X-ray flare on the single giant HR 9024

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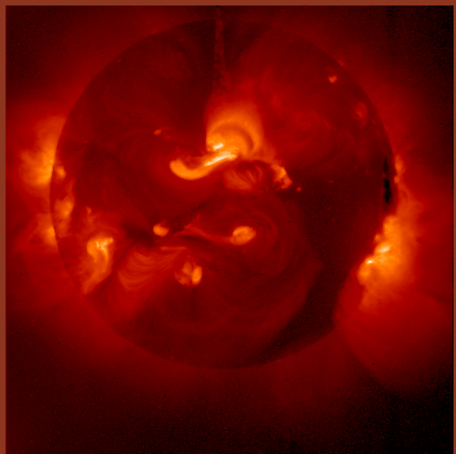

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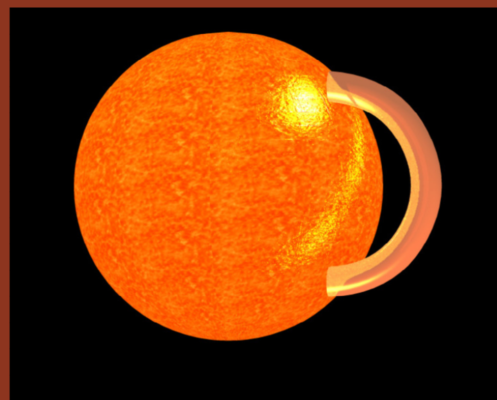


Courtesy I. Pillitteri

High resolution spectroscopy workshop - MSSL, UK, March 28 2006

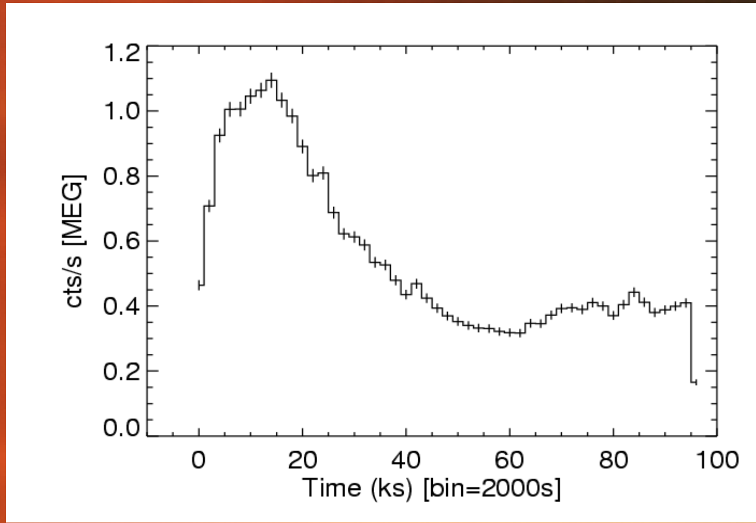
OUTLINE

- **geometry of stellar coronae:**
  - ➢ is L > or < $R_{\odot}$?
  - ➢ does it depend on activity level, evolutionary stage, stellar parameters ($R_{\odot}$, gravity, rotation, ..) ?
- **flare modelling as diagnostics for coronal geometry**
  - ➢ generally yields L < $R_{\odot}$ in late-type dwarfs
- **the case of HR 9024:**
  - ➢ single evolved star (G1 III); giants seem to show evidence for larger L (e.g. Ayres et al. 2003)
  - ➢ high resolution spectra HETG observation

GEOMETRY DIAGNOSTICS from FLARE MODELING

- stellar flares lightcurves analogous to solar flares

- size of flaring structures inferred from light curve, in particular the e-folding decay time (e.g. Kopp & Poletto 1984, White et al. 1986, van den Oord & Mewe 1989, Reale et al.1997)



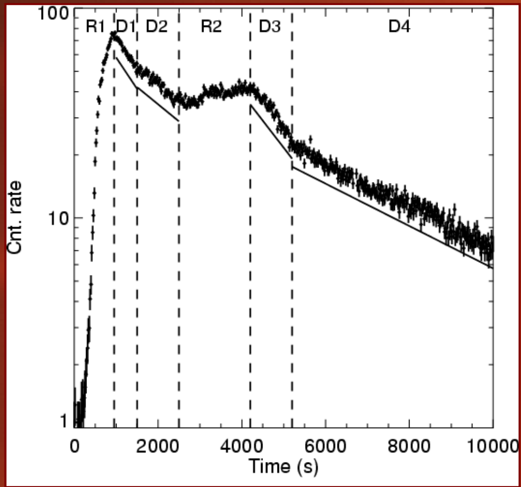
- thermodynamic decay time (van den Oord & Mewe 1989, Serio et al.1991; impulsive heating): $\tau \sim 120\ L_9\ (T_7)^{-1/2}$

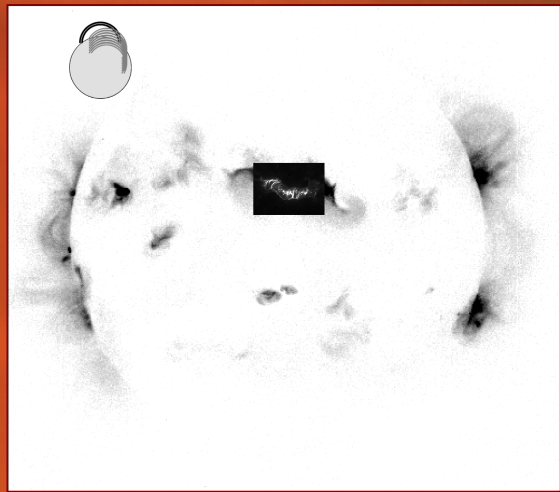
- Reale et al. (1997) take into account possible continuous heating ⇒ more realistic estimates of L (information of the trajectory of the flare in the temperature-density diagram; $L_9 = \frac{\tau_{lc}\sqrt{T_7}}{120 f(\zeta)}$; $f(\zeta) \geq 1$)

GEOMETRY DIAGNOSTICS from FLARE MODELING

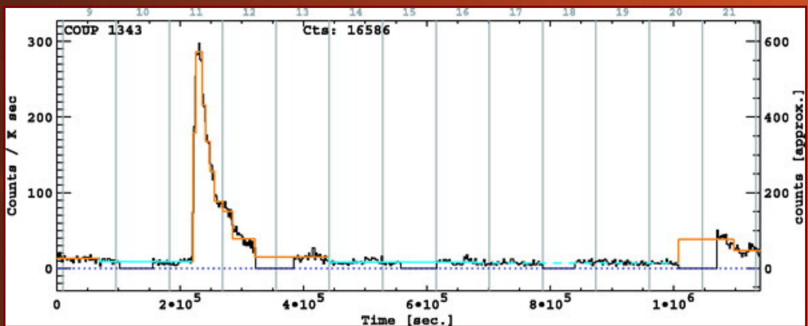
two recent examples:

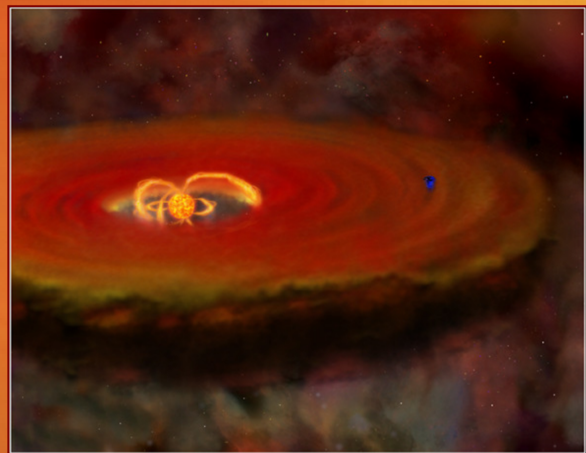
- Proxima Centauri (Reale et al. 2004)





- T Tauri stars (Favata et al. 2005; COUP data)



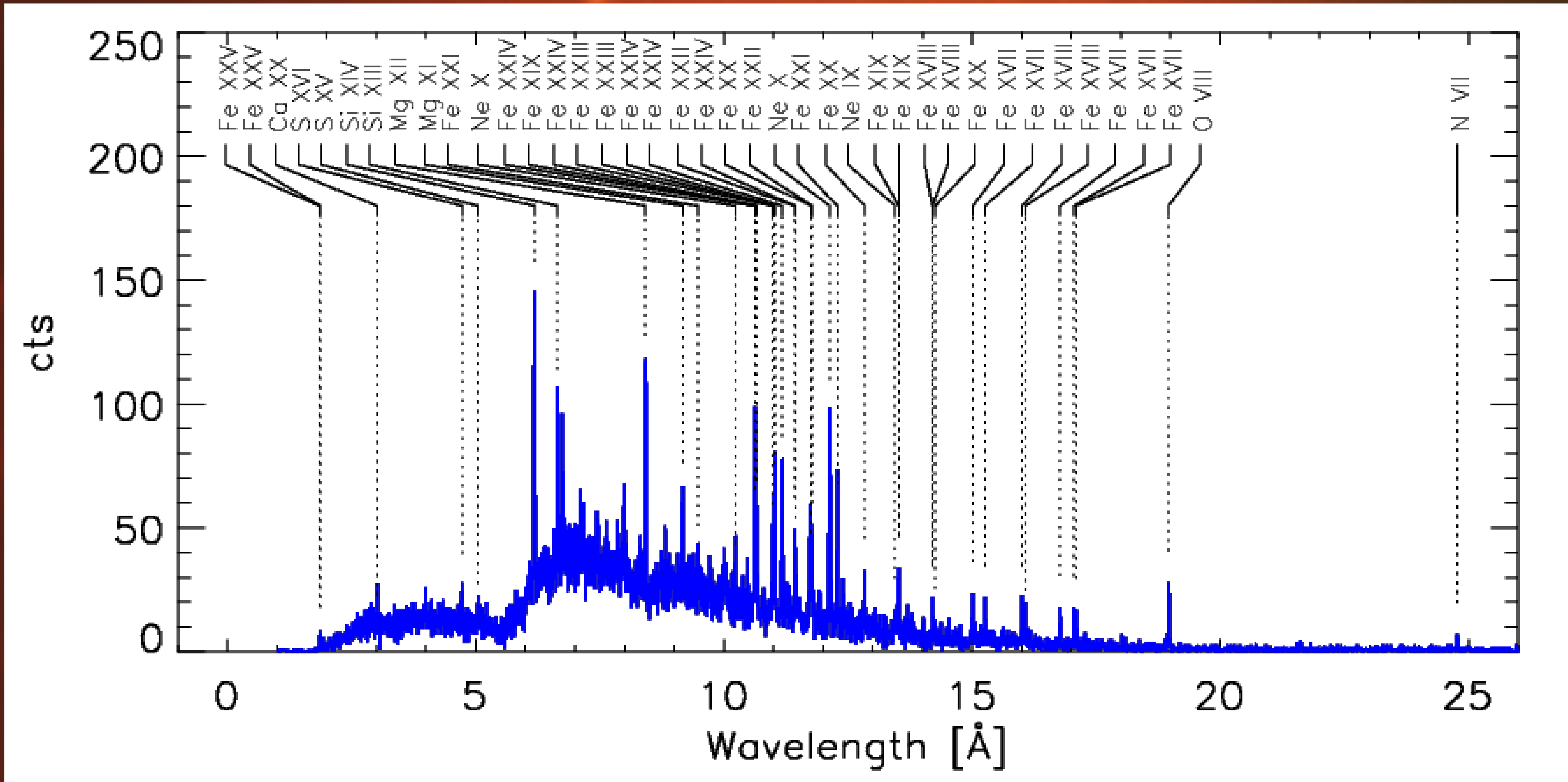


HR 9024

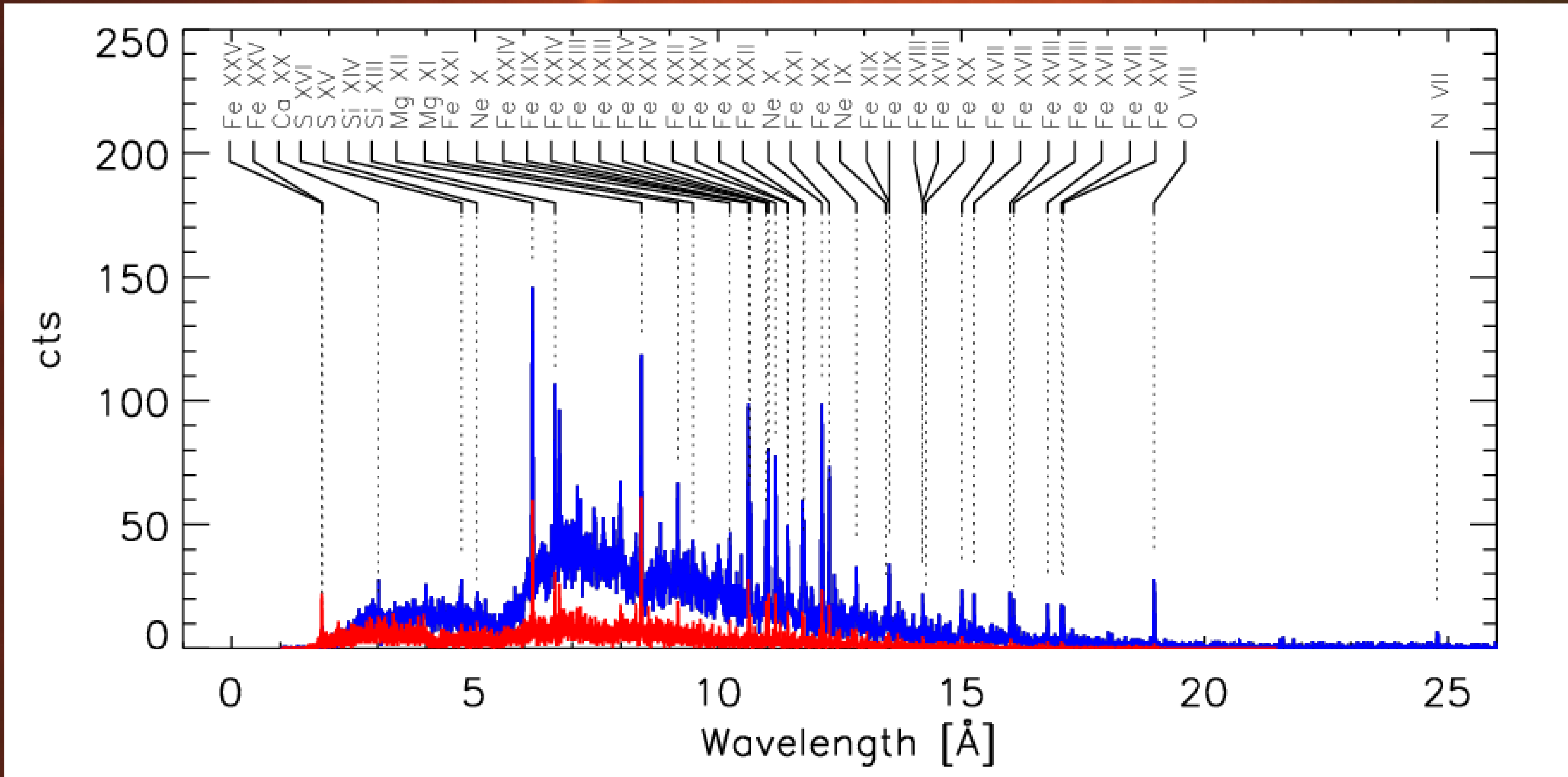
sp. type	d [pc]	R_* [$R_\odot$]	M_* [$M_\odot$]	L_{bol} [erg/s]	P_{rot} [d]	L_X [erg/s]	t_{exp} [ks]
G1 III	135	13.6	2.9	$2.7 \cdot 10^{35}$	23.25	$6 \cdot 10^{31}$	95.7

- single evolved star (G1 III)
- HETG observation (96 ks)

SPECTRUM

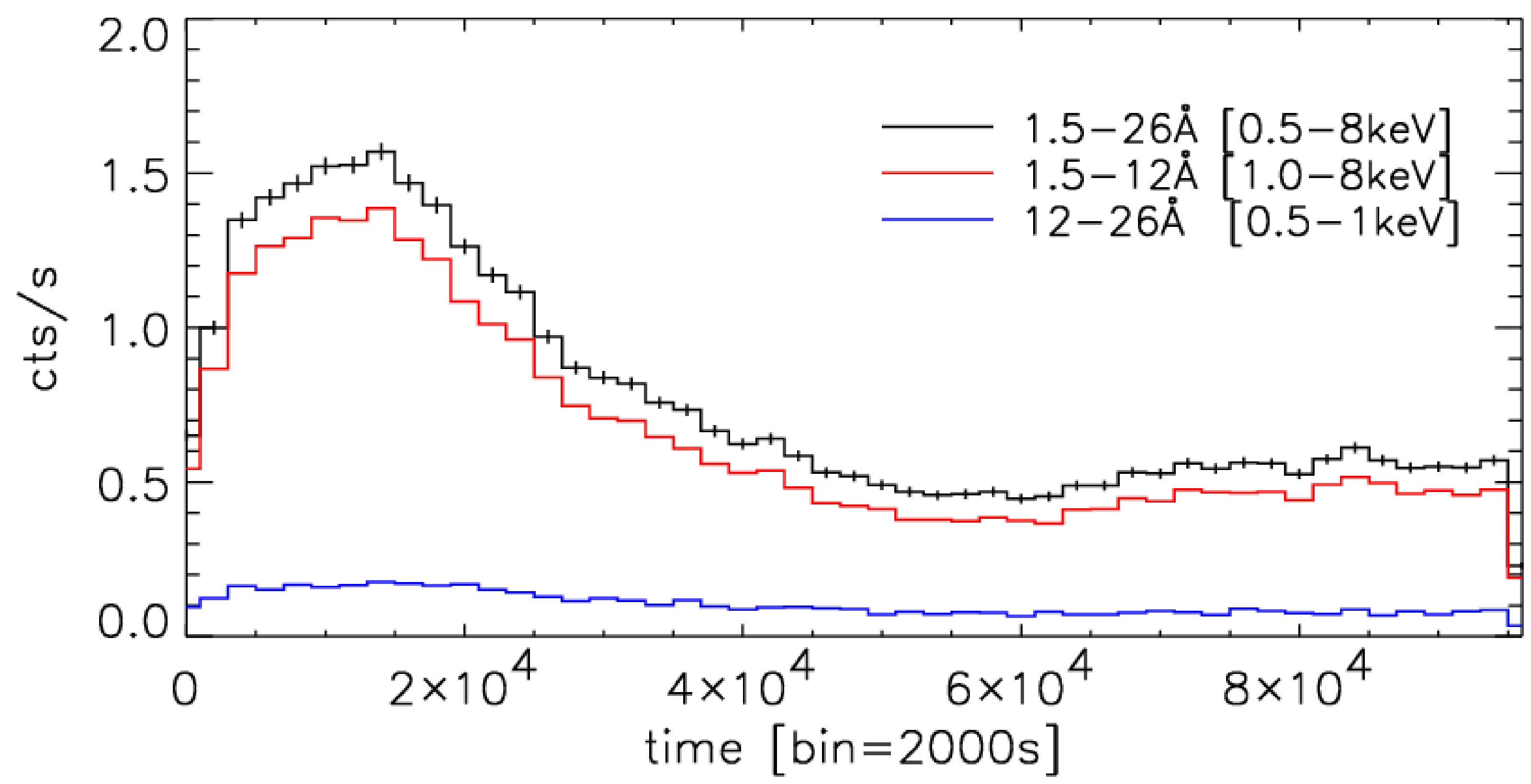

Fe XXV
Fe XXV
Ca XX
S XVI
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Fe XXI
Ne X
Fe XXIV
Fe XIX
Fe XXIV
Fe XXIII
Fe XXIII
Fe XXIV
Fe XXIV
Fe XXII
Fe XXIV
Fe XX
Fe XXII
Ne X
Fe XXI
Fe XX
Ne IX
Fe XIX
Fe XIX
Fe XVIII
Fe XVIII
Fe XX
Fe XVII
Fe XVII
Fe XVIII
Fe XVIII
Fe XVII
Fe XVII
Fe XVII
O VIII
N VII
250
200
150
100
50
0
cts
0
5
10
15
20
25
Wavelength [Å]

SPECTRUM



Fe XXV
Fe XXV
Ca XX
S XVI
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Fe XXI
Ne X
Fe XXIV
Fe XIX
Fe XXIV
Fe XXIII
Fe XXIII
Fe XXIV
Fe XXIV
Fe XXII
Fe XXIV
Fe XX
Fe XXII
Ne X
Fe XXI
Fe XX
Ne IX
Fe XIX
Fe XIX
Fe XVIII
Fe XVIII
Fe XX
Fe XVII
Fe XVII
Fe XVIII
Fe XVIII
Fe XVII
Fe XVII
Fe XVII
O VIII
N VII
250
200
150
100
50
0
cts
0
5
10
15
20
25
Wavelength [Å]

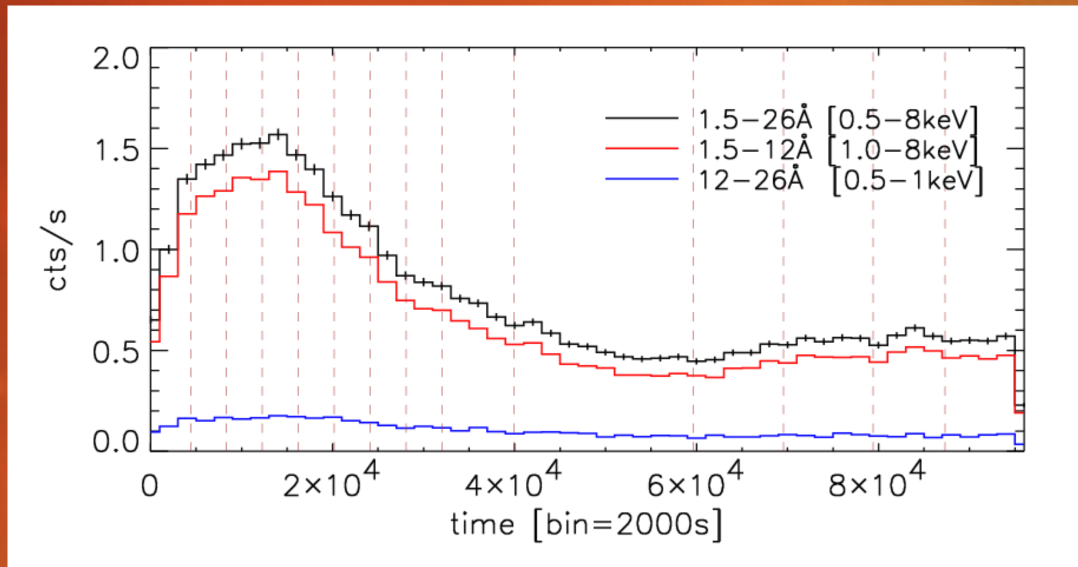
LIGHTCURVE



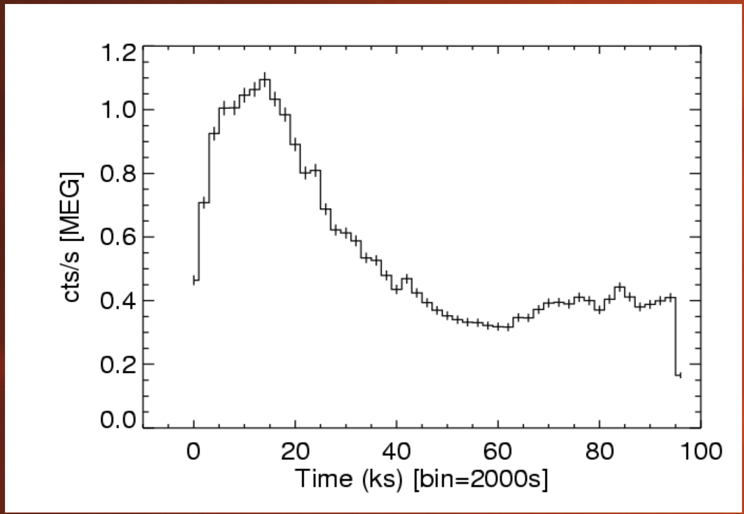
2.0
1.5
1.0
0.5
0.0
cts/s
0
2×10^4
4×10^4
6×10^4
8×10^4
time [bin=2000s]
1.5−26Å [0.5−8keV]
1.5−12Å [1.0−8keV]
12−26Å [0.5−1keV]

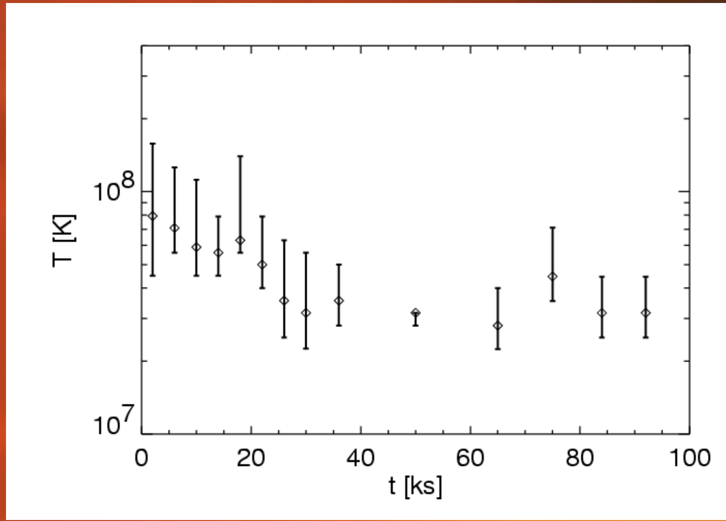
ANALYSIS

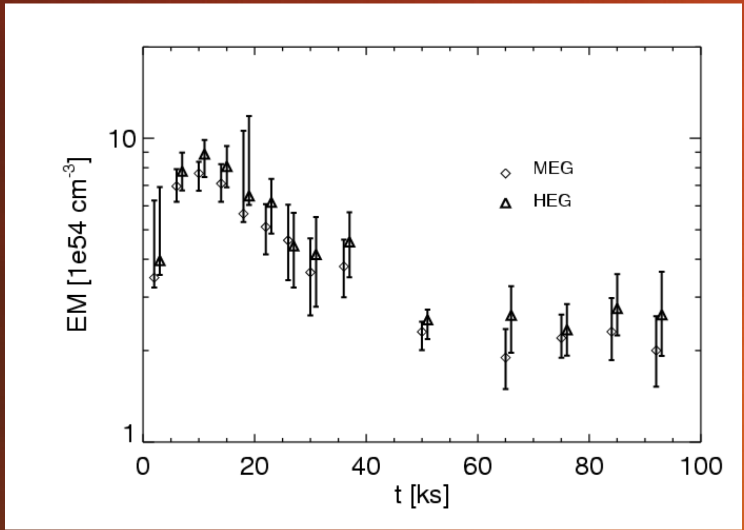
- DEM and abundances analysis
- derived evolution of T and EM during the flare
  - fit of continuum emission, selecting line-free spectral regions : T, EM (normalization parameter)

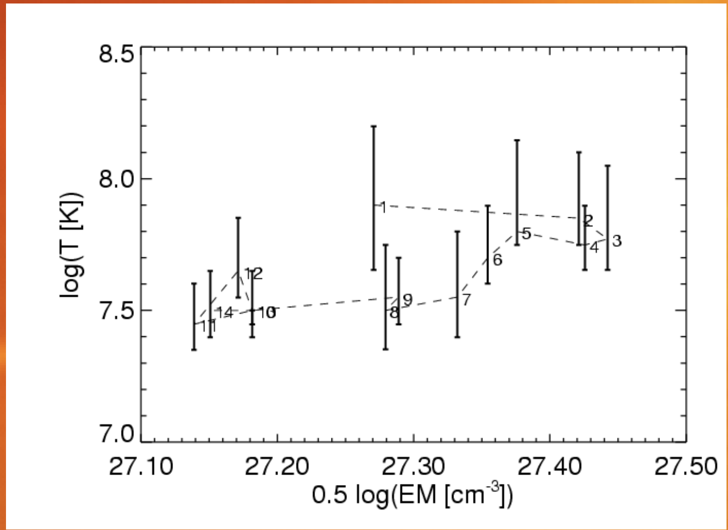


RESULTS


cts/s [MEG]
Time (ks) [bin=2000s]


T [K]
t [ks]


EM [1e54 cm-3]
t [ks]
MEG
HEG

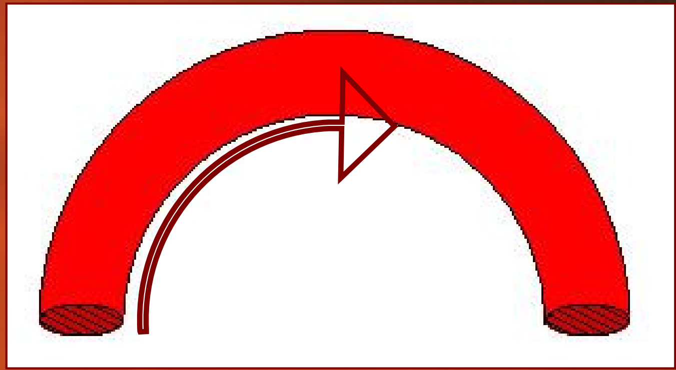

log(T [K])
0.5 log(EM [cm-3])

HYDRODYNAMIC MODEL

- coronal plasma **confined** by the B field: plasma motion and energy transport only along B field lines

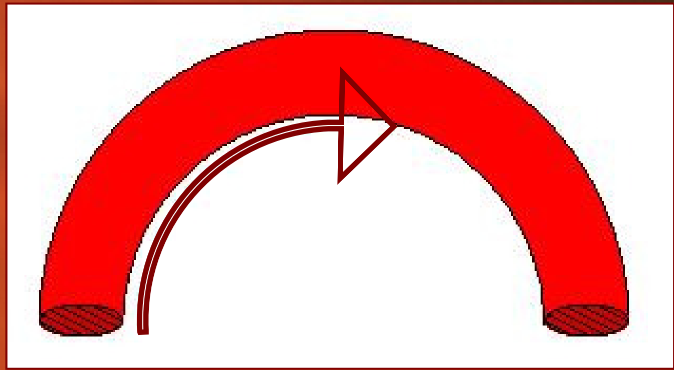
- 1D hydrodynamic model solving time-dependent plasma equations (density, momentum, energy) with detailed energy balance

- a time-dependent heating function defines the energy release triggering the flare



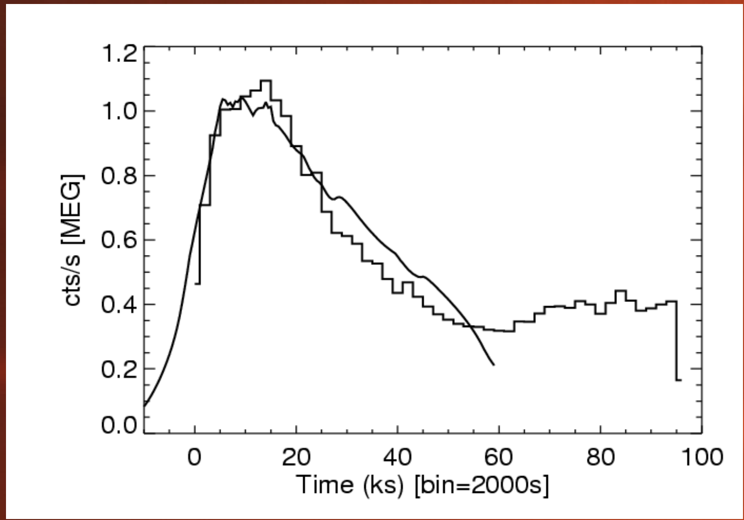
MODEL PARAMETERS

- loop semi-length L = 10^{12} cm (first estimate derived from the decay time $\tau \sim 120\, L_9\, (T_7)^{-1/2}$ [Serio et al. 1991,Reale et al. 1997])

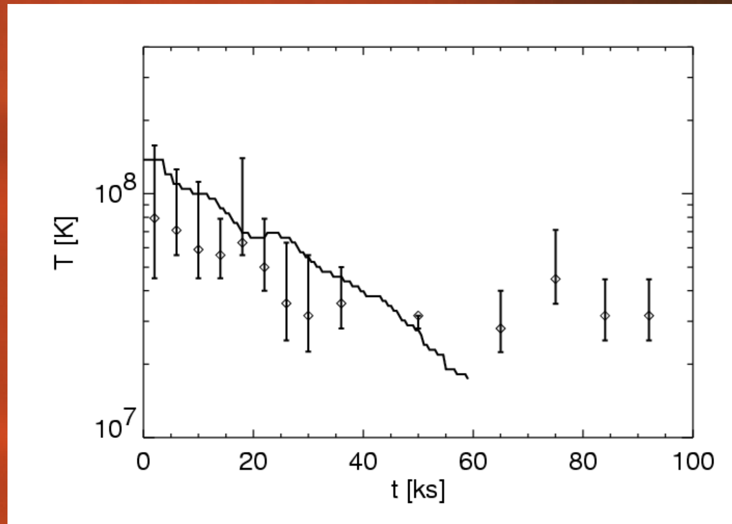


- initial atmosphere: hydrostatic, $T=2\times10^7$ K ; however initial conditions do not affect the plasma evolution after a very short time

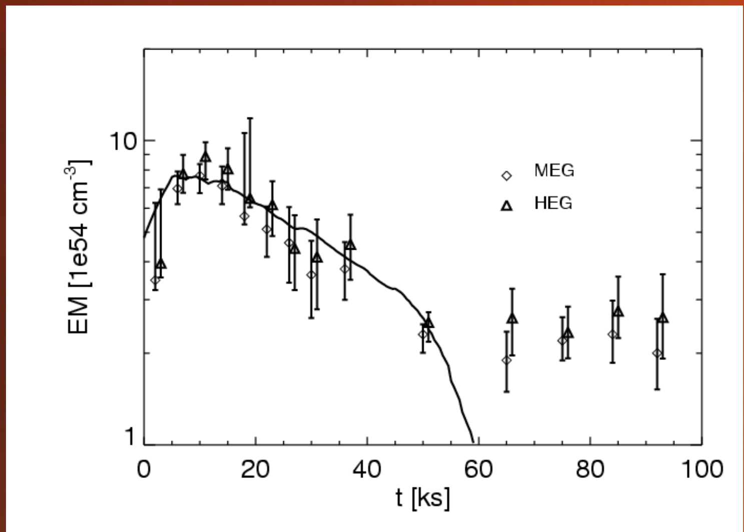
RESULTS



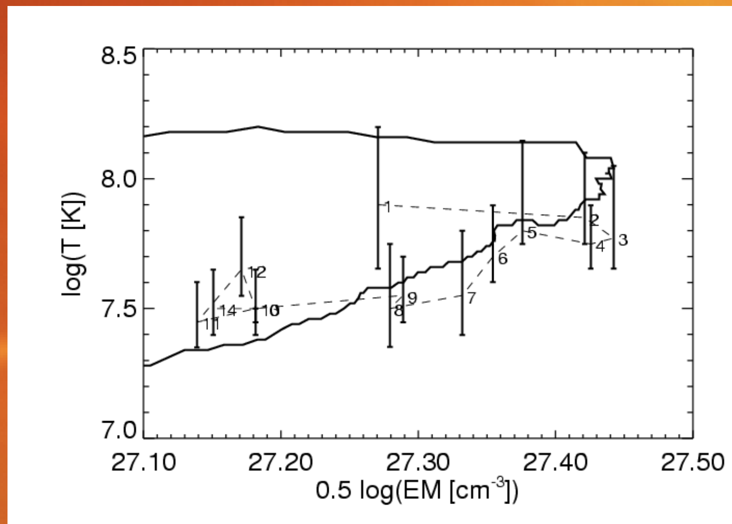
cts/s [MEG]
Time (ks) [bin=2000s]



T [K]
t [ks]

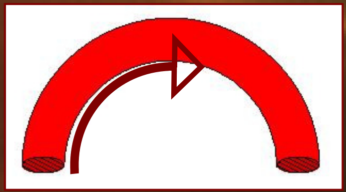


EM [1e54 cm-3]
t [ks]
MEG
HEG



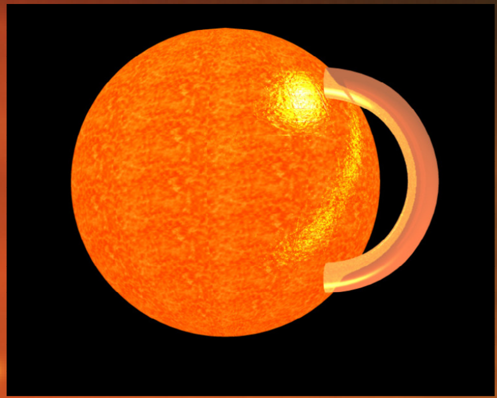
log(T [K])
0.5 log(EM [cm-3])

RESULTS



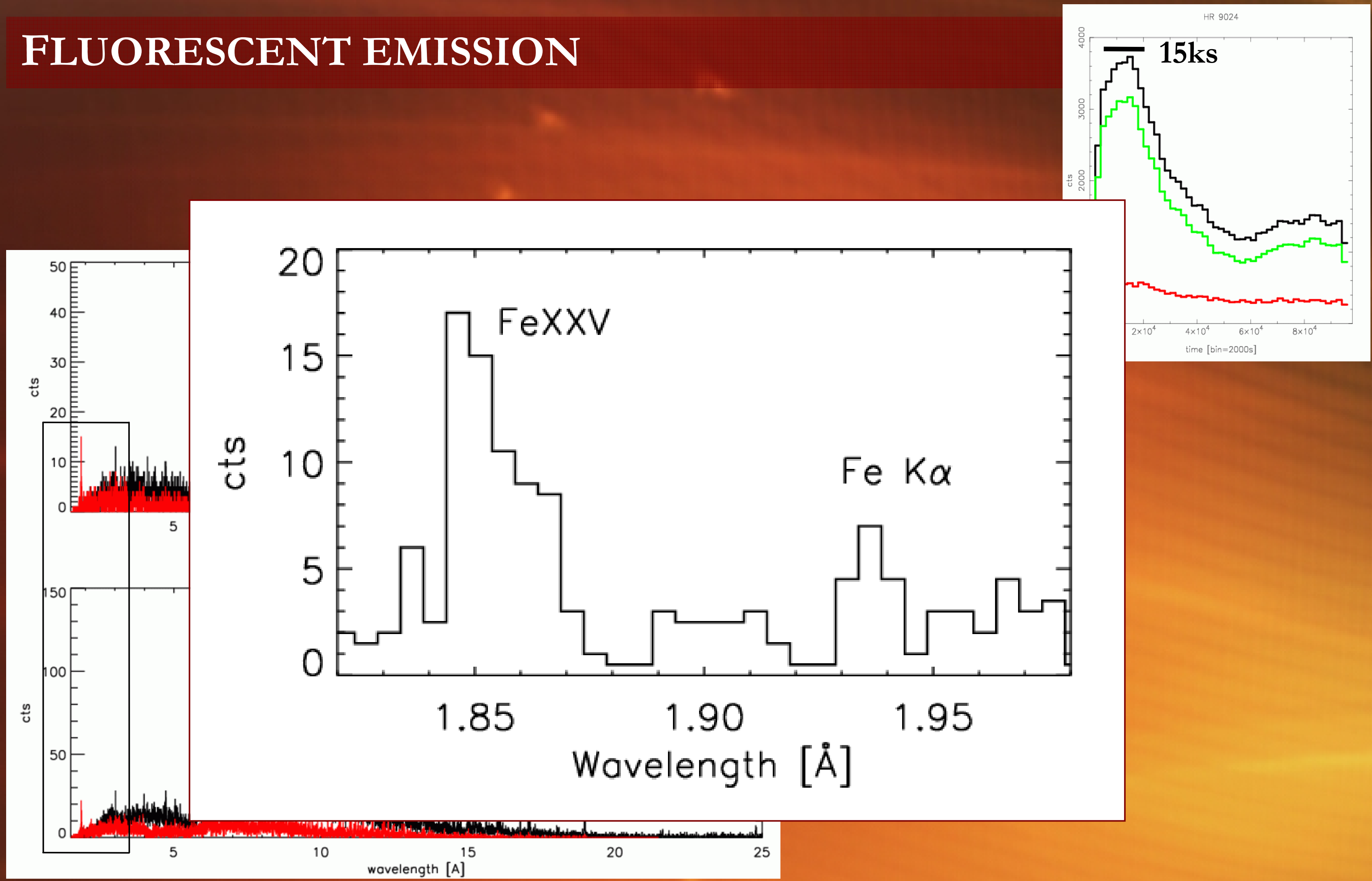
- loop semi-length L = 10^{12} cm
- heating:
  - impulsive (20ks), shifted by 15ks preceding the beginning of the observation
  - located at footpoints
  - no sustained heating (i.e. pure cooling)
  - volumetric heating ~10 erg/cm^3/s; heating rate ~8×10^{32} erg/s
- cross-section radius r ~ 2.3×10^{10} cm, i.e. aspect ratio α ~ 0.023 (from the normalization of the model lightcurve)

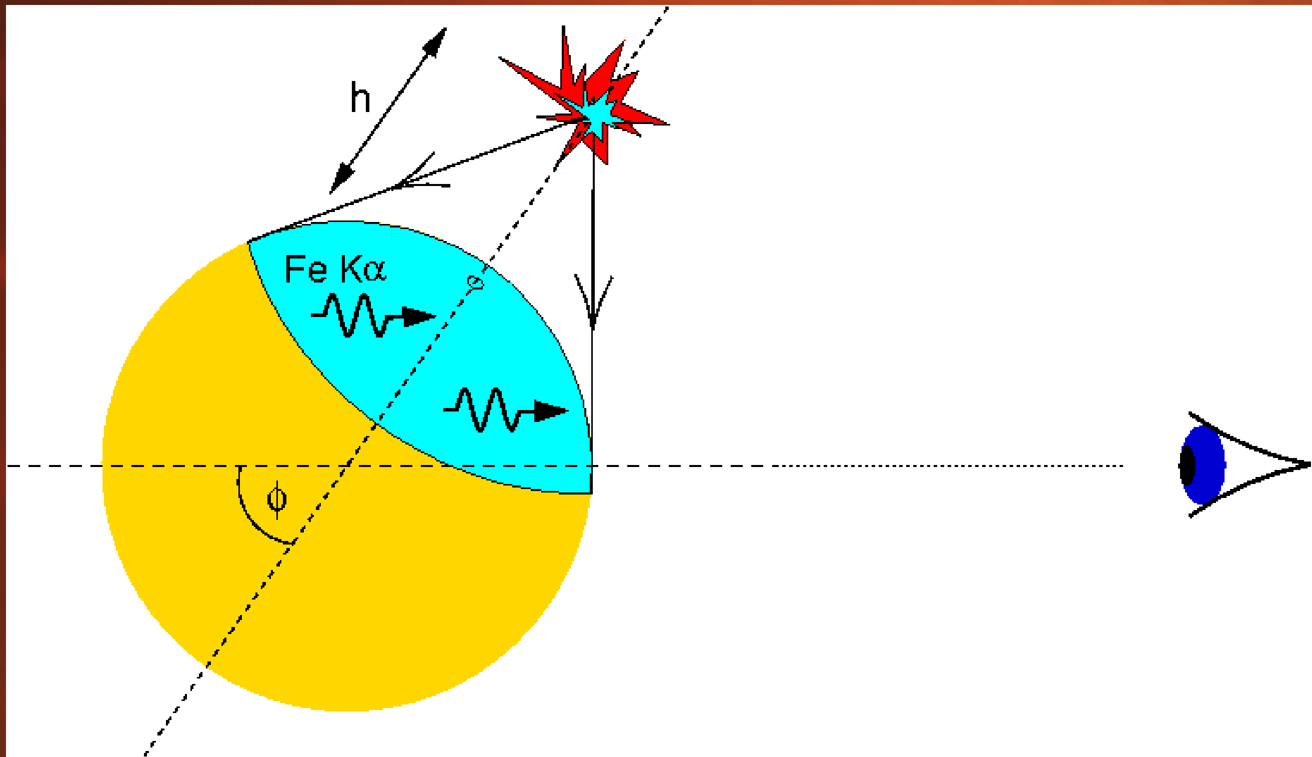
CONCLUSIONS

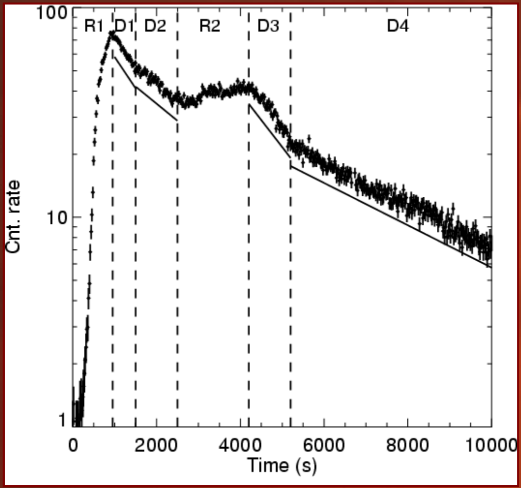


- large flare, unusual in single evolved stars
- very hot corona, even in quiescence
- loop semi-length comparable with R☞
- we can compare model and observation with high spectral resolution
- fluorescent emission — approved Suzaku observation (independent geometry diagnostics)
- recurrent pattern of lightcurve with two flares (HR9024, Prox Cen, Algol, the Sun,..) may represent a general characteristics of solar and stellar flares (as suggested by Reale et al. 2004)

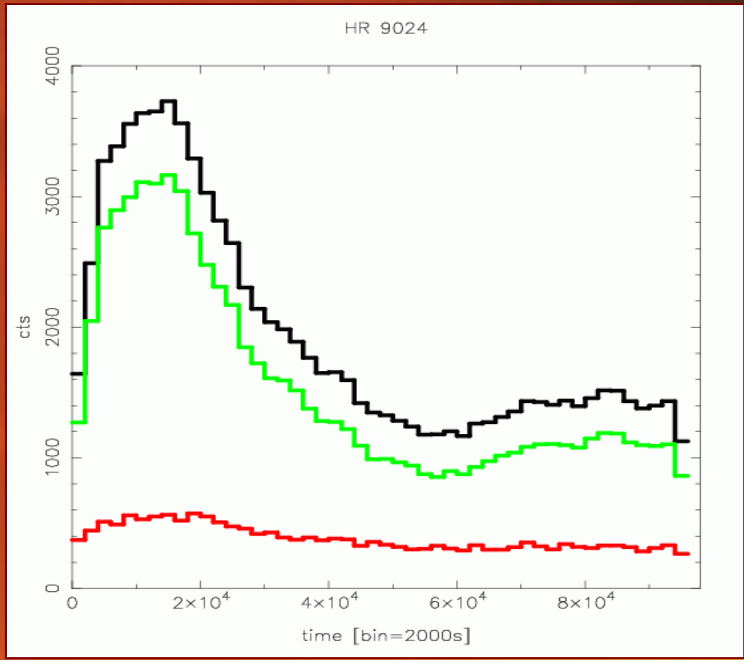
FLUORESCENT EMISSION



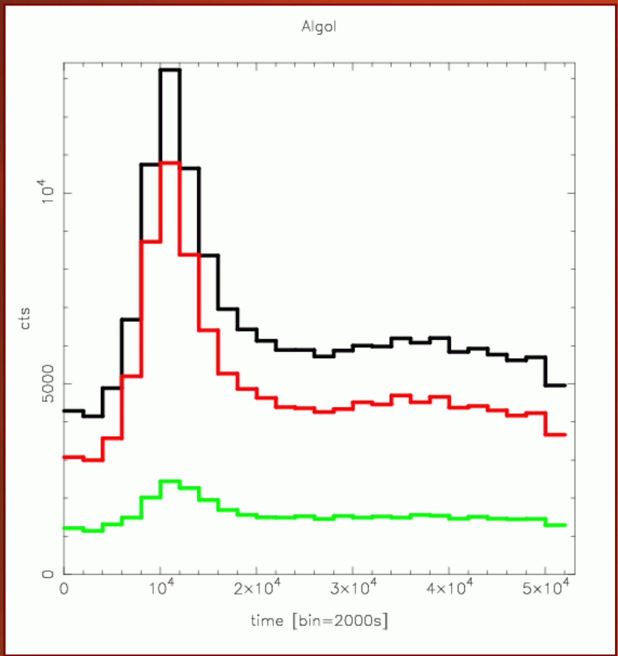

h
Fe Kα
ϕ



R1
D1
D2
R2
D3
D4
Cnt. rate
Time (s)

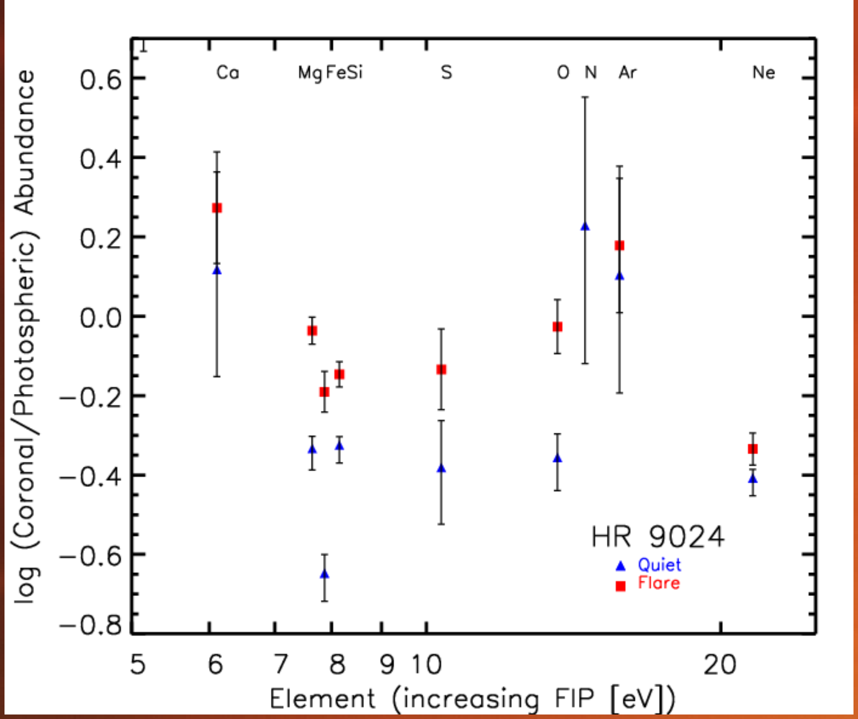


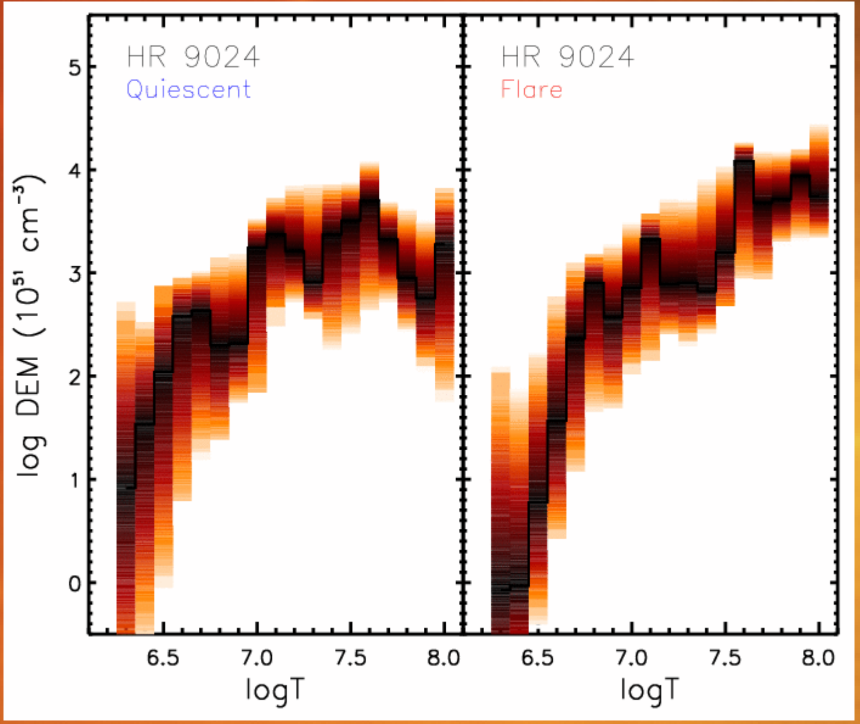
HR 9024
cts
time [bin=2000s]



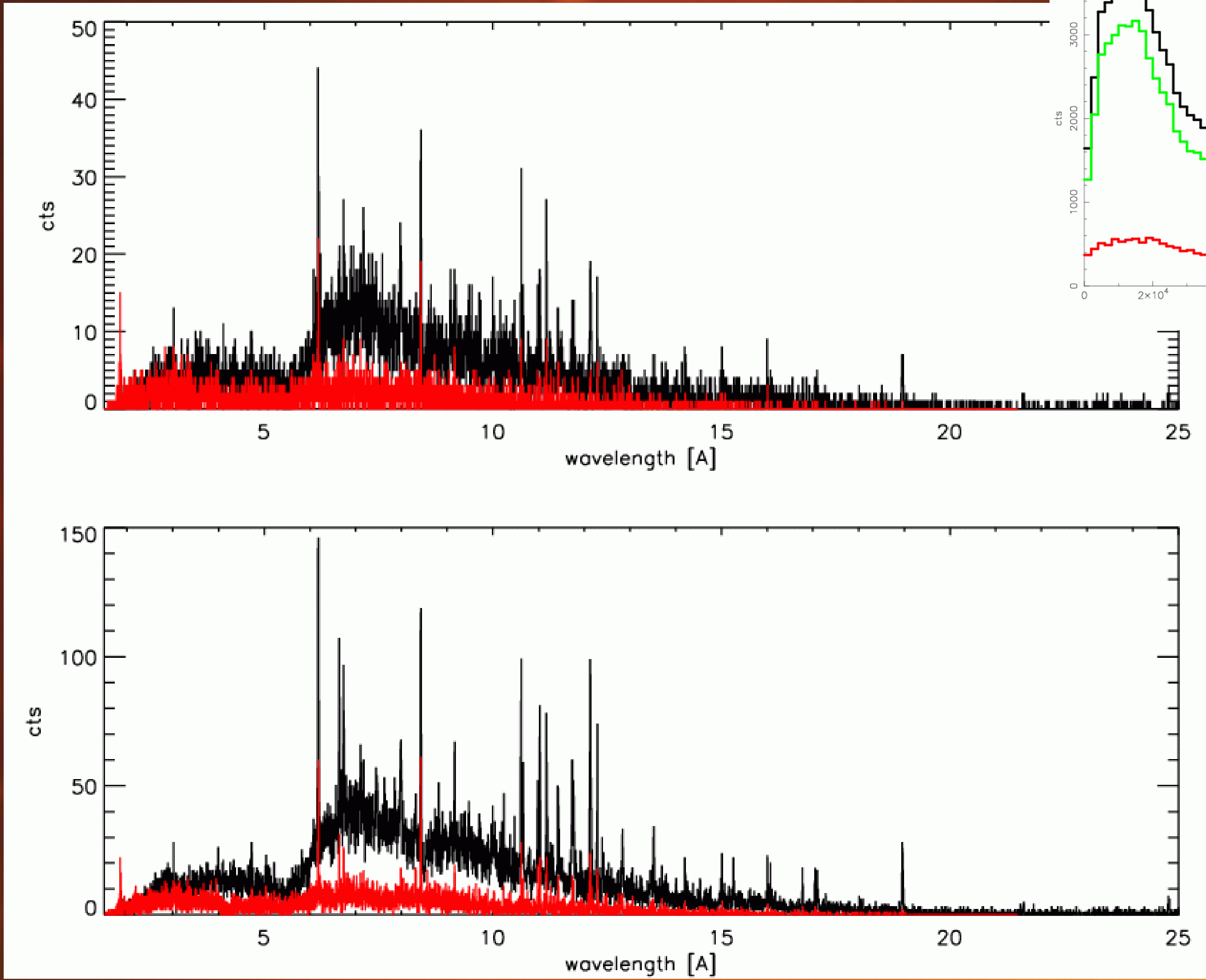
Algol
cts
time [bin=2000s]

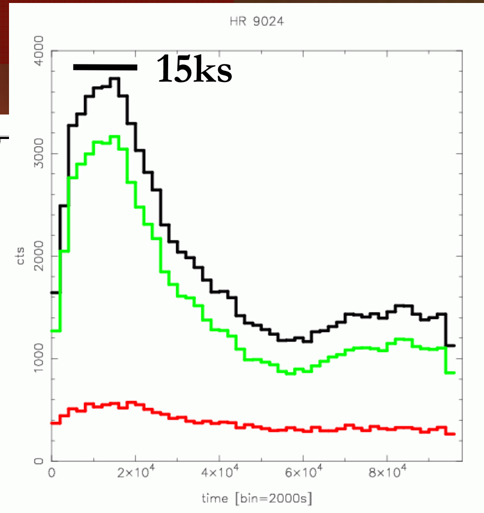
DEM and ABUNDANCES



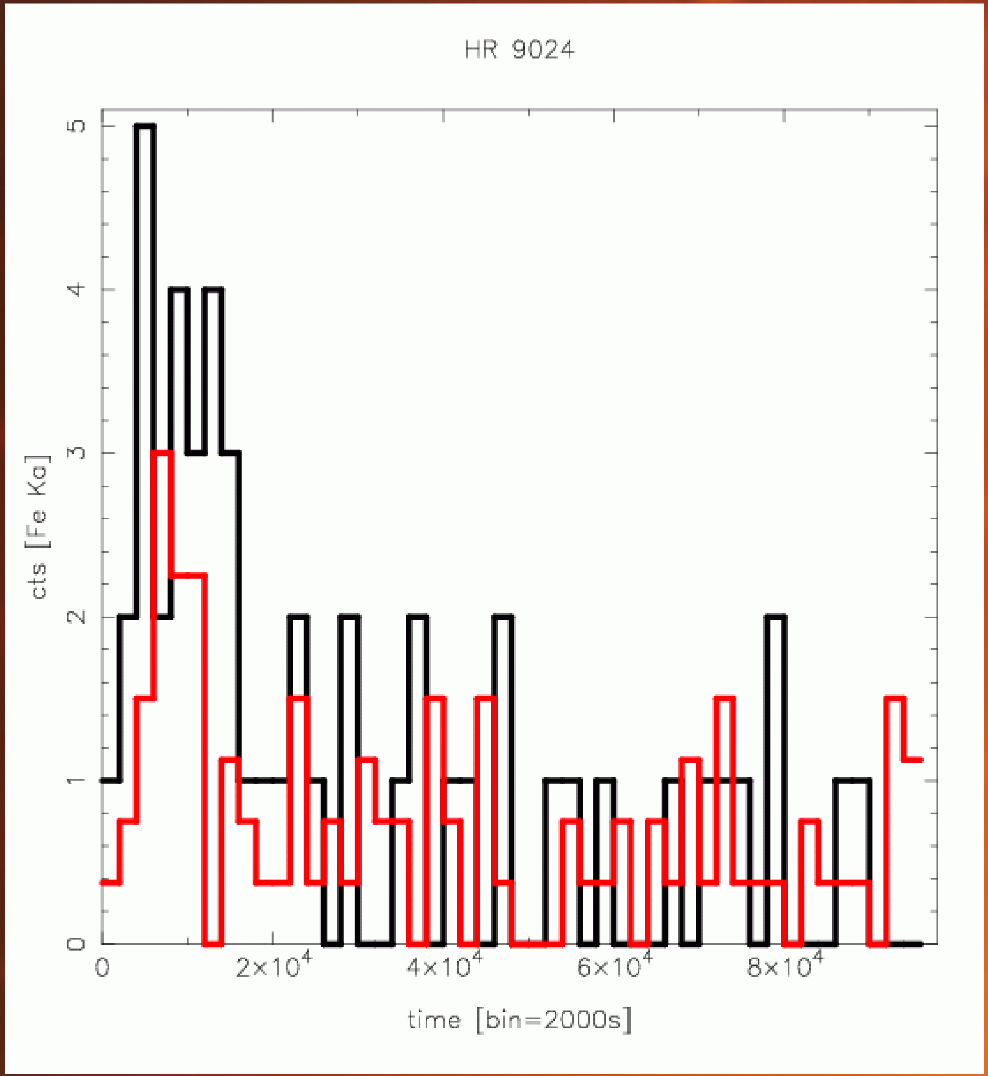


SPECTRA


cts
0
10
20
30
40
50
5
10
15
20
25
wavelength [A]
cts
0
50
100
150
5
10
15
20
25
wavelength [A]


HR 9024
15ks
cts
0
1000
2000
3000
4000
0
2×10^4
4×10^4
6×10^4
8×10^4
time [bin=2000s]

FLUORESCENT EMISSION - Lightcurve



— Fe Kα line

— continuum

K-S test :

Probability of being two realizations of the same distribution

0:96 ks P ~ 0

0:20 ks P ~ 0

20:96 ks P ~ 73%

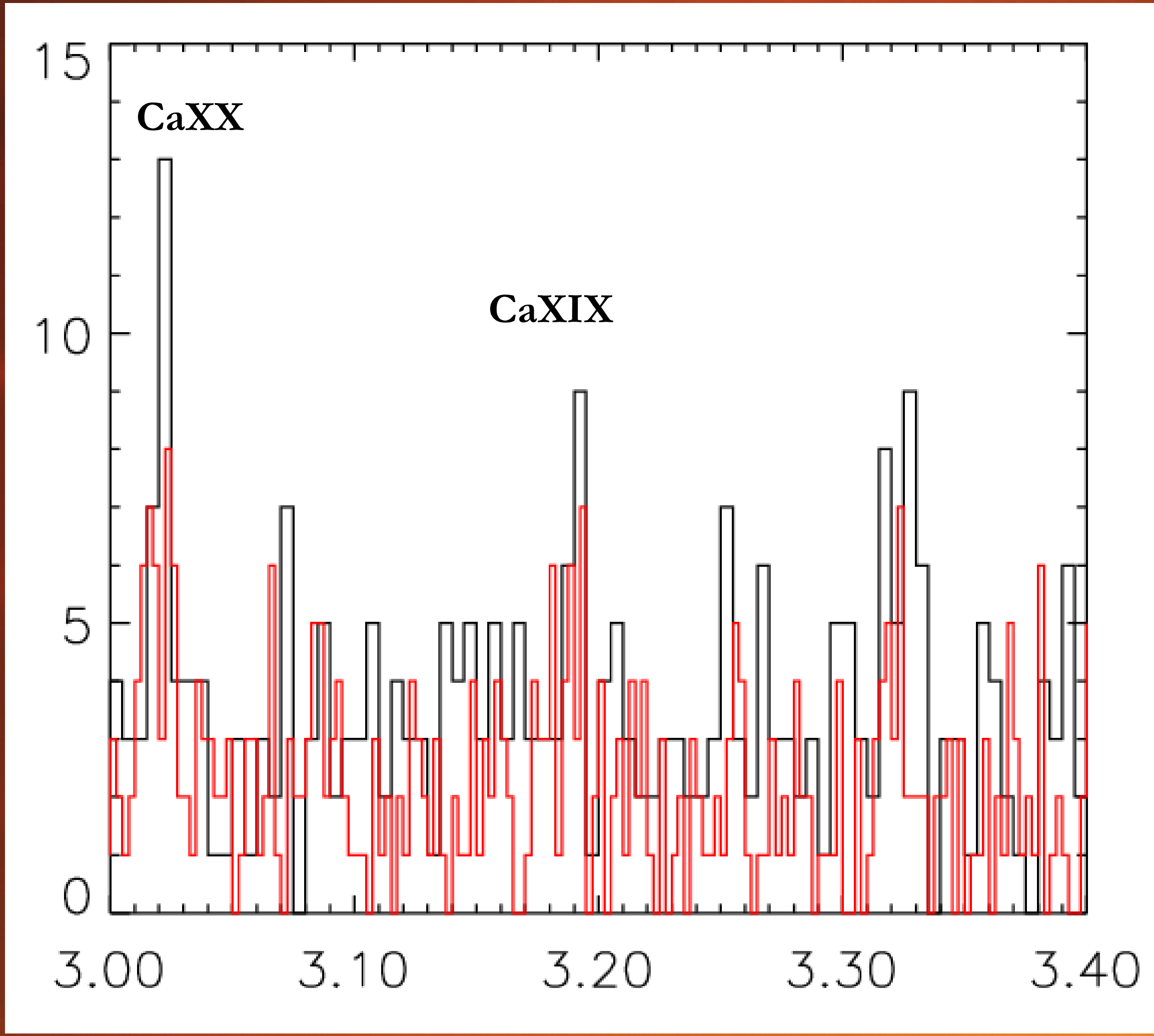
40:96 ks P ~ 94%

FLUORESCENT LINES?

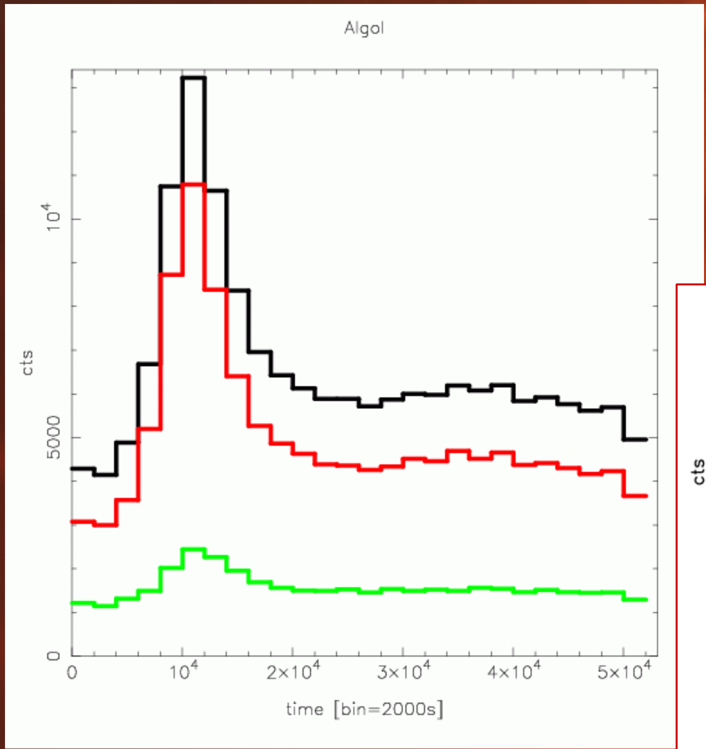
- Fe Kα line (1.93-1.94Å [6.4keV]) observed in solar flares (e.g. Parmar et al. 1984, and several others), in YSO (e.g. Tsujimoto et al. 2005, Favata et al. 2005), in X-ray binaries (e.g. Goldstein et al. 2004, van der Meer et al. 2005, Boroson et al. 2003,…)

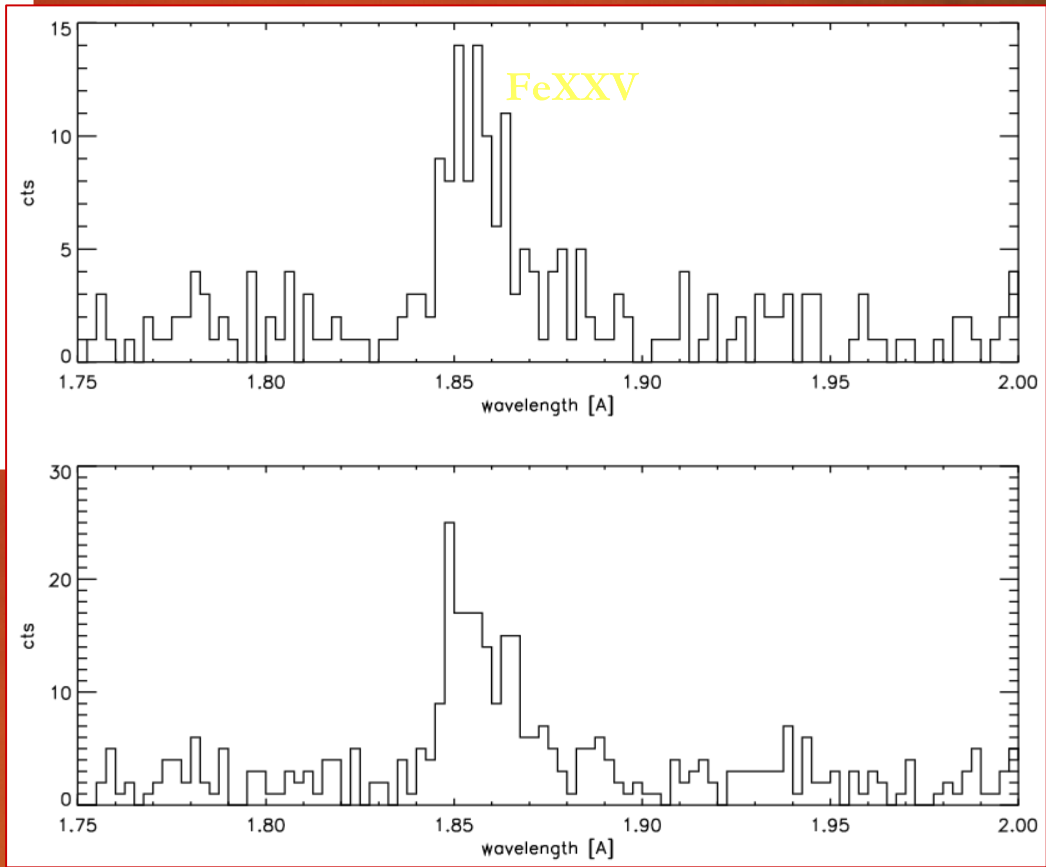
NEVER BEEN OBSERVED IN LATE-TYPE EVOLVED STARS

FLUORESCENT LINES?

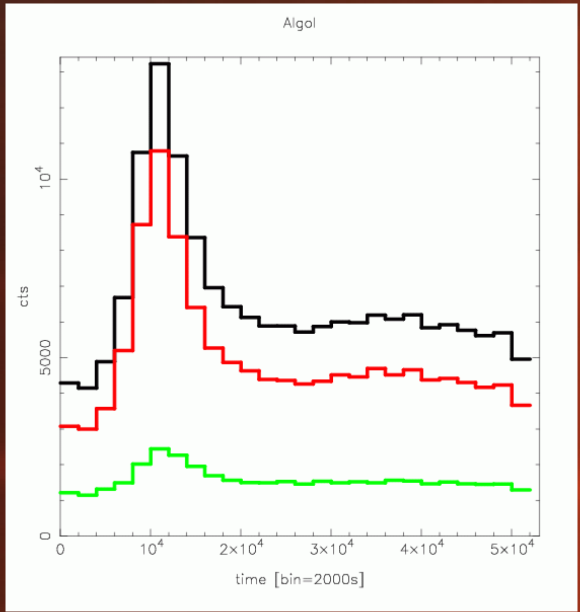


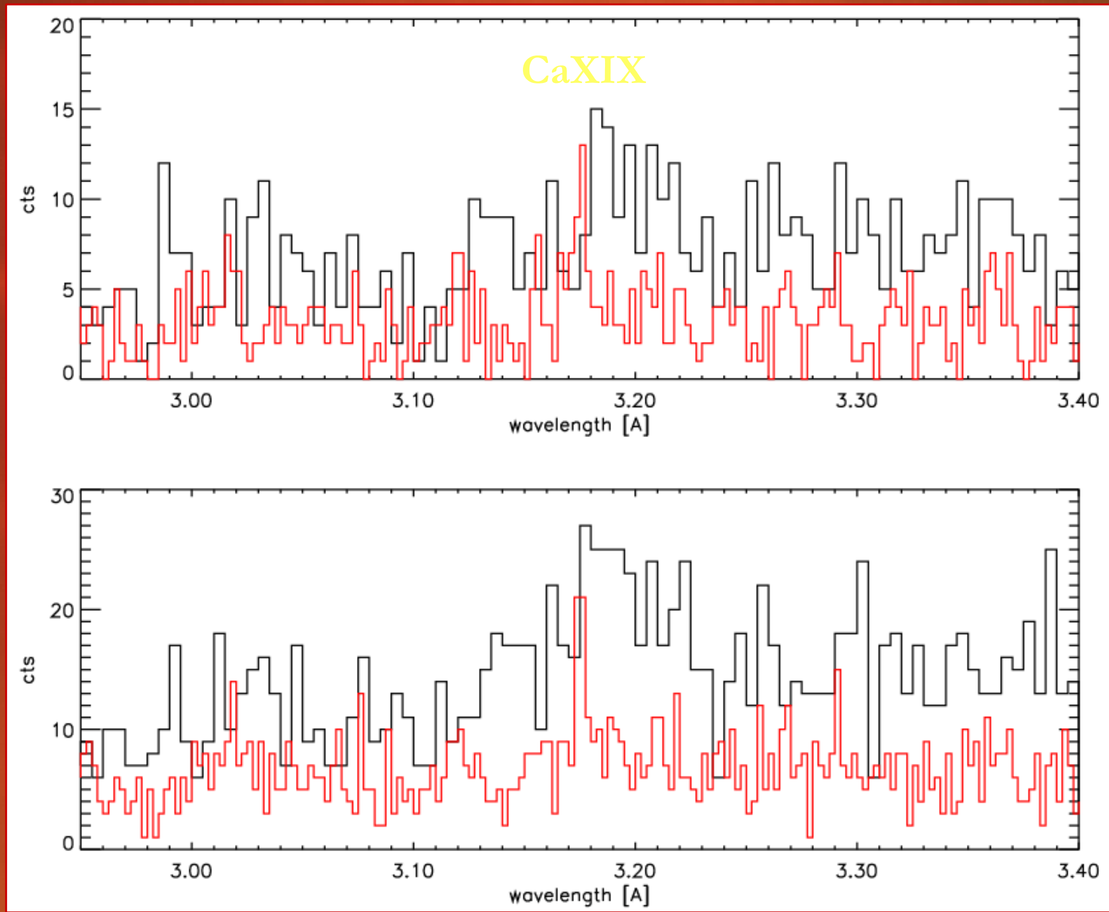
FLUORESCENT LINES? - Algol





FLUORESCENT LINES? - Algol





FLUORESCENT LINES?