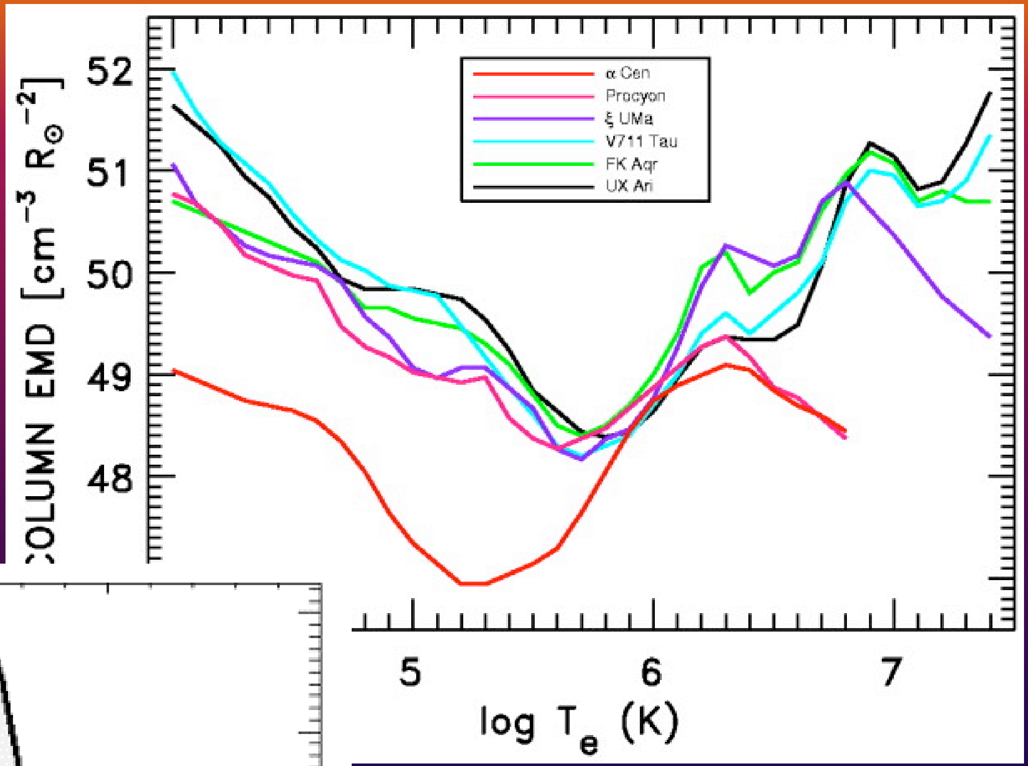
Note that this is a volume emission measure; some spectroscopists (notably solar coronal types) use a *column emission measure*. Also note that the definition of the DEM can be slightly different as well (dlogT or dT, n_e^2dV or $n_e n_H dV$).

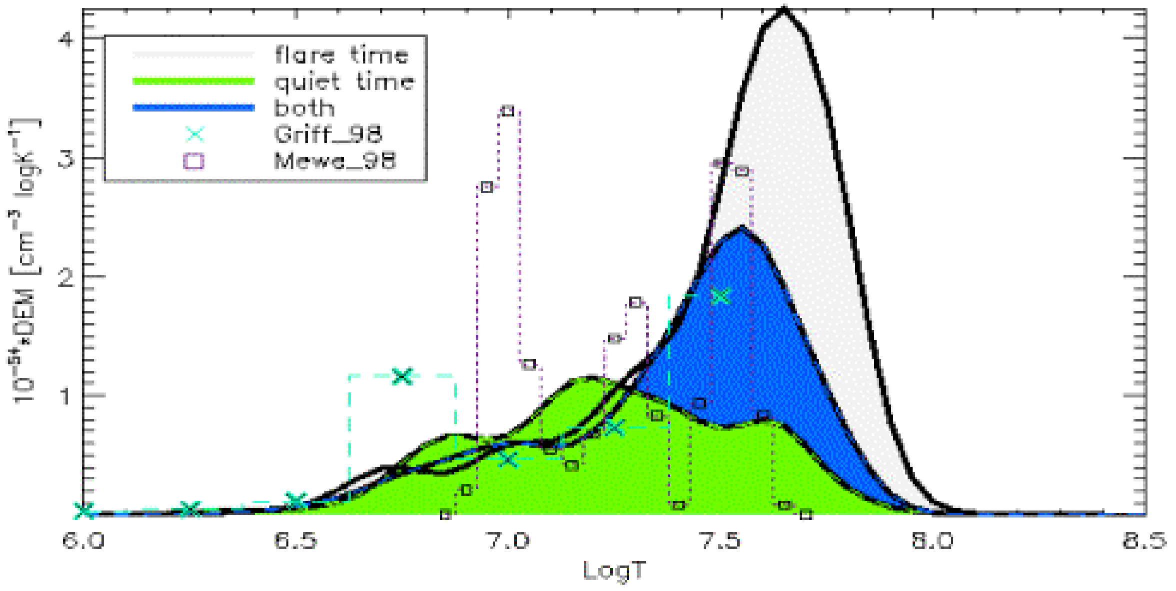
Temperature



DEM of active stars

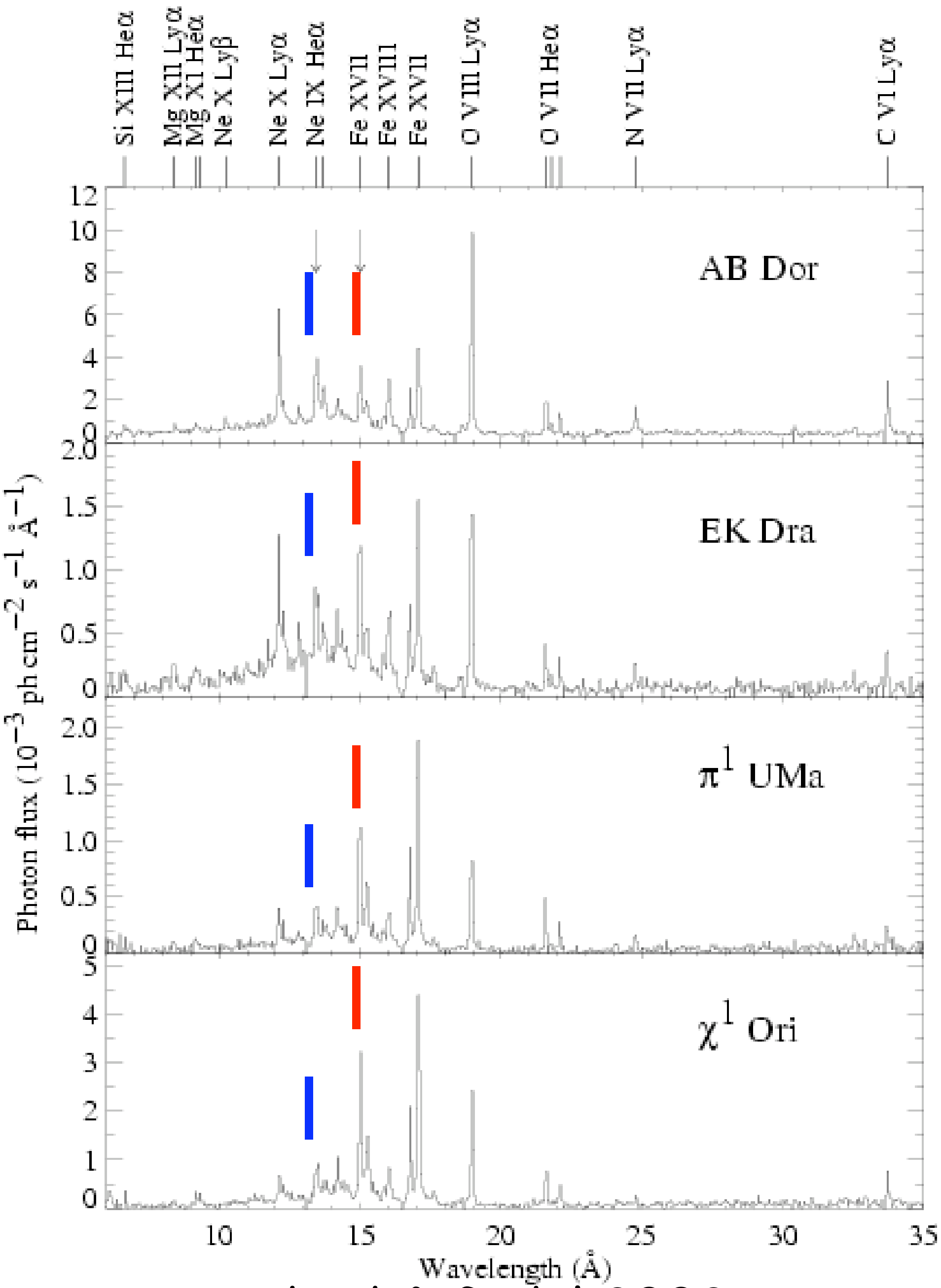
Sanz-Forcada et al. (2003)
a Cen, like Sun, has peak in coronal DEM at ~ few MK
More active stars have peaks at higher temps.





Huenemoerder et al. (2001)
Flare and quiescent states of the active binary II Peg

Spectral diagnostics: Abundances



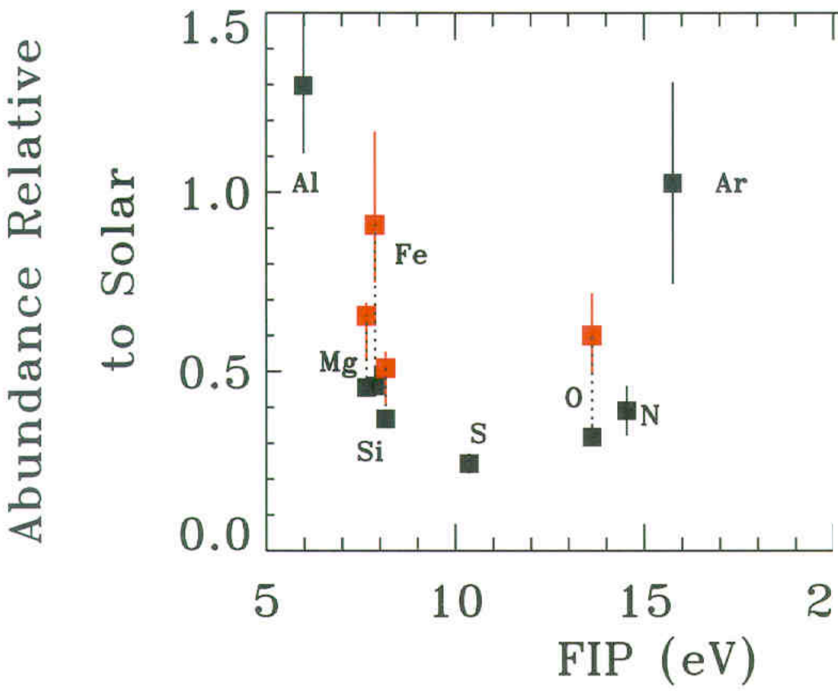
Audard & Güdel 2002

For elements with similar T_{form}, changing line ratios indicate changing abundances

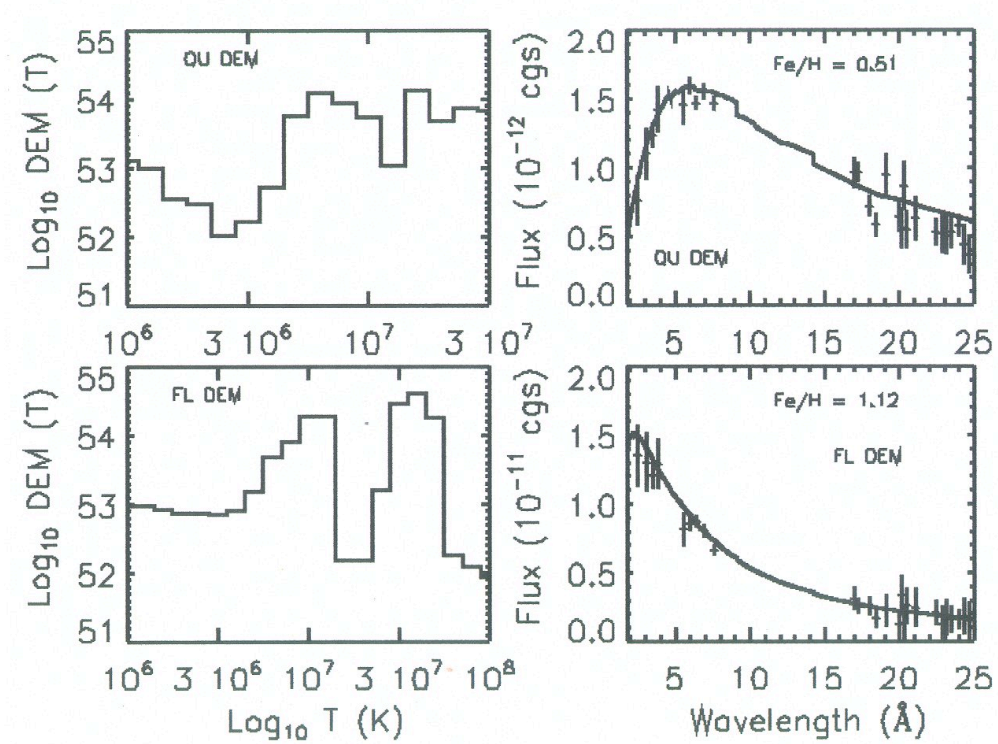
Full DEM modelling of lines and continuum is needed get [X/H]

Continuum mostly H, He free-free, but signif. contributions from elemental free-bound, e.g.

Spectral diagnostics: Abundances

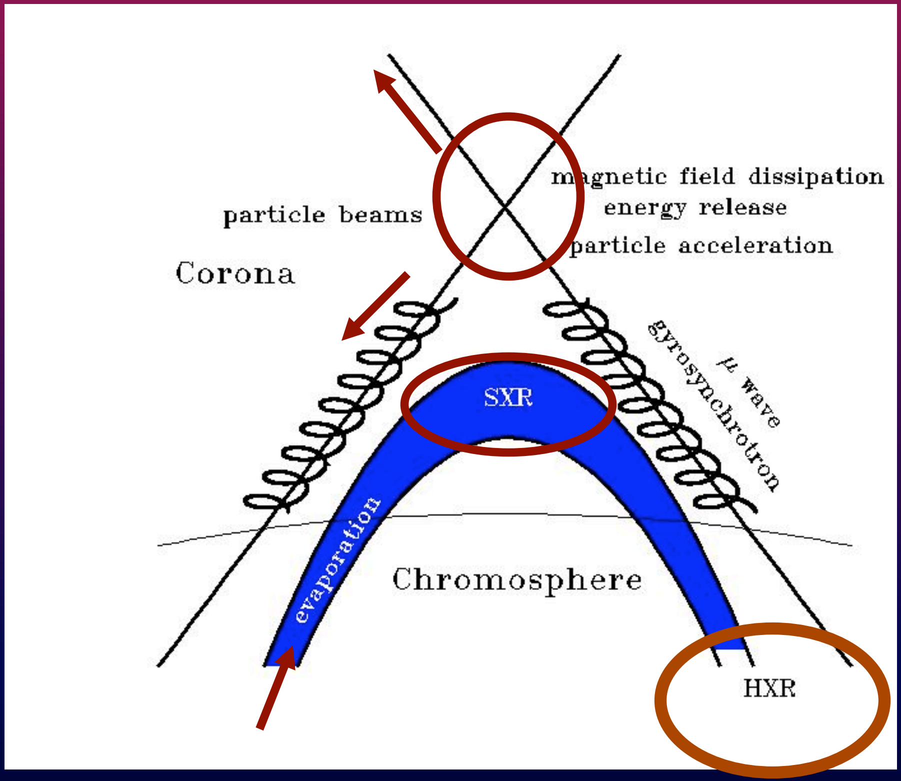


Changes during flare indicate creation of hot plasma, increase of abundances => photospheric abundance material being dredged into corona



σ^2CrB (F9V+G0V): Osten et al. 200

Basic Flare Scenario



Interrelation of thermal / nonthermal processes constrains underlying heating, dynamics, energetics

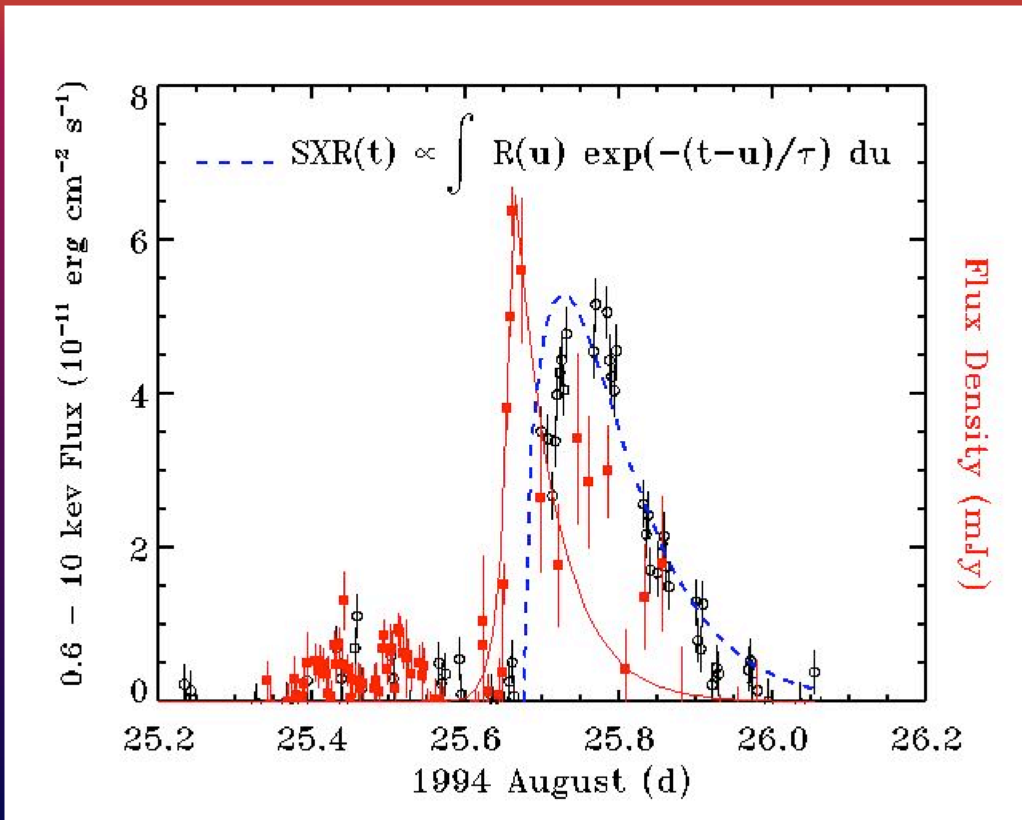
Neupert Effect = Observational temporal relationship between (incoherent) signatures of accelerated particles and plasma heating

$SXR(t) = \int_{t0}^{t} HXR(t')dt'$

or $MW(t')$

Multi-wavelength flare correlations: Neupert effect

HR 1099; Osten et al. 2004



μwave gyrosynchrotron emission occurs outside of flares on active stars as well, requires continuous particle acceleration to sustain emissions

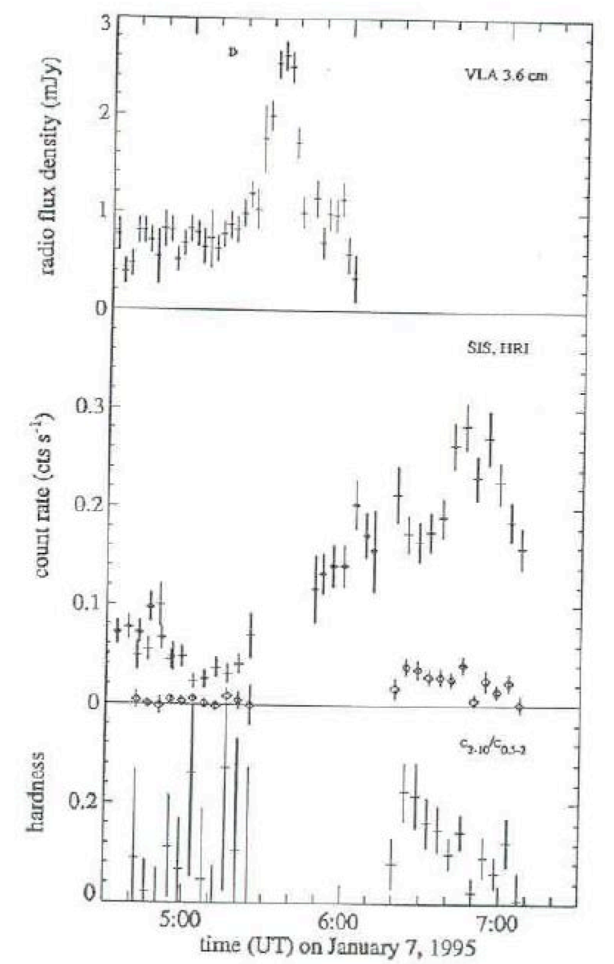
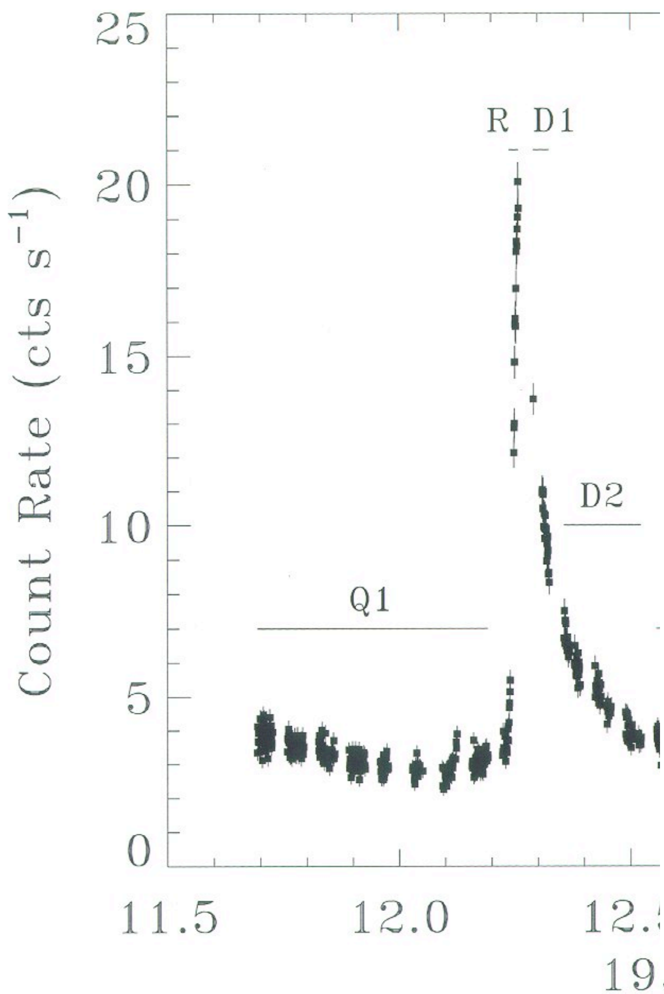


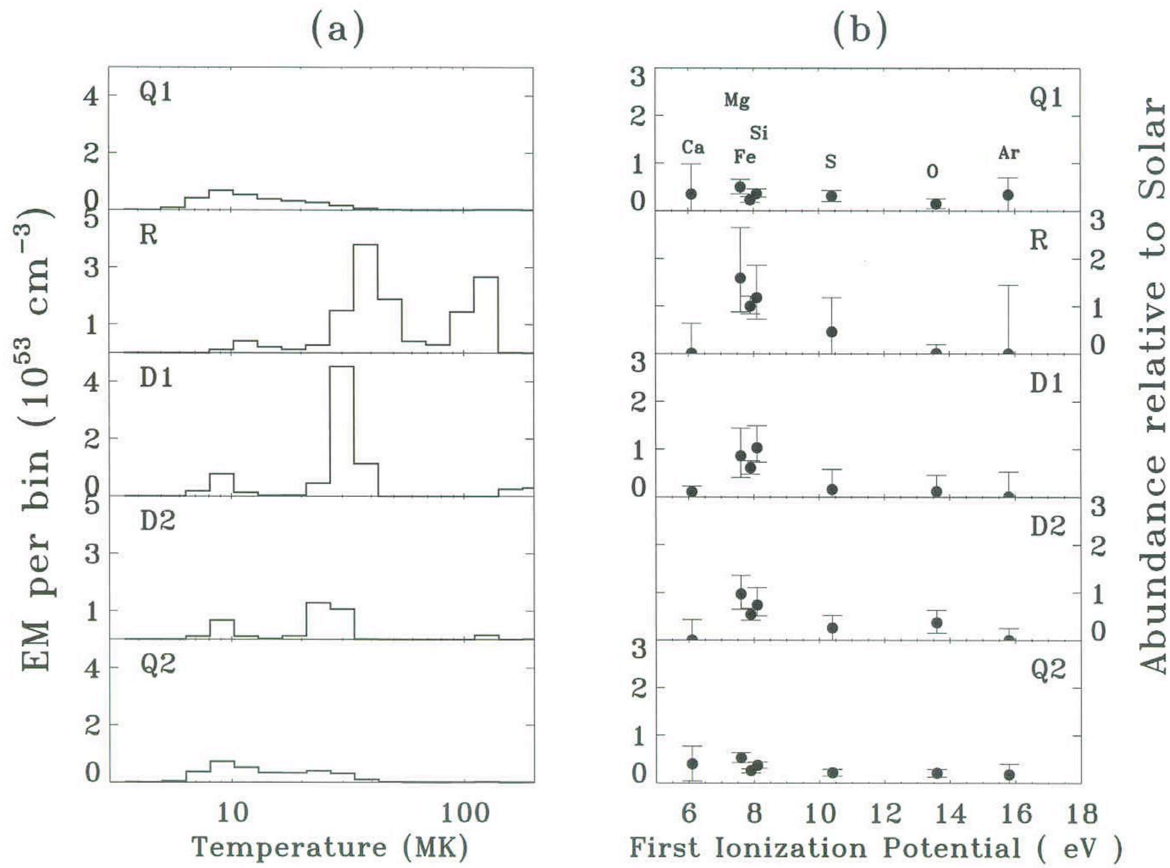
FIG. 4.—Similar to Fig. 3, for flare *D* on day 2. Radio data are binned to 150 s.

UV Cet (dM5.5); Güdel et al. 1996

Dynamic,magnetically heated plasma

σ^2CrB: Osten et al. 2000





Want to determine not only plasma parameters, but their changes during flare episodes, or as f'n of some other relevant timescale (P_{rot}, P_{orb})

Electron density

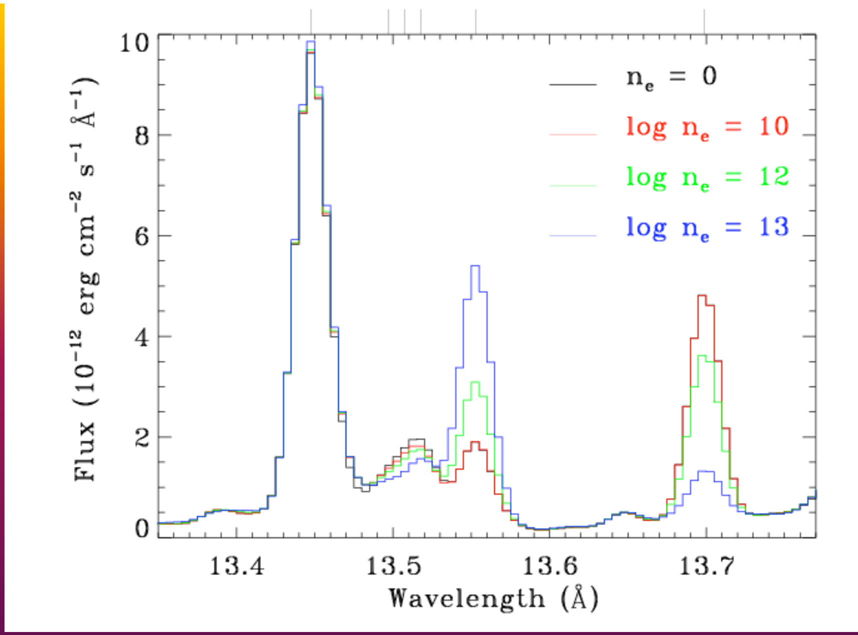
Issues for (cool) stars:

(1) T_e

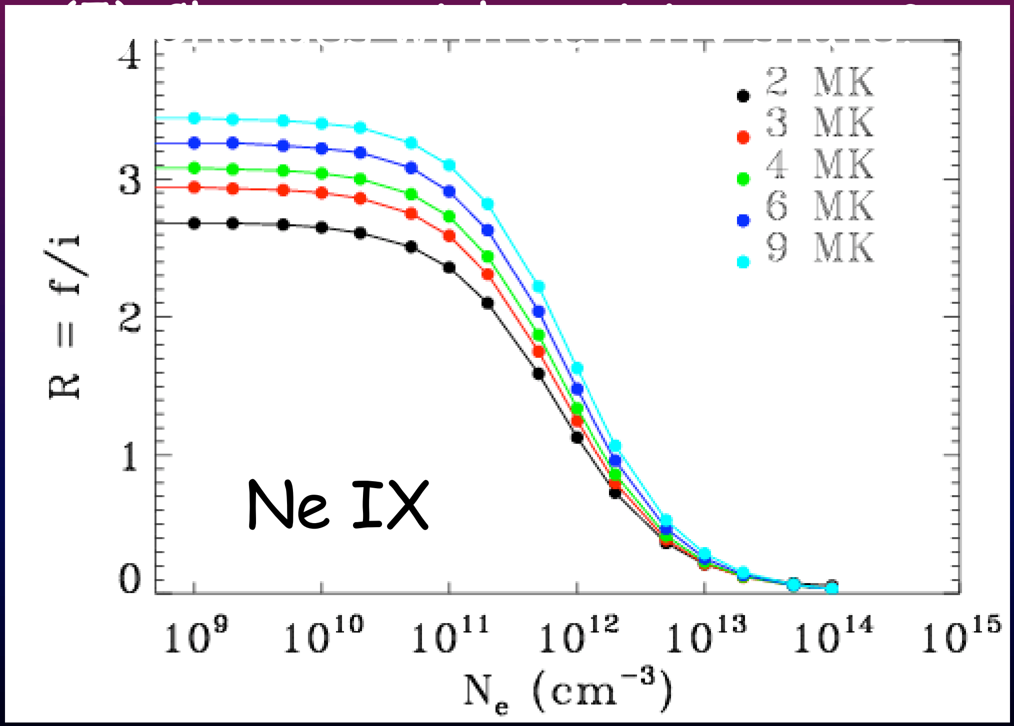
(2) Line blending

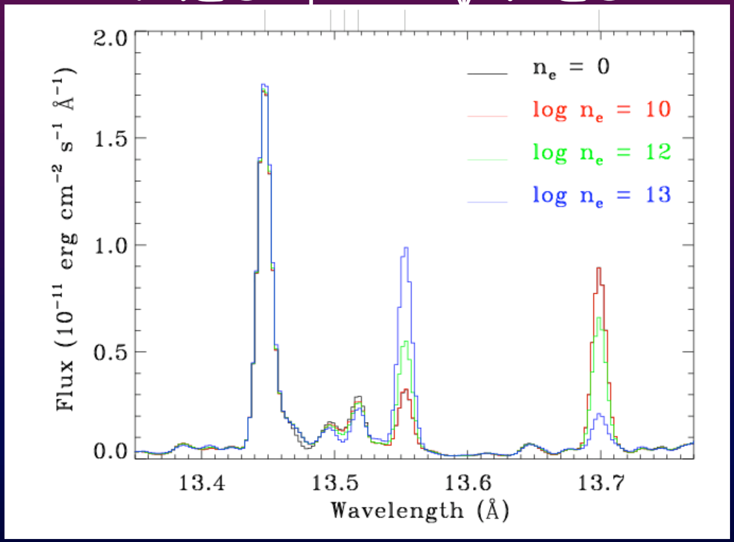
(3) Radiation field?

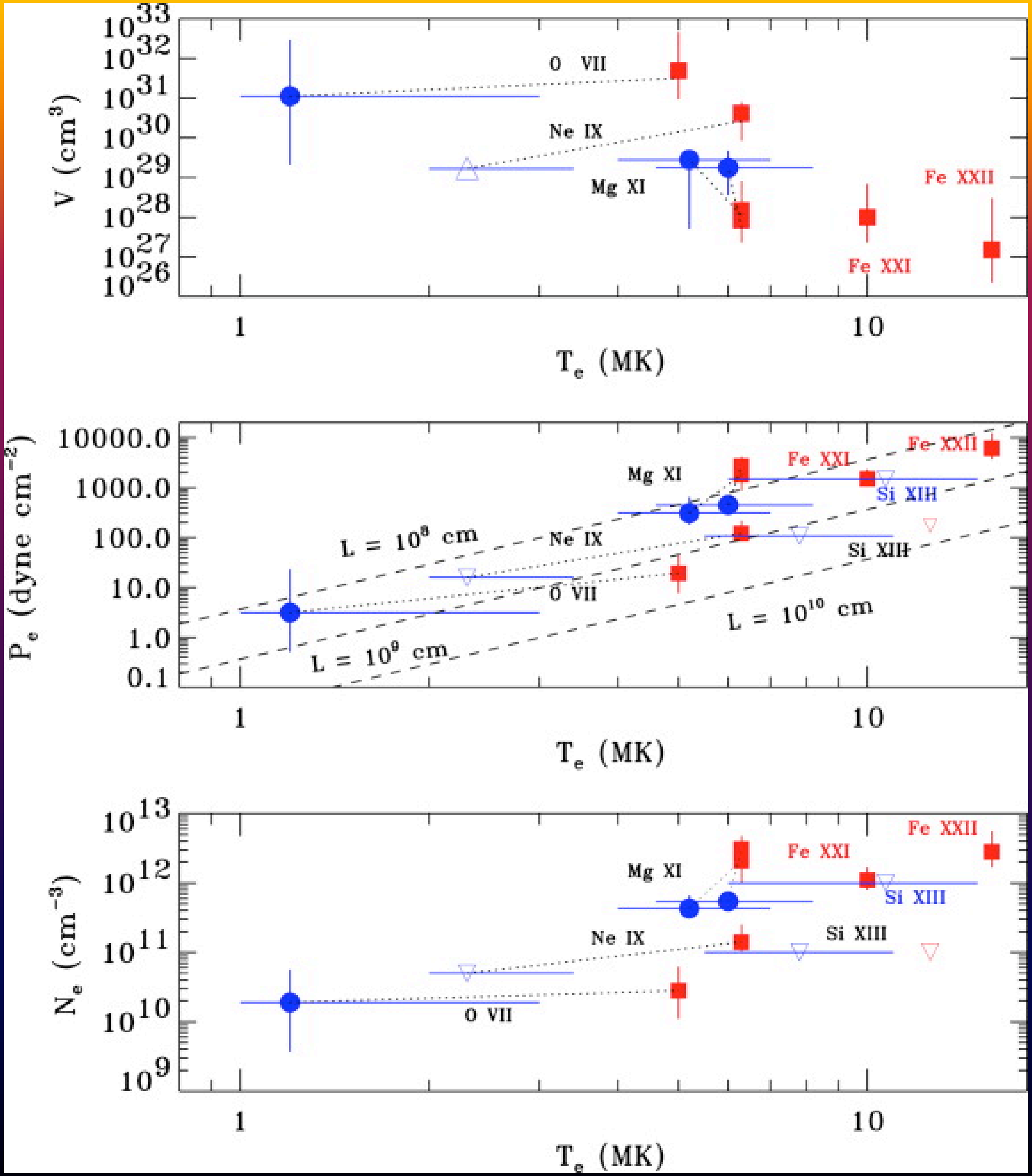
(4) Isobaric corona?



MEG ↑ ↓ HEG



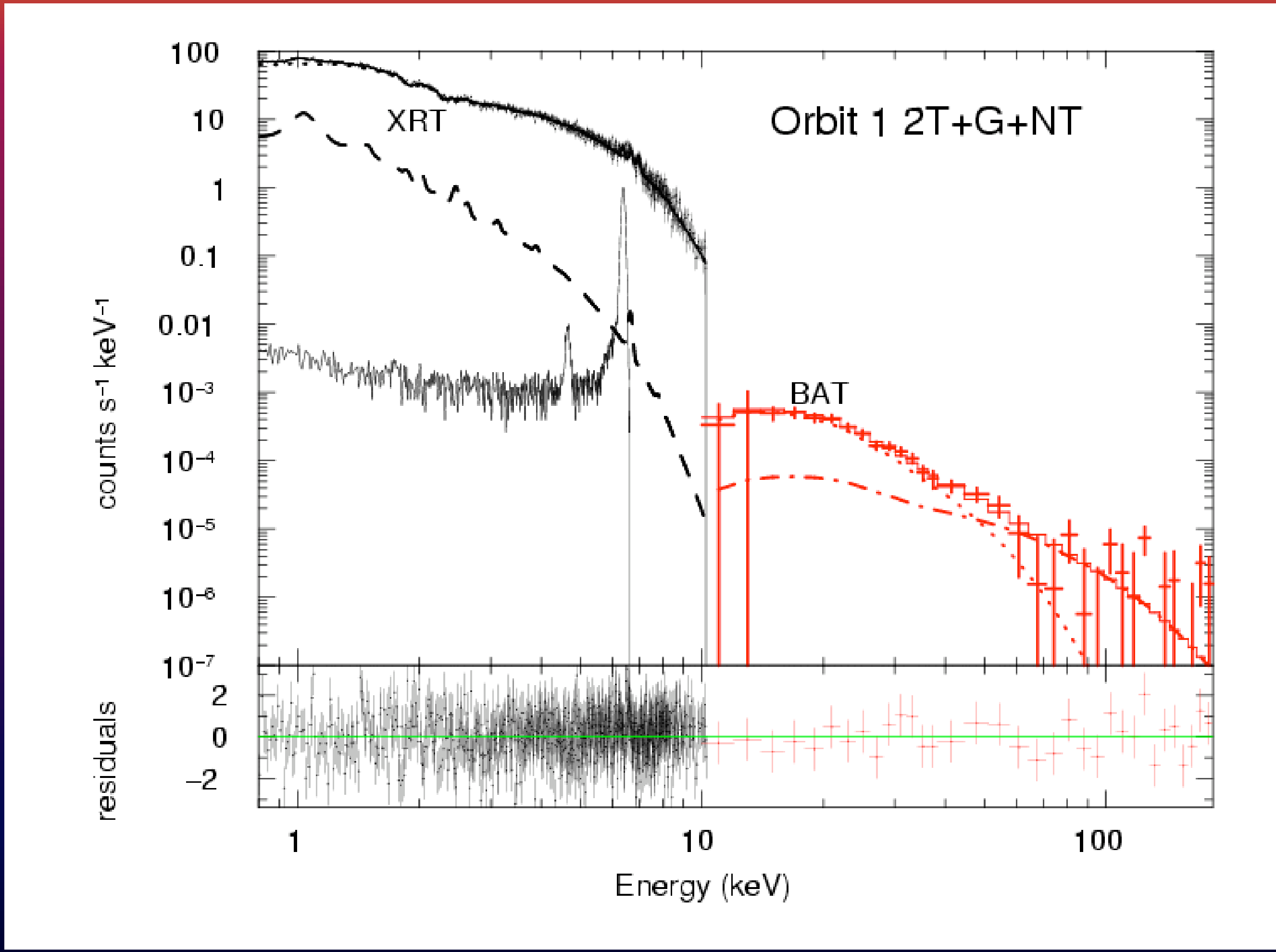




Combining density, emission measure

σ^2CrB; Osten et al. 2003

Other diagnostics : nonthermal emission

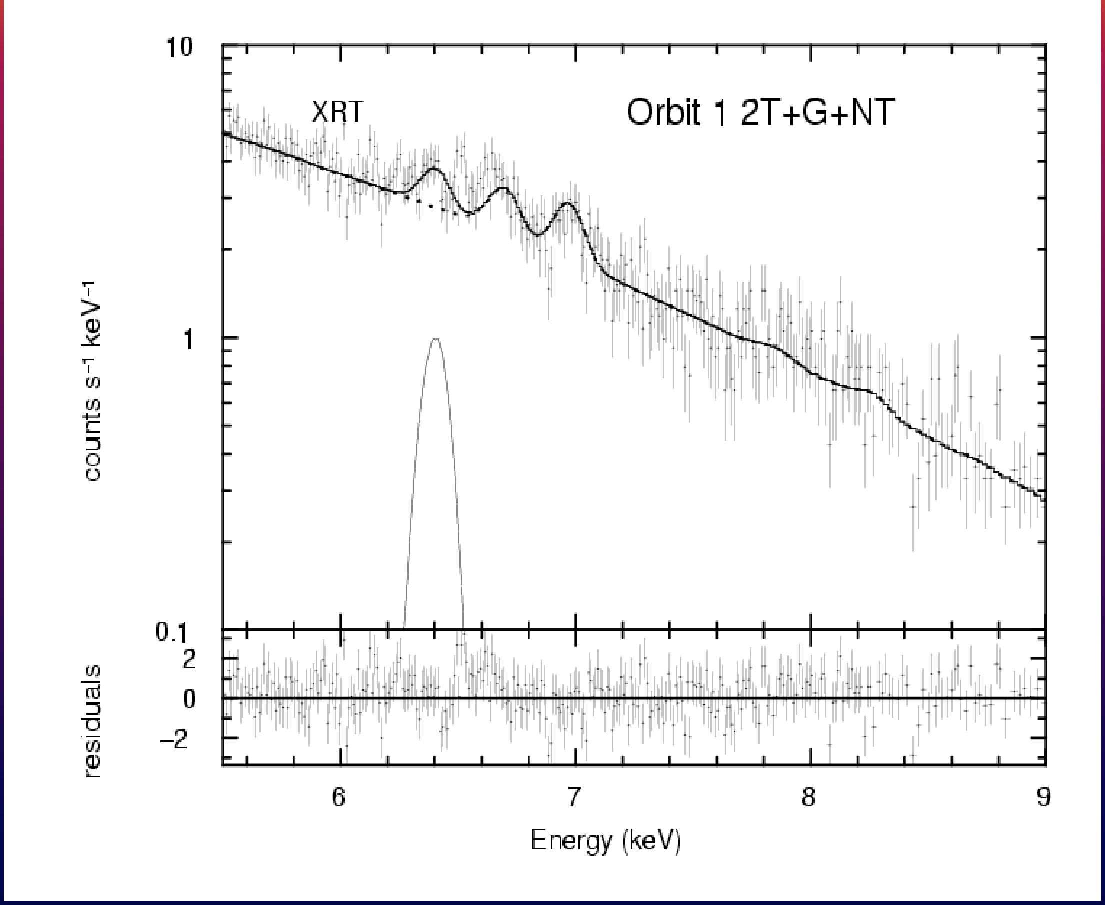


1st detection of NT Hard X-ray emission in a stellar flare!

Superflare on II Peg; Osten et al. 2007

Other diagnostics: Fe Kα 6.4 keV

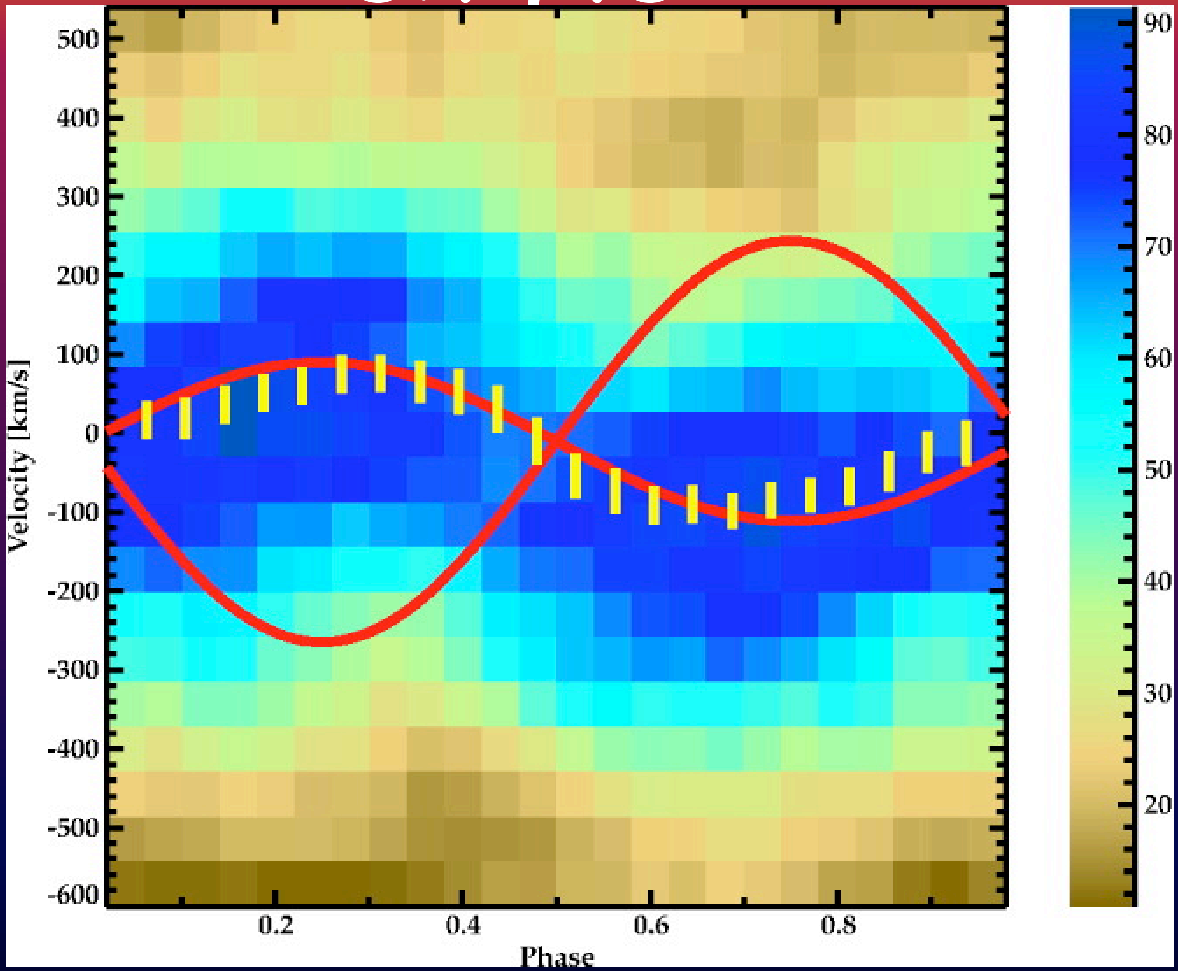
6.4 keV "cold" iron (Fe I—XVI) can be formed by high E (>7 keV) continuum emission "shining" on stellar photosphere, illuminating a disk, or possibly also by the action of accelerated electrons



Superflare on II Peg; Osten et al. 2007

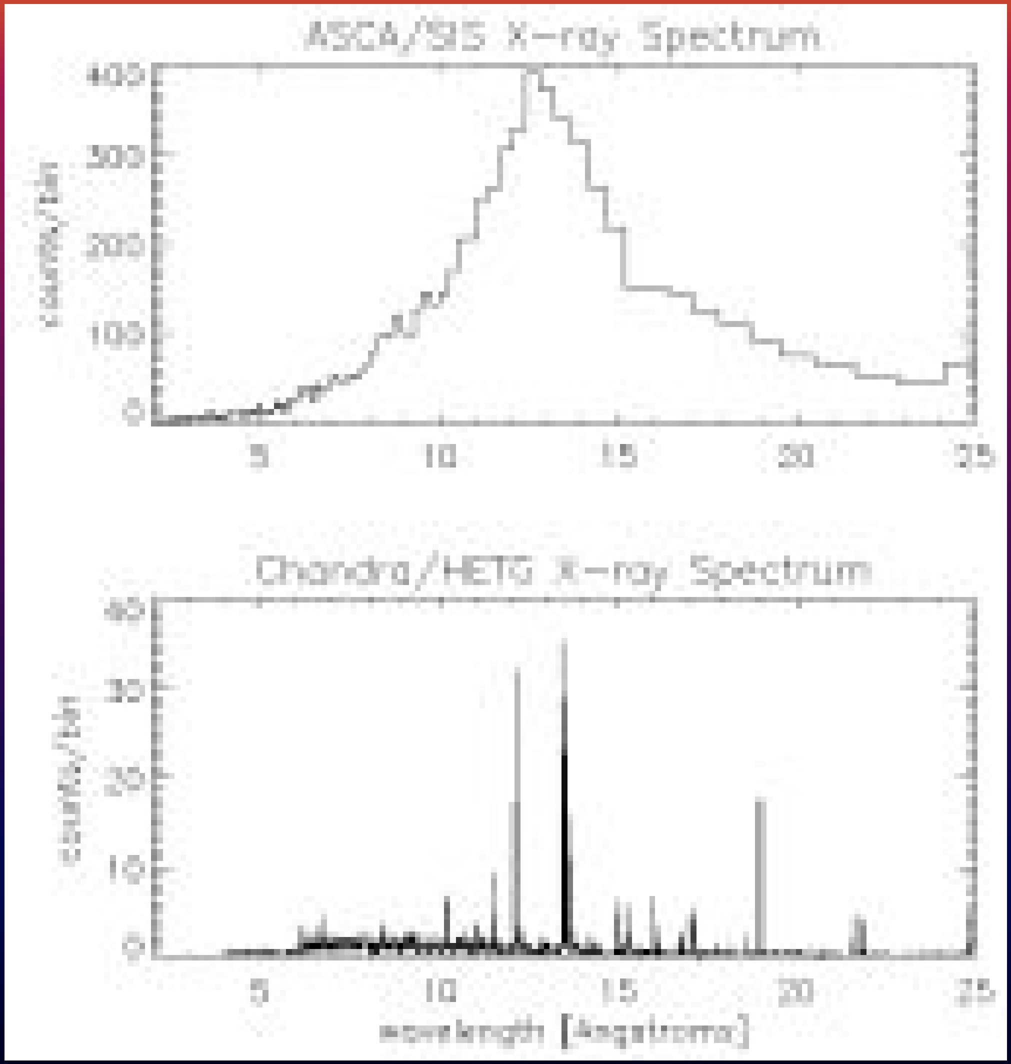
Other diagnostics: velocity shifts

X-ray emission follows the more massive star in the binary



VW Cep; Huenemoerder et al. 2003

CCD vs grating spectral resolution



Gratings allow one to see the trees, not just the forest, of coronal emission lines

However, there are many more CCD resolution spectra in the Chandra & XMM-Newton archives than grating spectra, due to efficiency considerations, so need to understand

Future. . .

Longer grating observations of bright stars, or long grating observations of X-ray fainter stars, with current facilities

Need more detailed observations in order to get a better grasp of the physics, not just phenomenology:

→higher spectral resolution ("thermal limit spectroscopy")

→ more collecting area, to observe more than just "the usual suspects" with high spectral resolution

→ coordinated multi-wavelength observations to extract the most information possible out of the obs'ns, use complementary approaches