Unusual patterns of line intensities seen on RESIK soft X-ray flare spectra

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RESIK

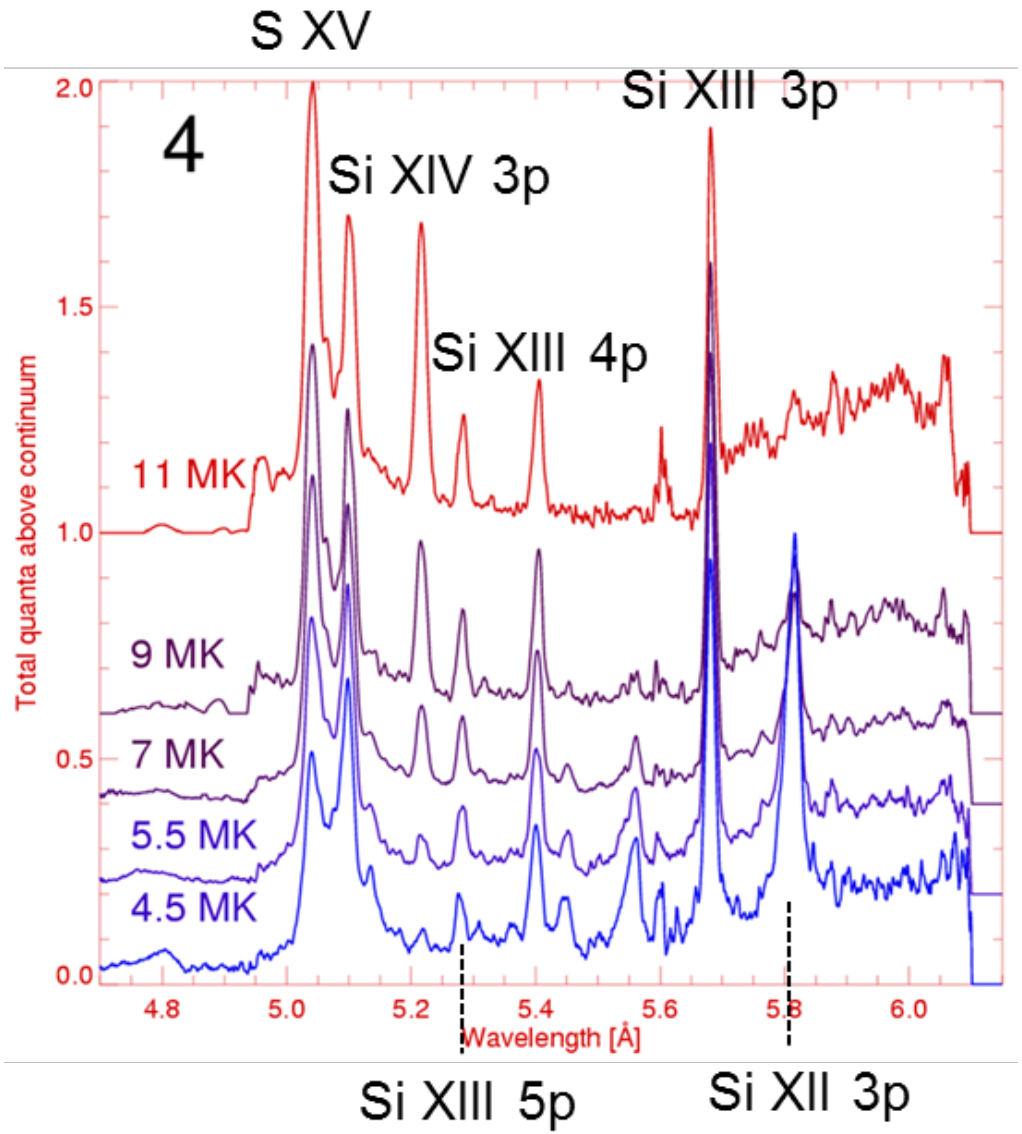
The RESIK instrument (**Re**ntgenovskij **S**pectrometer s **I**zognutymi **K**ristalami) consists of two double detector (spares from *Yohkoh* BCS) and four mono-crystal wafers of Quarts and Si bent to desired radius. This X-ray spectrometer collected spectra in four bands:

channel 1: 3.37 - 3.88 Å
channel 2: 3.82 - 4.33 Å
channel 3: 4.31 - 4.89 Å
channel 4: 4.96 - 6.09 Å

RESIK was the most recent solar soft-X-ray Bragg spectrometer, flown in 2001. Resik observed numerous (>100) flares as well as active region emissions. During large flares, the spectra collection times (DGI- data gather interval) could be as short as 2 s. For non-flaring periods DGI was ~5 min. By now the spectra for 75 flares have been reduced to so-called level 2 (science grade absolute fluxes).

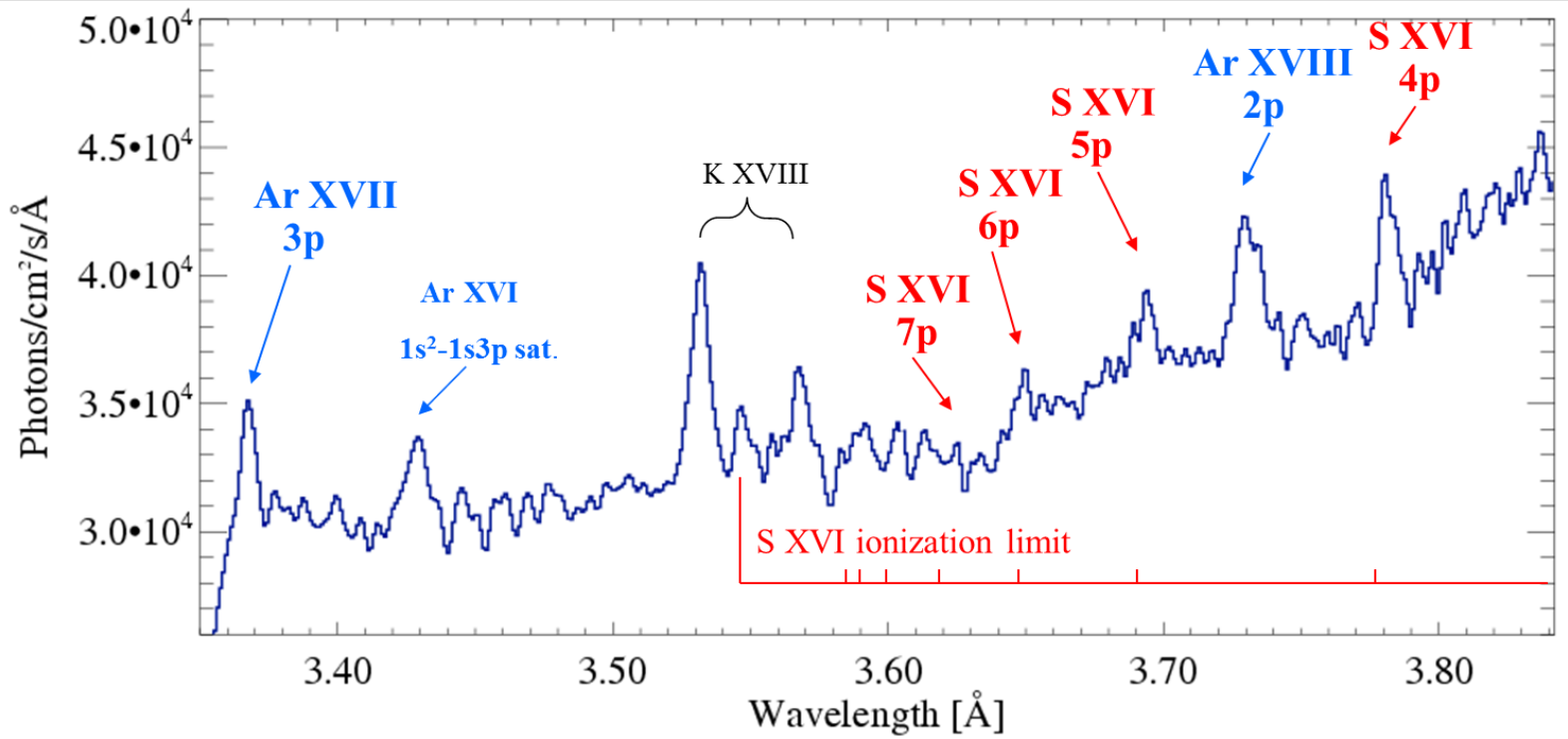
Many measurements were taken during the flares' rise phase. For some impulsive events peculiar line intensity ratios are sometimes observed, reflecting presence of non-"standard" conditions in flaring plasma. For some lines, observed intensity ratios cannot be explained even in the multi-temperature approach.

Temperature ordered channel 4 spectra



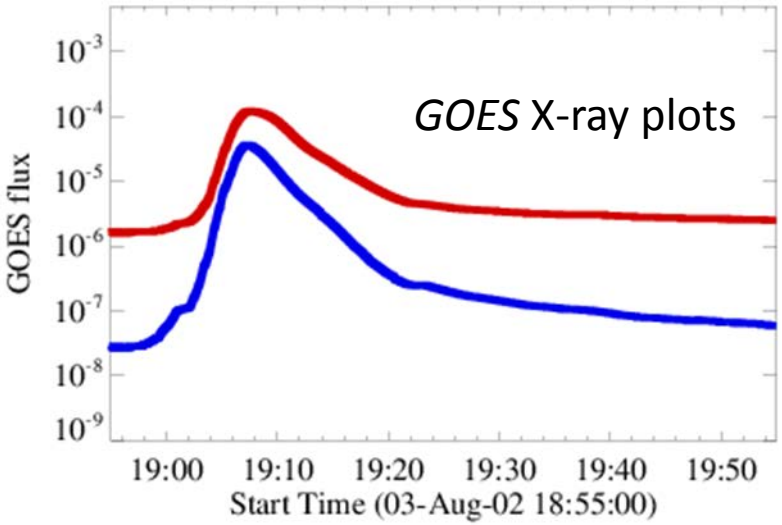
1163 RESIK spectra collected between
1 January and 14 March 2003 (best observing sequences) were grouped according to the emitting plasma temperature and averaged in order to reveal spectral features in detail. The collected set of spectra covers as well lower class events (~B4) as few M class flares. (Sylwester, B. et al., Adv. Space Res., 38, 1534, 2006)

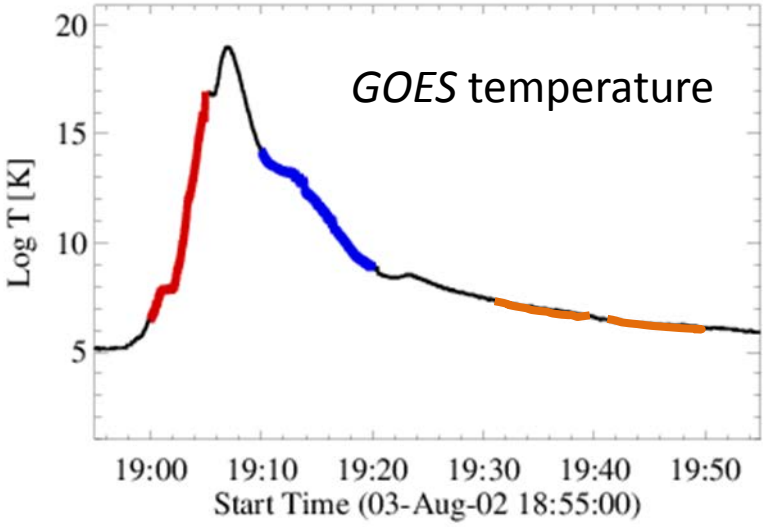
Average channel 1 spectrum for 14 flares (2003, Δt≈9h)

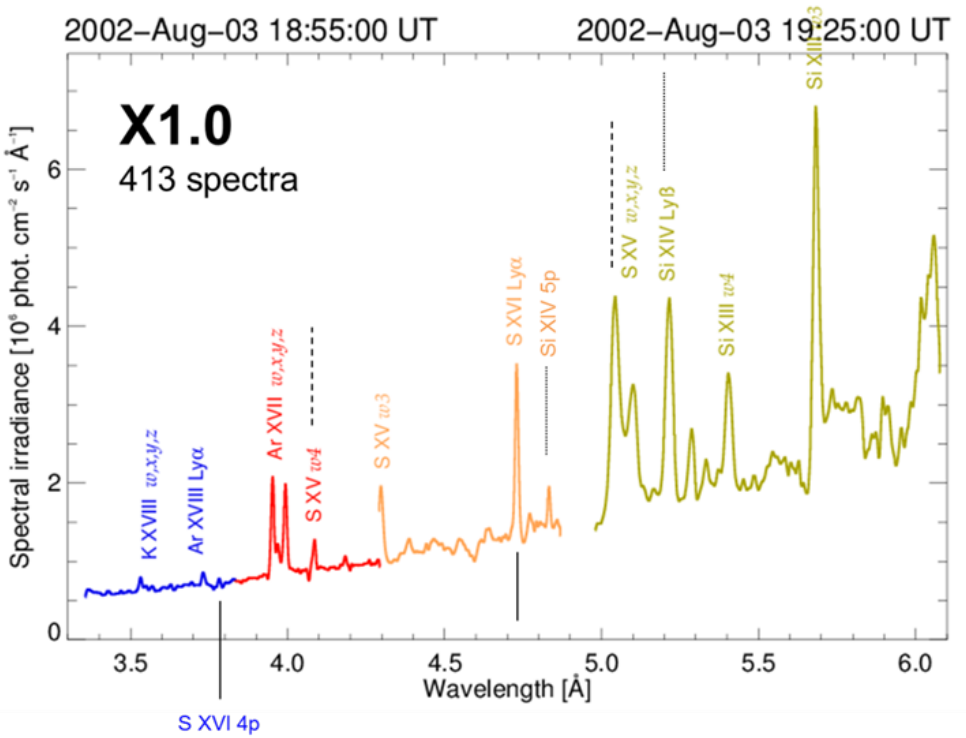


RESIK channel 1 (3.37 Å to 3.83 Å) includes many strong emission lines due to transitions $1s^2$ - 1s(np) and 1s - np, in He-like and H-like ions respectively; the n = 2 and 3 lines have been routinely observed for Si, S and Ar ions in numerous previous experiments. Here, for the first time we have observed for some flares enhanced emission in spectral features coinciding with transitions for **n up to 7**. Respective observed line series intensity decrements have been determined and discussed in the paper by Kepa et al., 2006 (Adv. Space Res., 38, 1538).

SOL2002-08-03T19:07

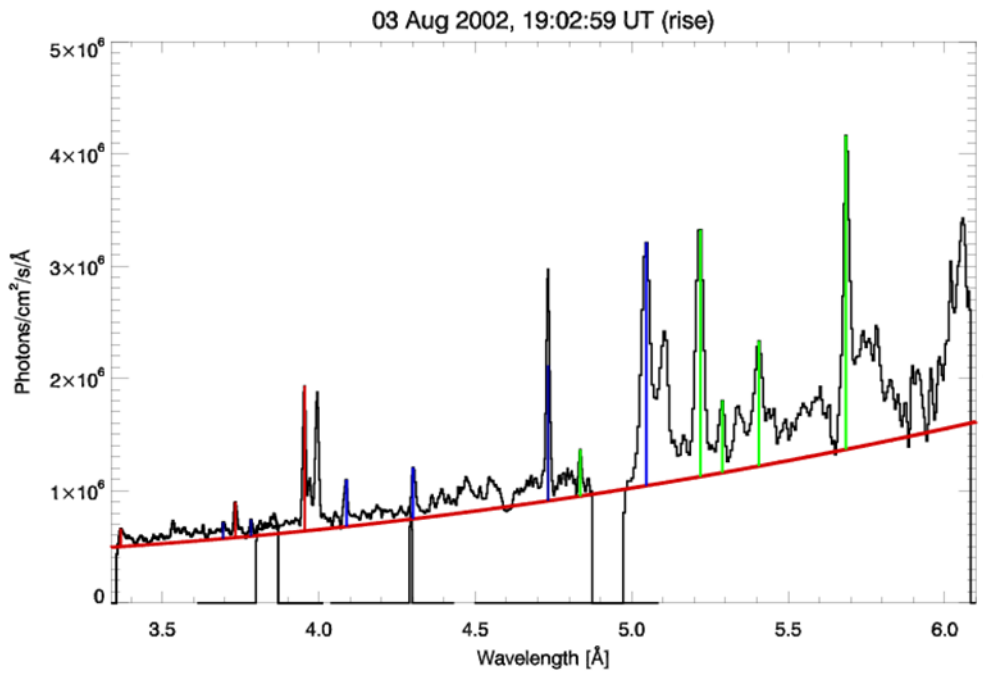


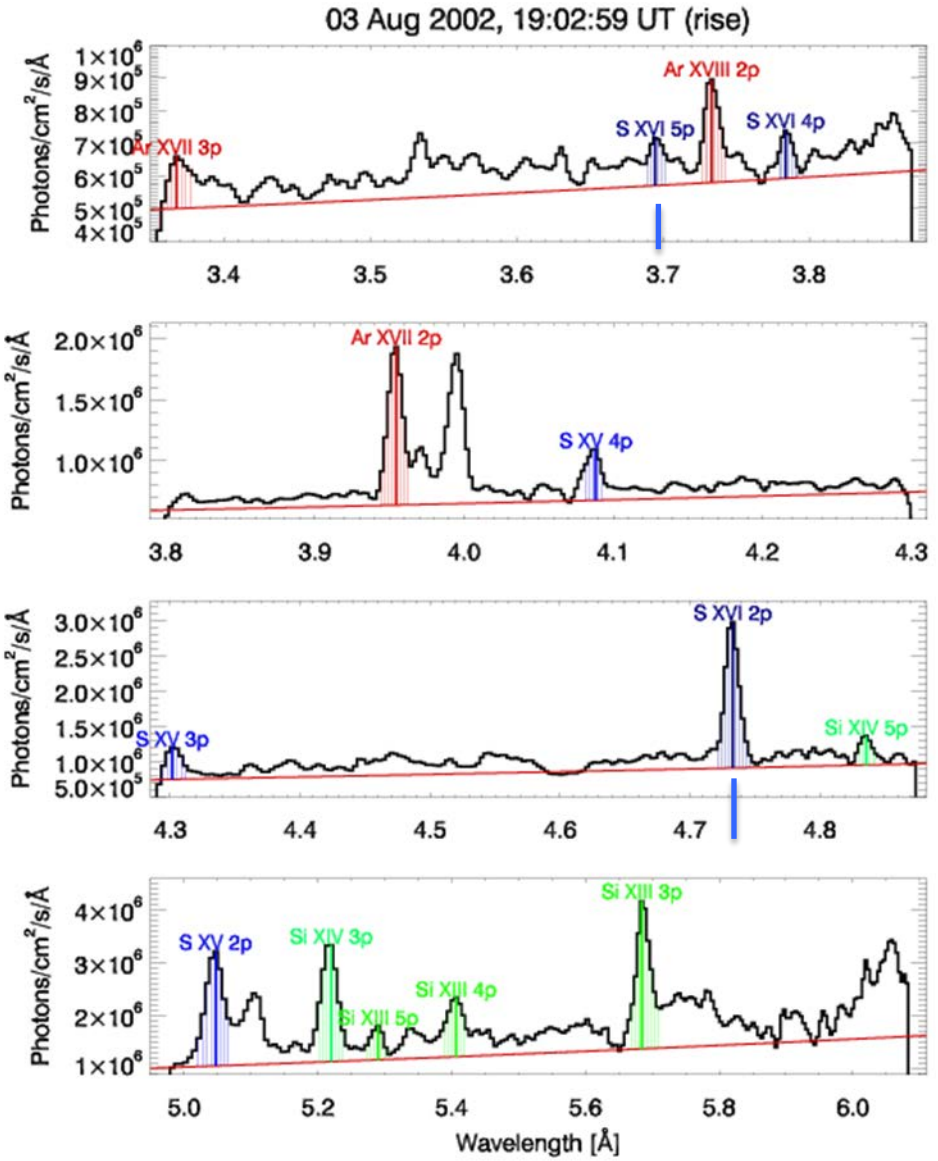




GOES lightcurves and the temperature profile – red part denotes rise phase observed with RESIK and blue decay phase. Close to maximum, detectors were saturated as the flare was a strong X1 flare. RESIK observed also late decay part (orange) of the evolution. **This was the most intense flare recorded by RESIK!**

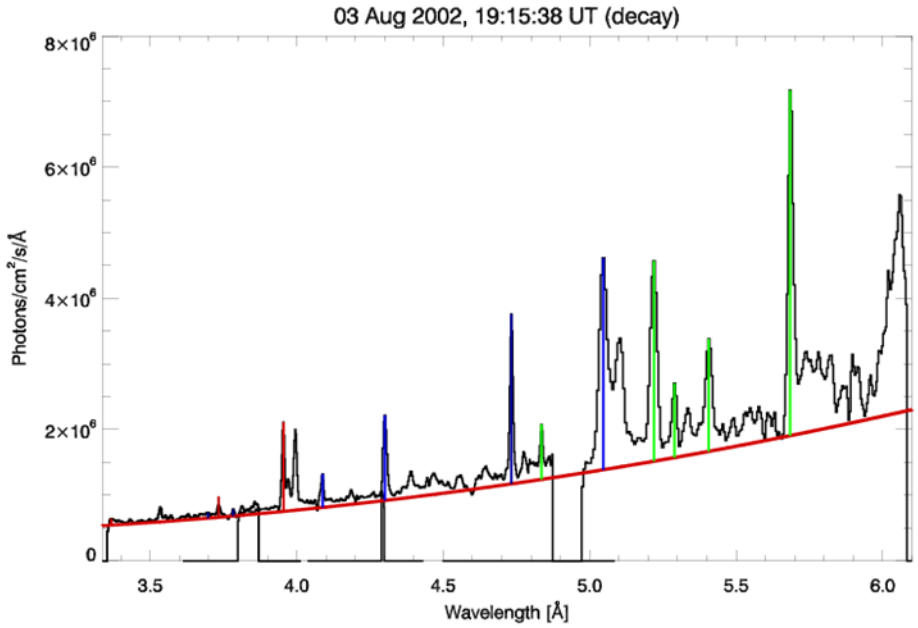
Flare rise time spectra

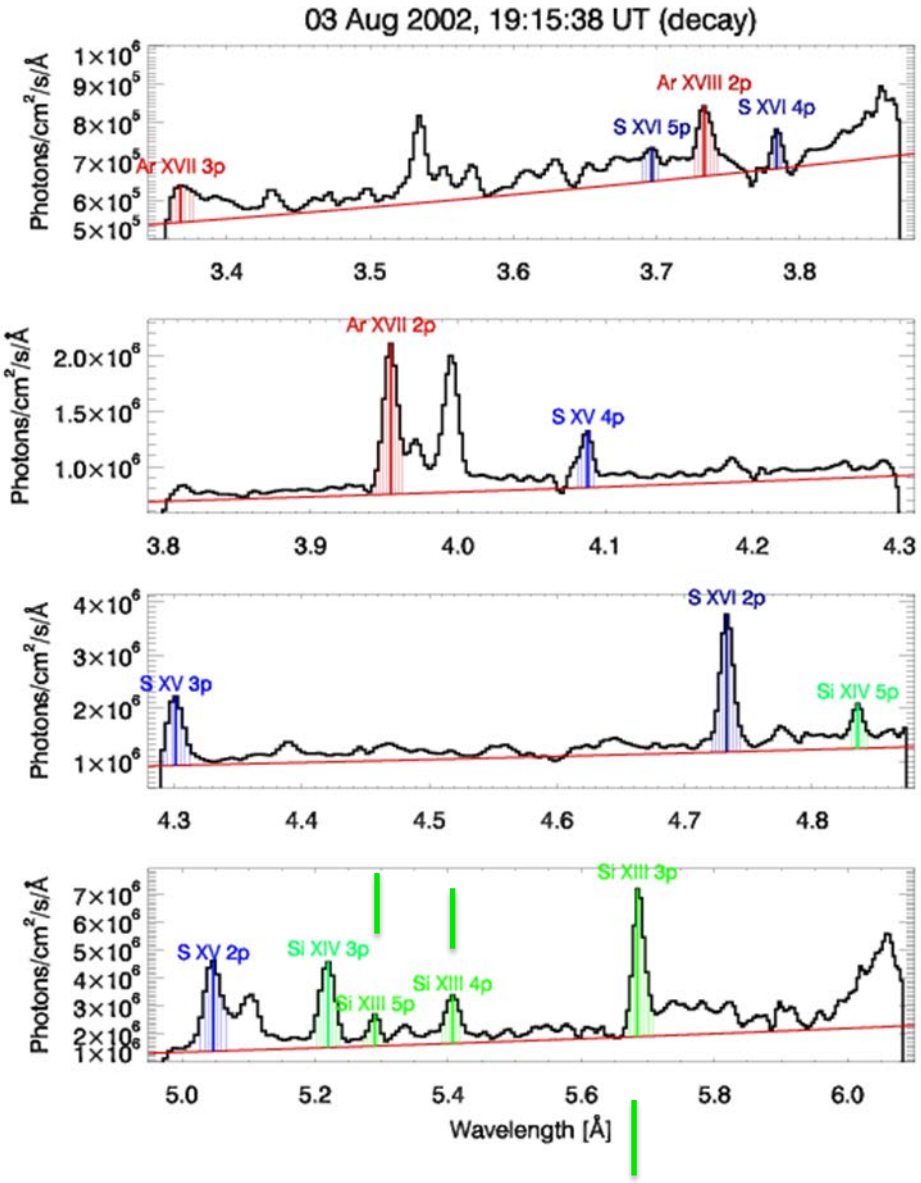




SOL2002-08-03T19:07 rise phase spectrum. The continuum is shown as the red line. **Fluxes in line features were estimated as corresponding to count rates seen above the continuum.** Colours represent respective elements. Features corresponding to n=2, 3, 4 & 5 transisions are clearly seen.

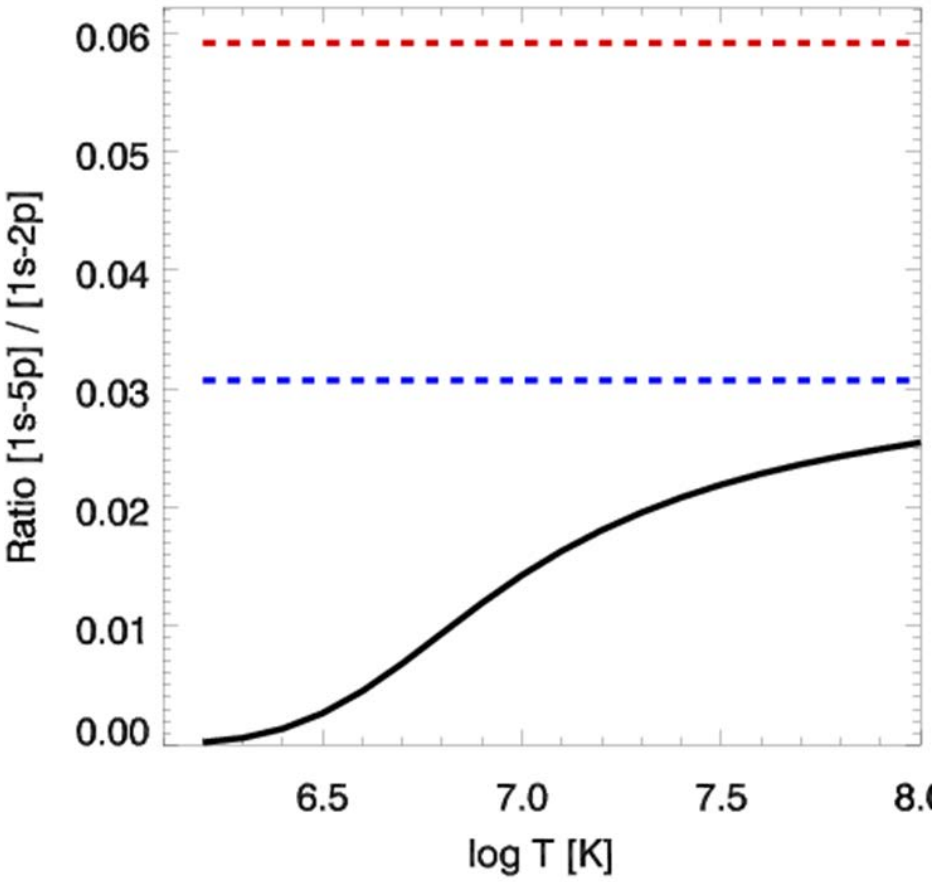
Flare decay time spectra





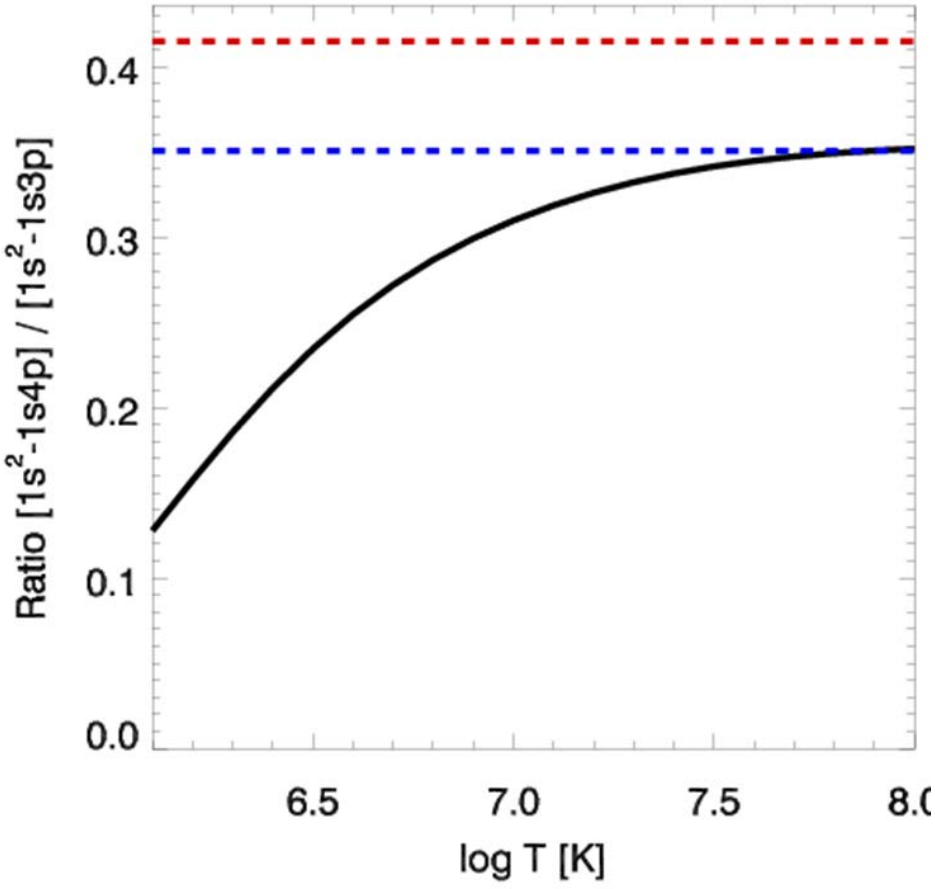
SOL2002-08-03T19:07 decay phase spectrum. The continuum is indicated. Colours represent respective elements. Again, spectral features corresponding to n=2, 3, 4 & 5 transisions are well pronounced.

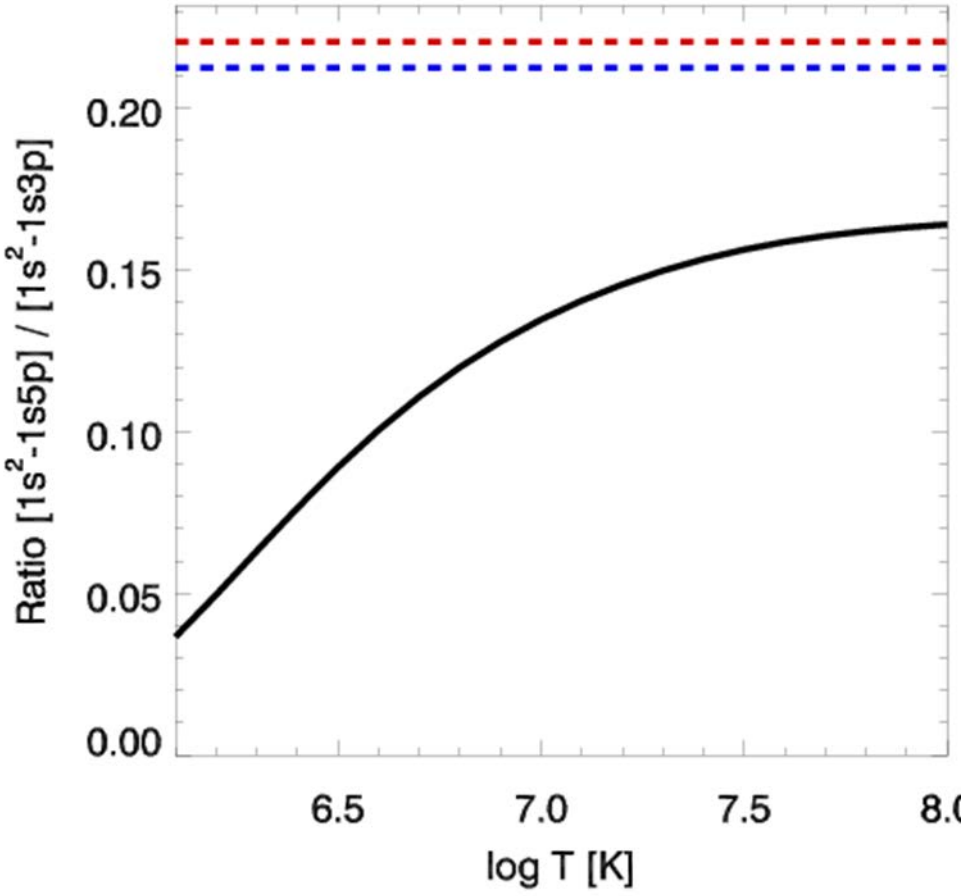
The **S XVI** hydrogen-like ion intensity ratio *n*=5 to *n*=2 transitions



Based on the observed count rate in lines, their averaged fluxes have been determined for the **rise phase** and the **decay**. Respective intensity ratios have been determined (dashed lines) and compared with the theoretical predictions. As the lines originate from the same ion by collisional excitation, their ratios can be calculated easily. Here we have calculated values of this ratio using CHIANTI 7.0 routines (**solid black line**) for a number of temperatures assuming maxwellian particle distribution function (pdf).
For both the rise and decay phases, the observed ratios are above theoretical - possibly indicating non-maxwellian pdf.

The **Si XIII** helium-like ion intensity ratio: *n*=4 & 5 to *n*=3 transitions

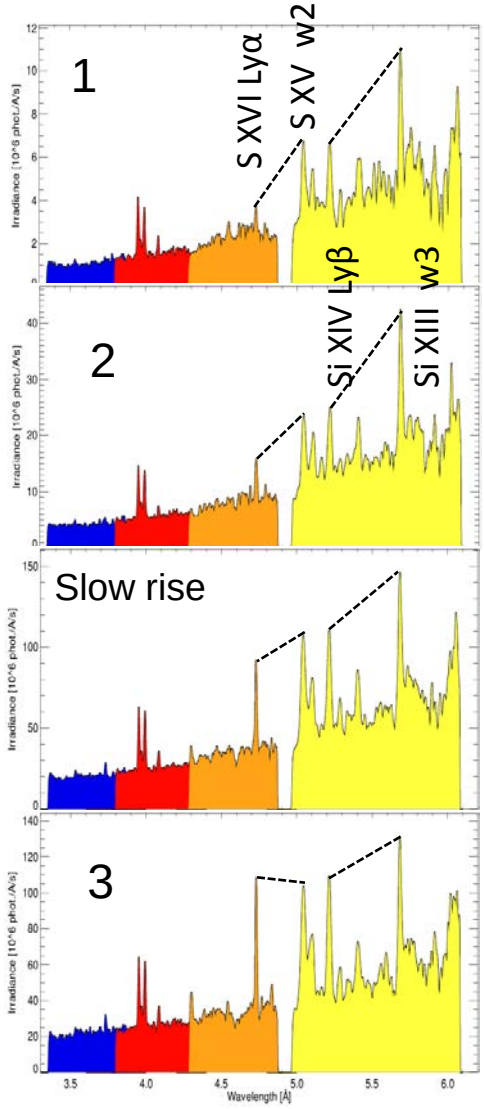


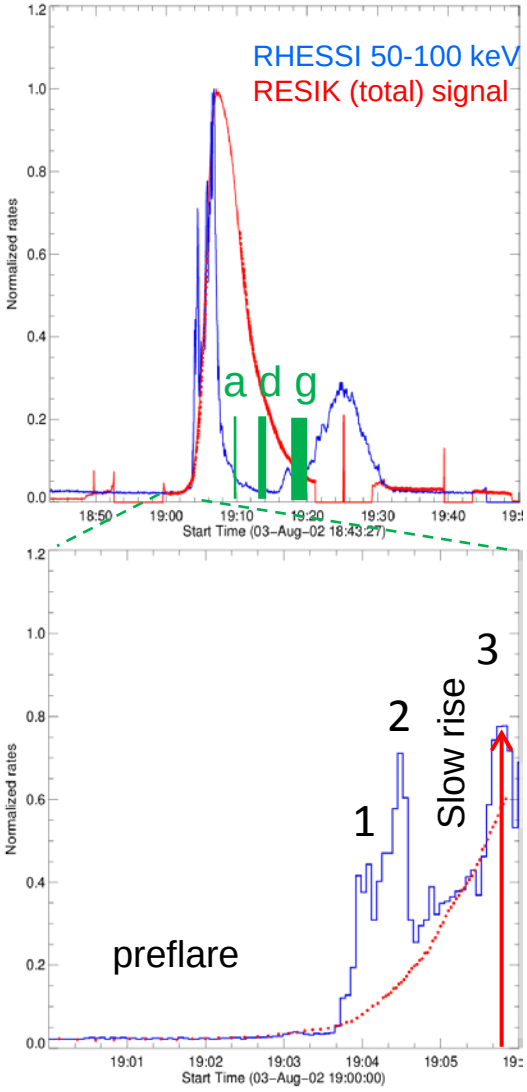


A similar pattern is observed, **excluding** assumed thermal character of upper-level population

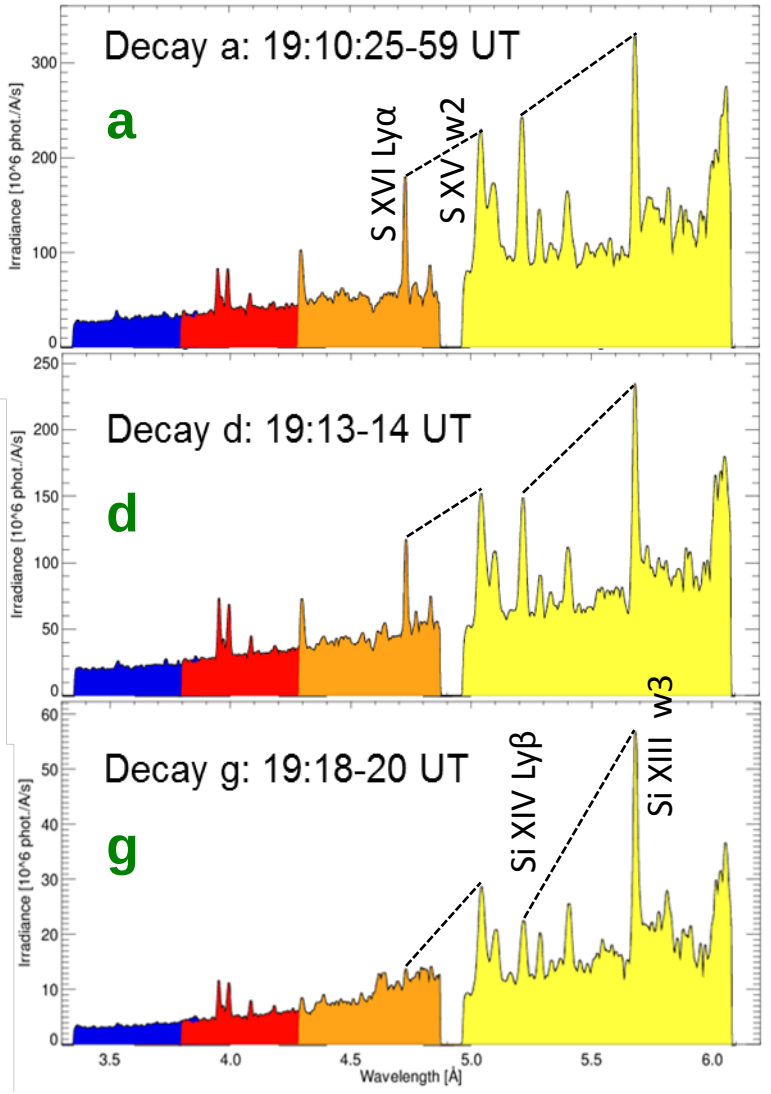
Details of SOL2002-08-03T19:07 spectra & their evolution

RISE phase spectra

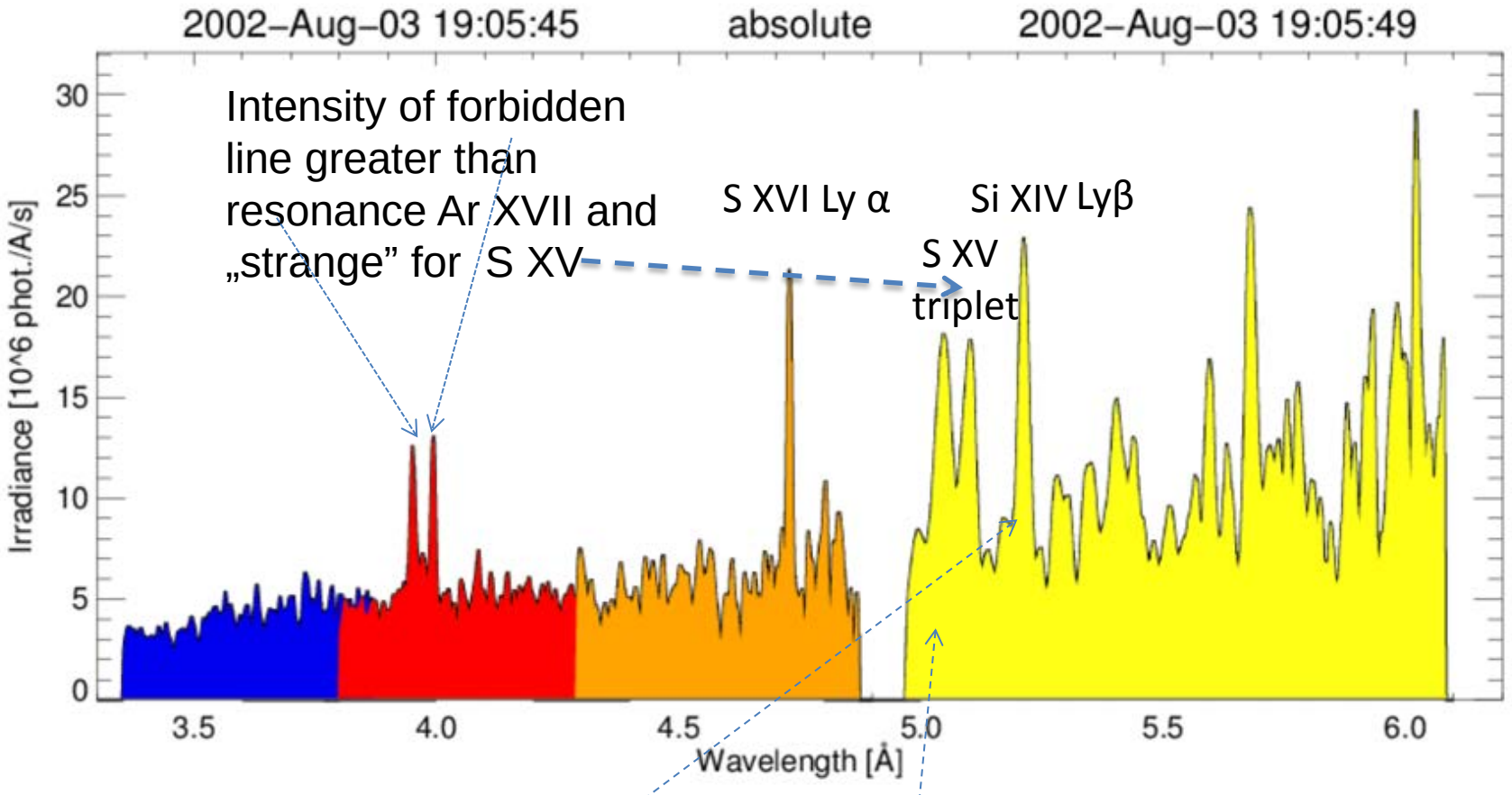




DECAY

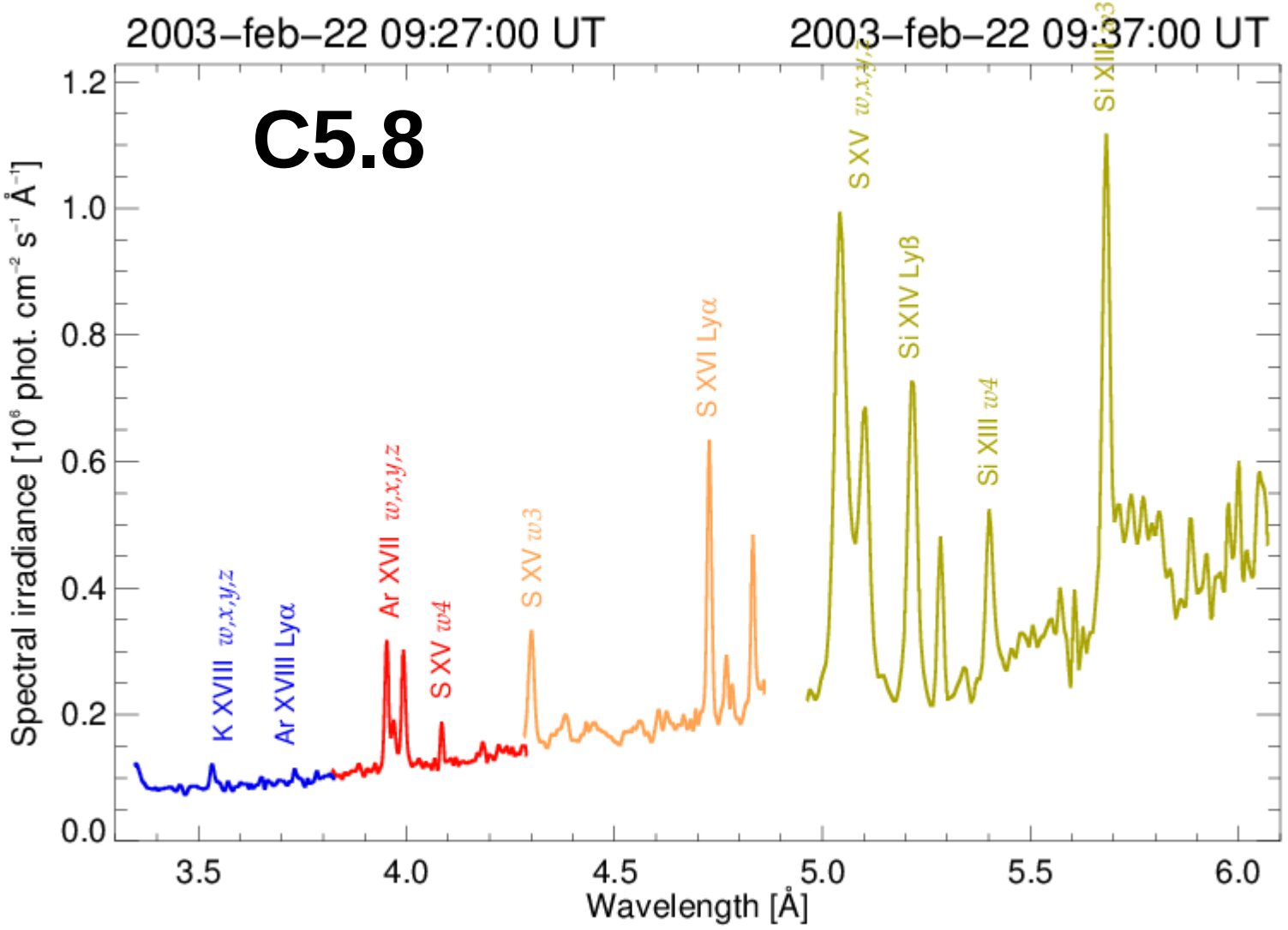


The unusual 4s DGI spectrum seen at the peak of HXT impulse „3” (red arrow on previous)



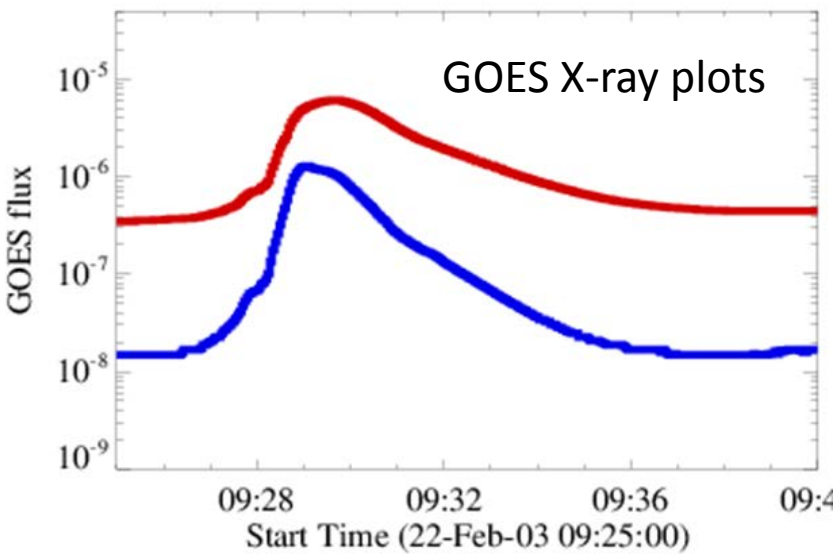
In **hot** thermal plasma, the intensities of triplet lines preserve a well known pattern with the strongest resonance transition, weaker forbidden and the weakest intercomination lines. The relative intensity of Si XIV Lyβ line exeeds the S XVI Ly α line intensity which is unusual.

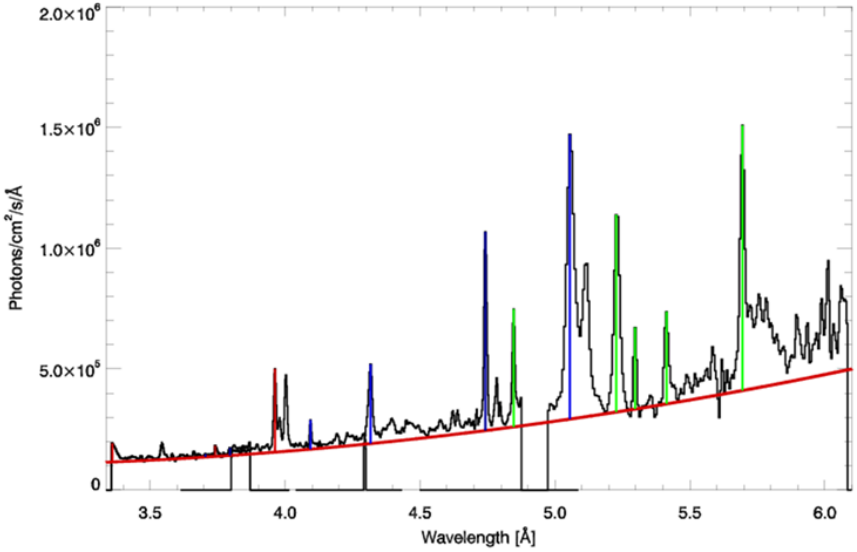
Another flare: SOL2003-02-22T09:29

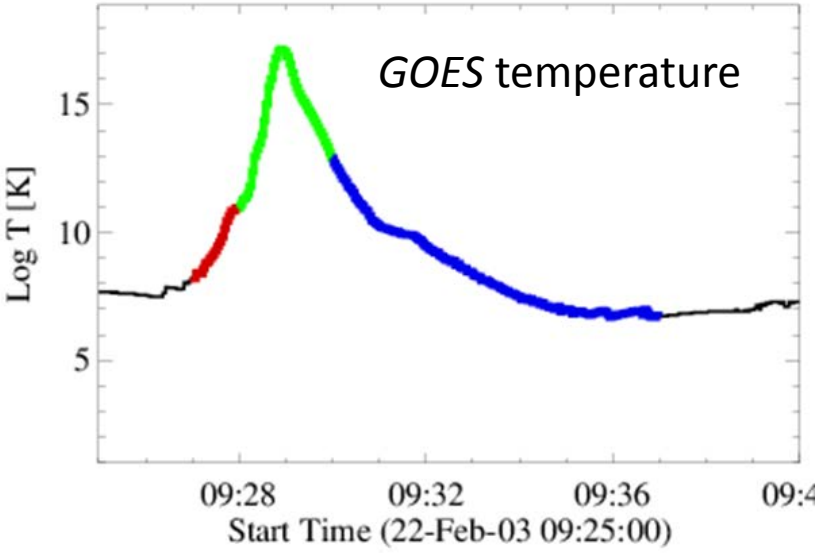


Event summed spectrum. Spectrum collection time was 600 s.

2003/02/22 09:29:00 **C5.8**

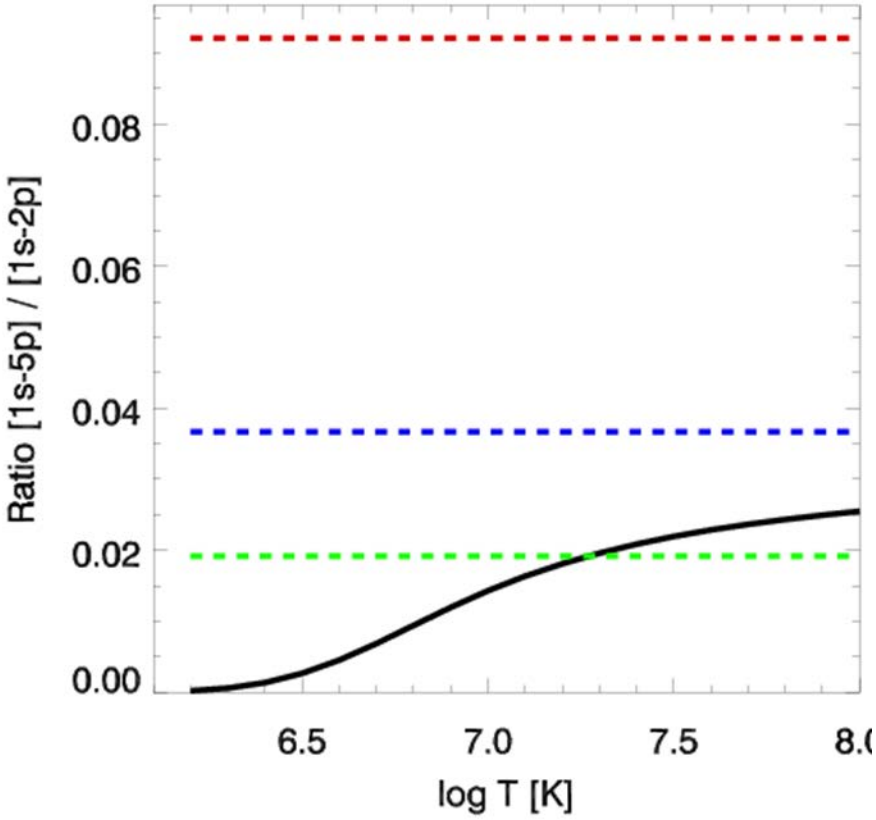


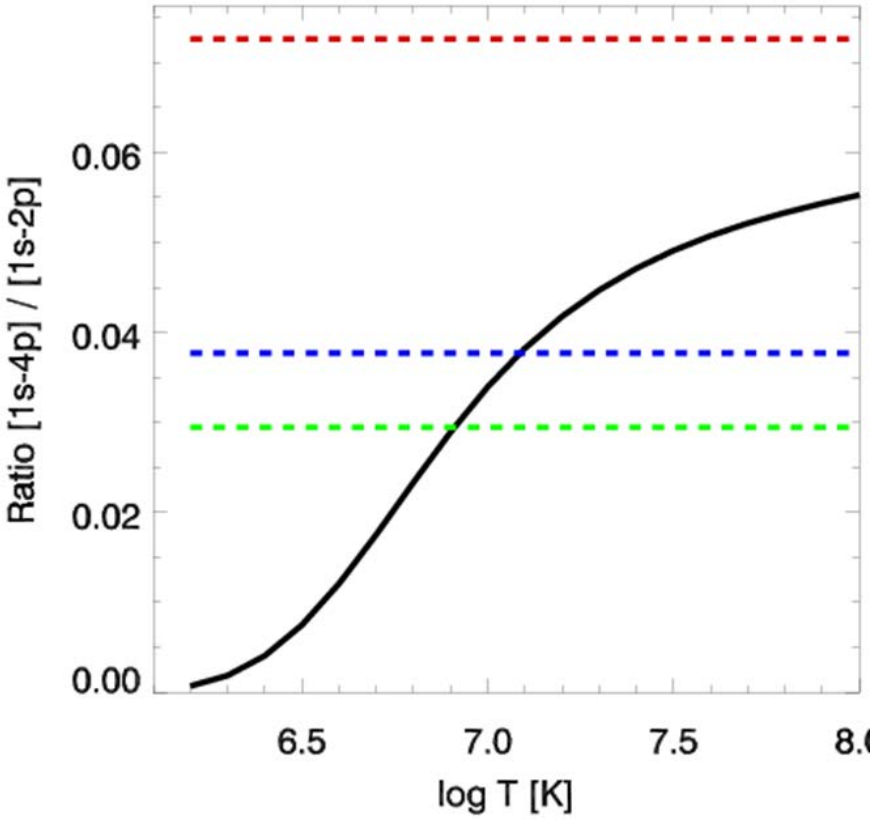




GOES lightcurves and the temperature profile for a **moderate class** flare. The RESIK spectrum above was time integrated over the maximum phase. Here the colours indicate: **the rise phase**, **maximum**, and the **decay**.

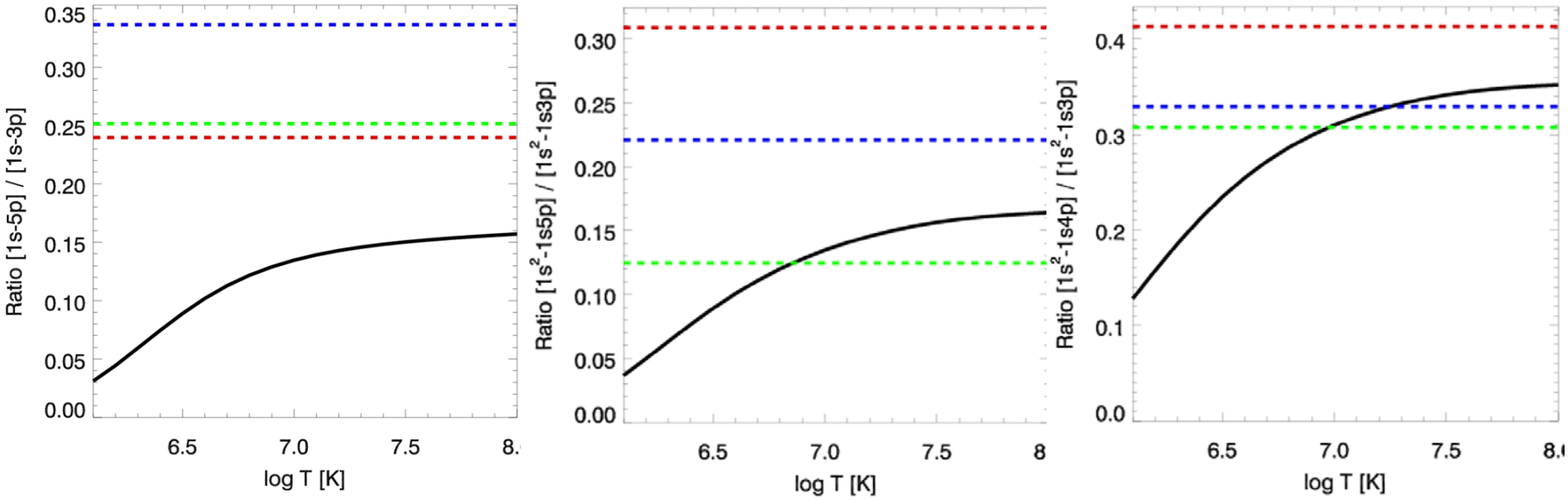
The **S XVI** hydrogen-like ion intensity ratio ***n*=5** & **4** to ***n*=2** transitions





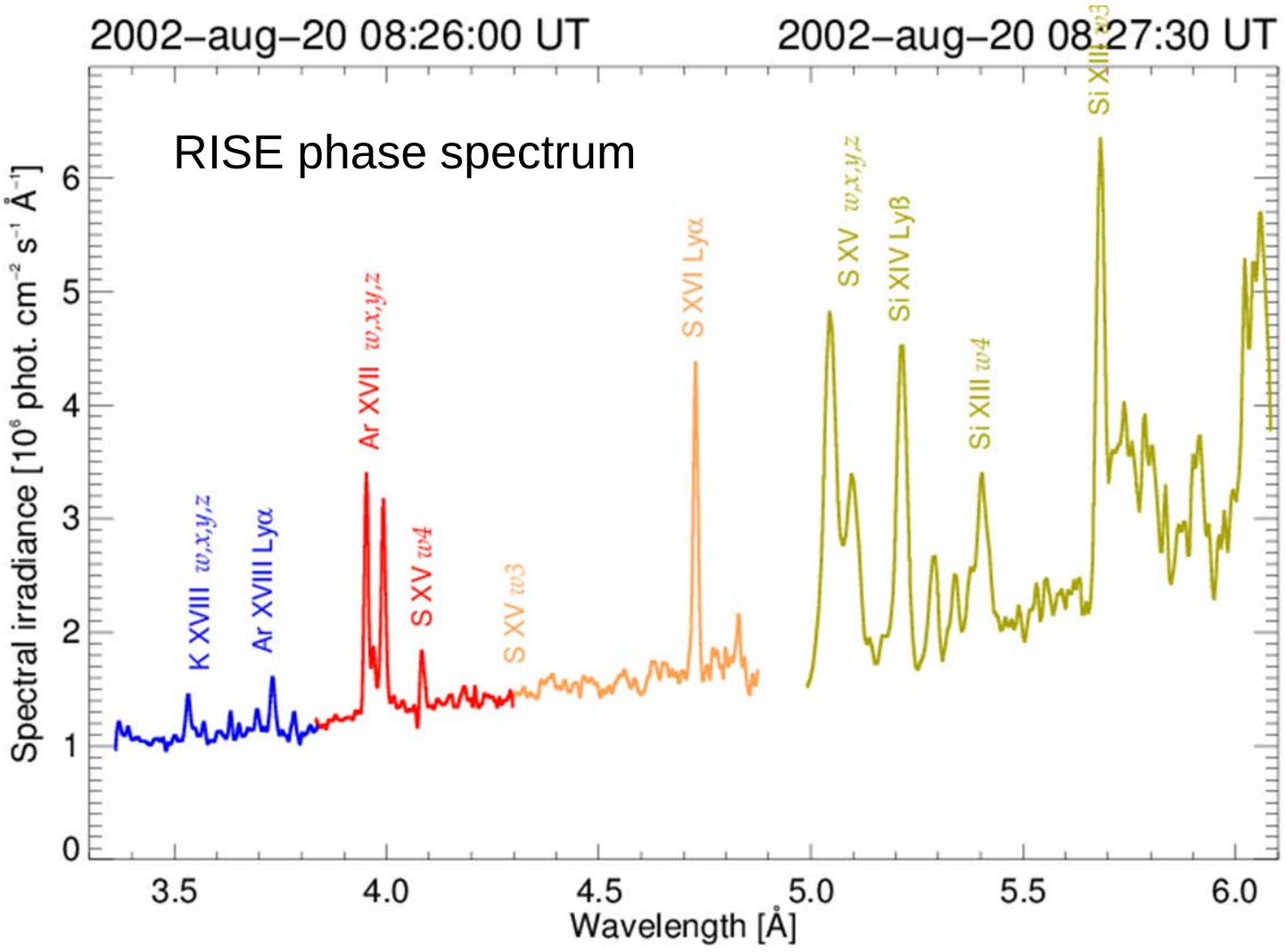
In this case, thermal excitation model is marginally possible for maximum and decay flare phase but **NOT** for rise phase.

The **Si XIV** H-like and **Si XIII** He-like ion intensity ratios for *n*=5 & 4 to *n*=3 transitions

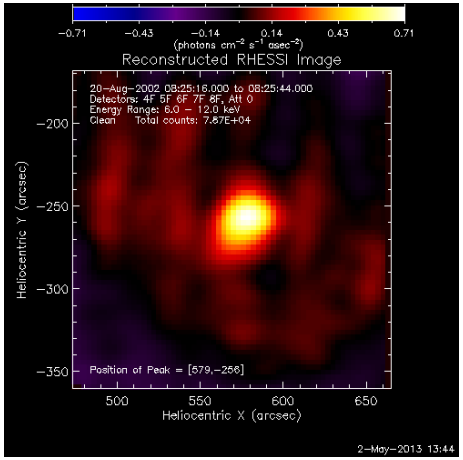


Again, thermal excitation model is marginally possible for maximum and decay flare phase, but only in case of helium-like ion transitions. H-like excitations cannot be explained in the coronal equilibrium excitation scenario.

Another flare: SOL2002-08-20T08:25

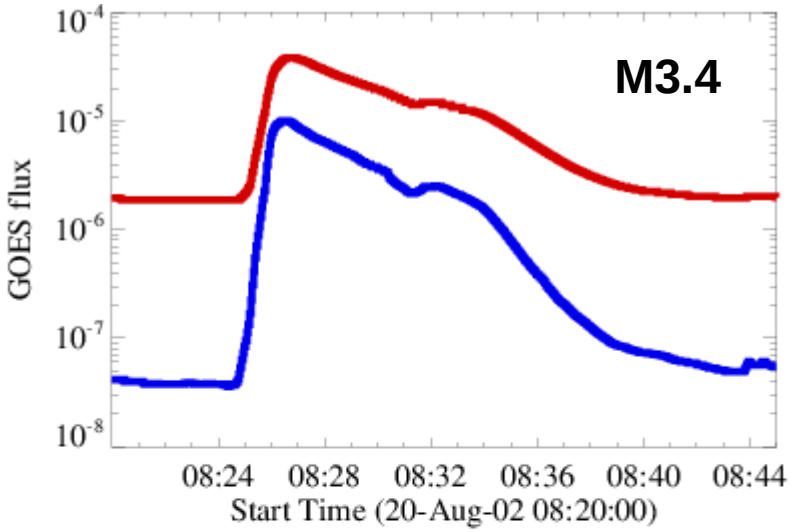


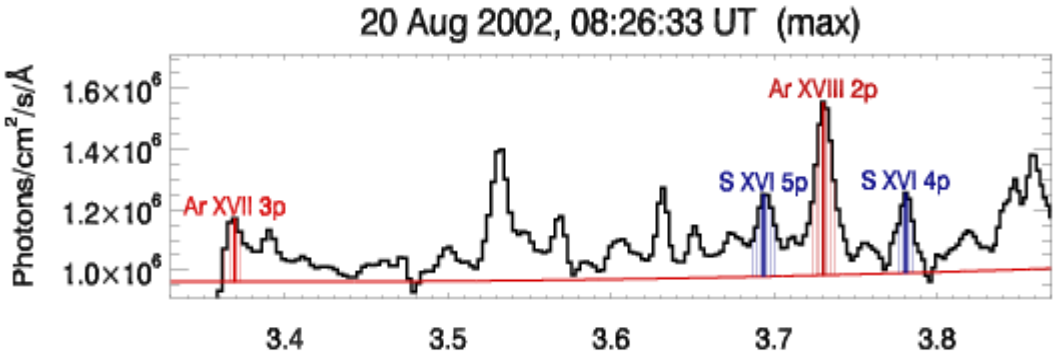
Spectrum summed over 90 s during the impulsive rise phase.

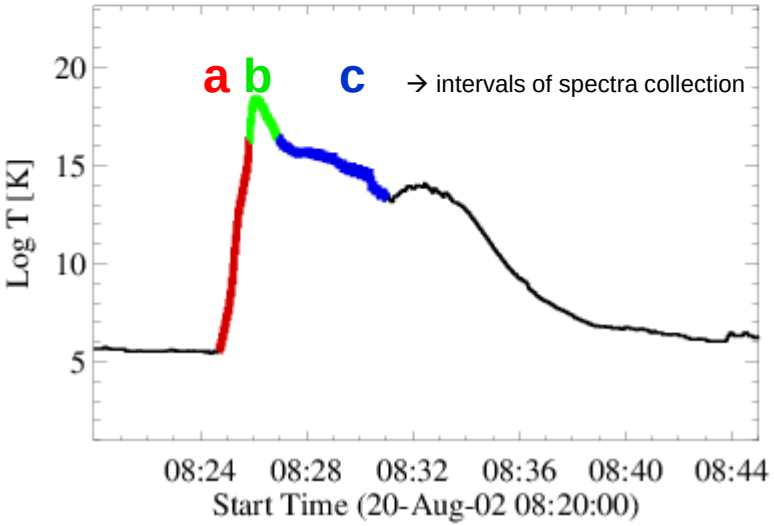


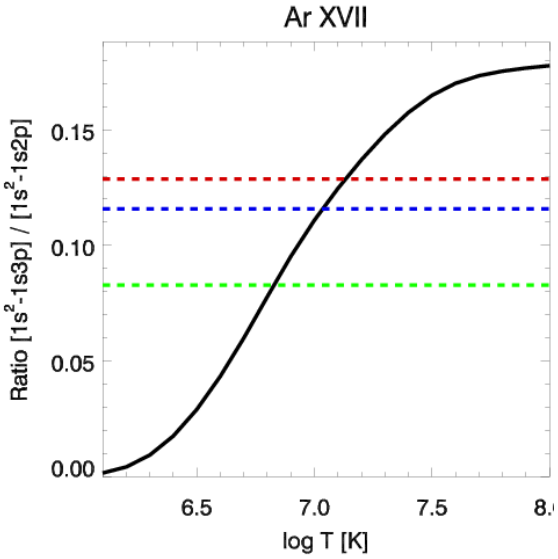
RHESSI reconstructed image (6-12 keV, maximum phase).

This SOL2002-08-20T08:25 was the most impulsive among the events analysed

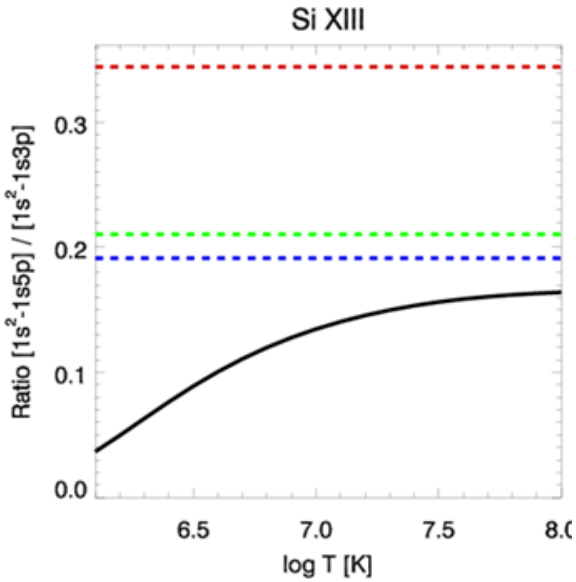


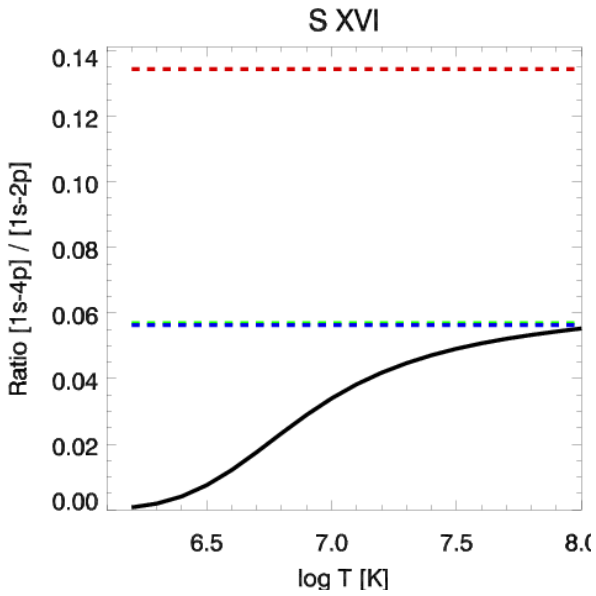


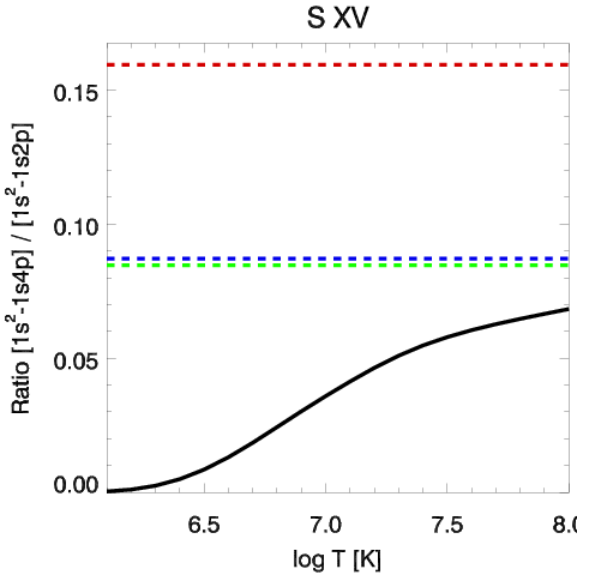


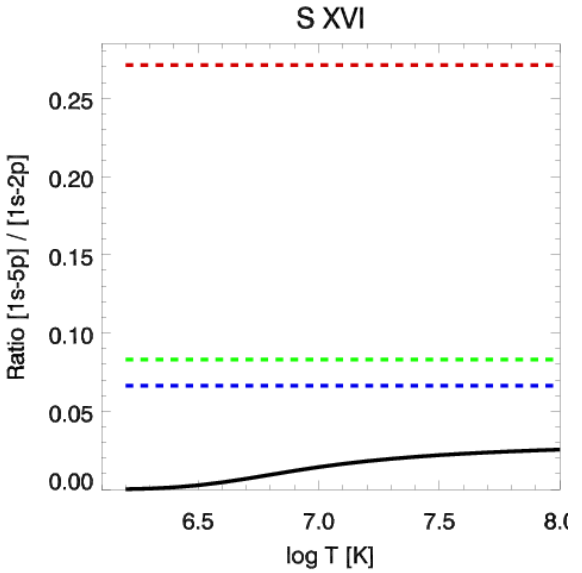


SOL2002-08-20T08:25









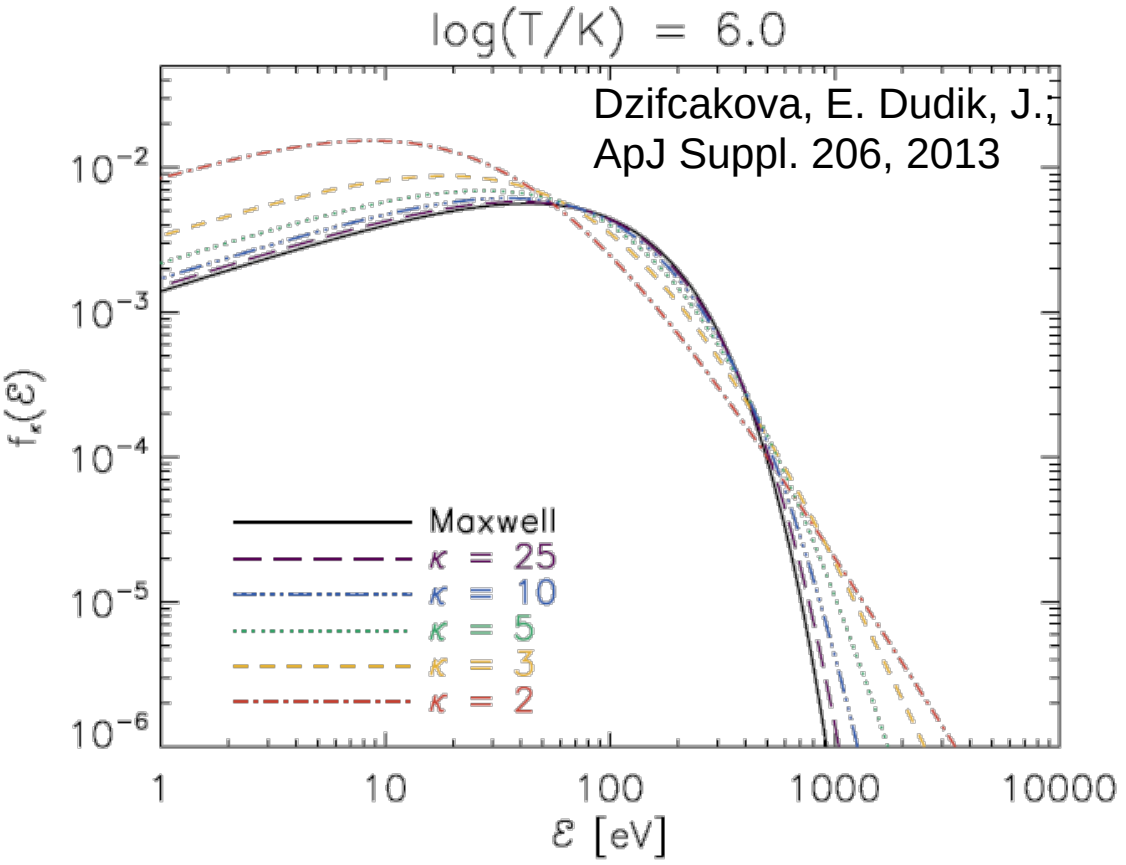
Also for this flare we were not able to account for some observed lines' intensities in the framework of standard Maxwellian particle distribution function.

Idea of κ distributions

Can frequently used **κ** (kappa) – distributions help in the interpretation of the presented strange lines' intensity pattern?

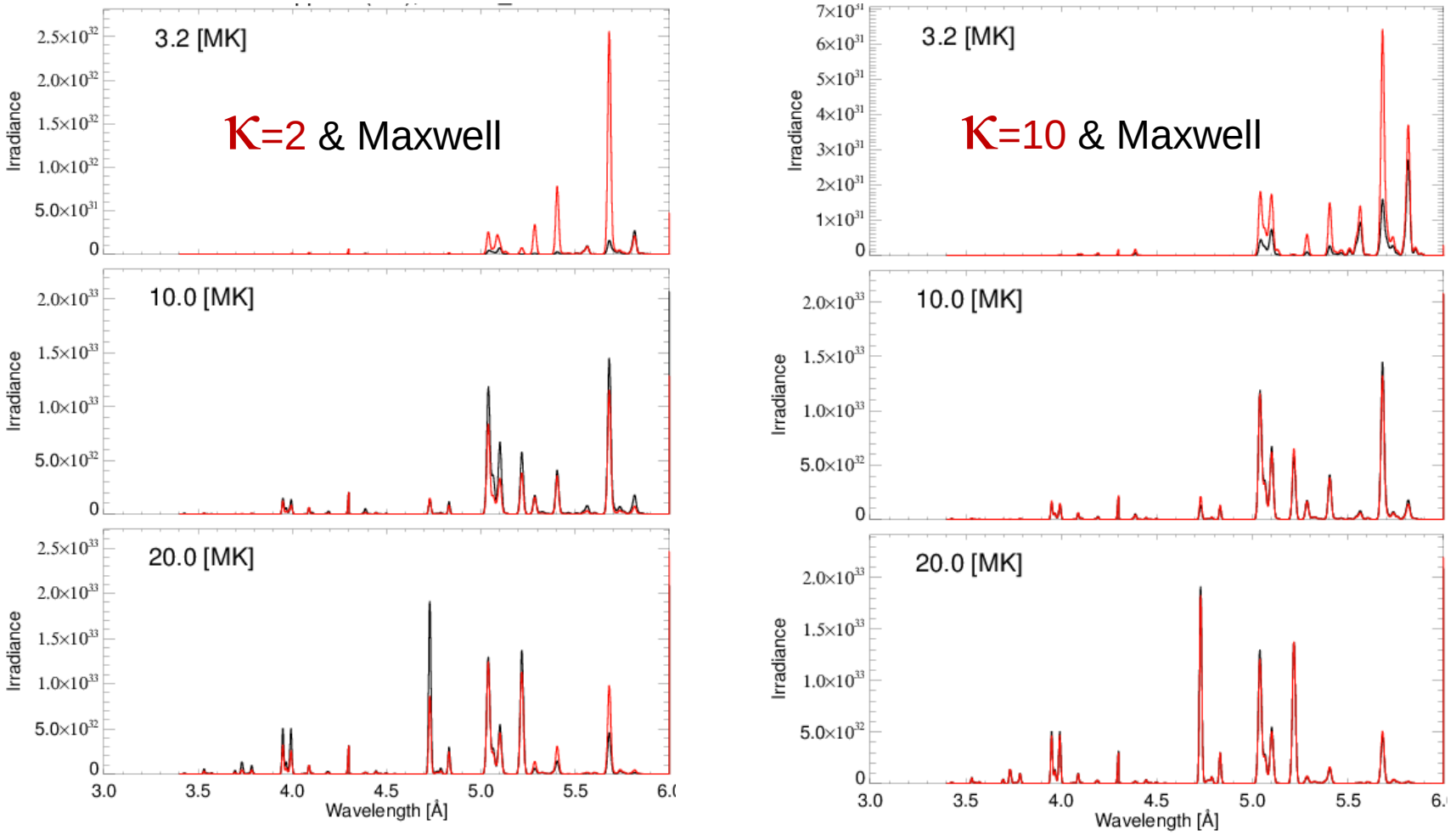
κ distributions for κ=2, 3, 5, 10,25 and the Maxellian distribution (log T(K)=6.0)

The **κ** distributions of electron energies E represent a family of non-Maxwellian distributions characterised by a power-law high-energy tail with two parameters, **κ** and T:
A_κ- normalised constant
k_B – Boltzmann constant
κ→ 3/2 corresponds to the largest deviation from Maxwellian distribution
κ→∞ corresponds to Maxwellian distribution
$\langle E \rangle = 3k_BT/2$ the mean energy of **κ** distribution



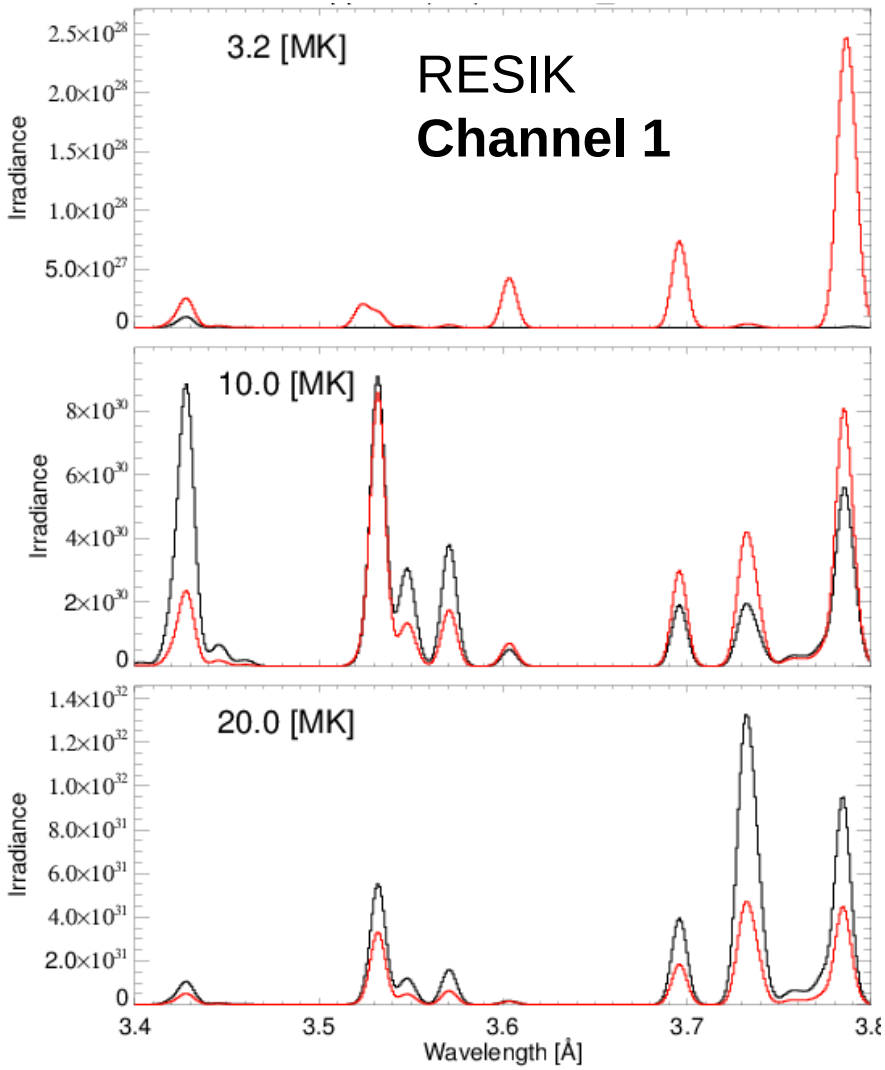
$$f(E,\kappa)\mathrm{d}E = A_\kappa \frac{2}{\sqrt{\pi}(k_\mathrm{B}T)^{3/2}} \frac{E^{1/2}\mathrm{d}E}{\left(1+\frac{E}{(\kappa-3/2)k_\mathrm{B}T}\right)^{\kappa+1}}$$

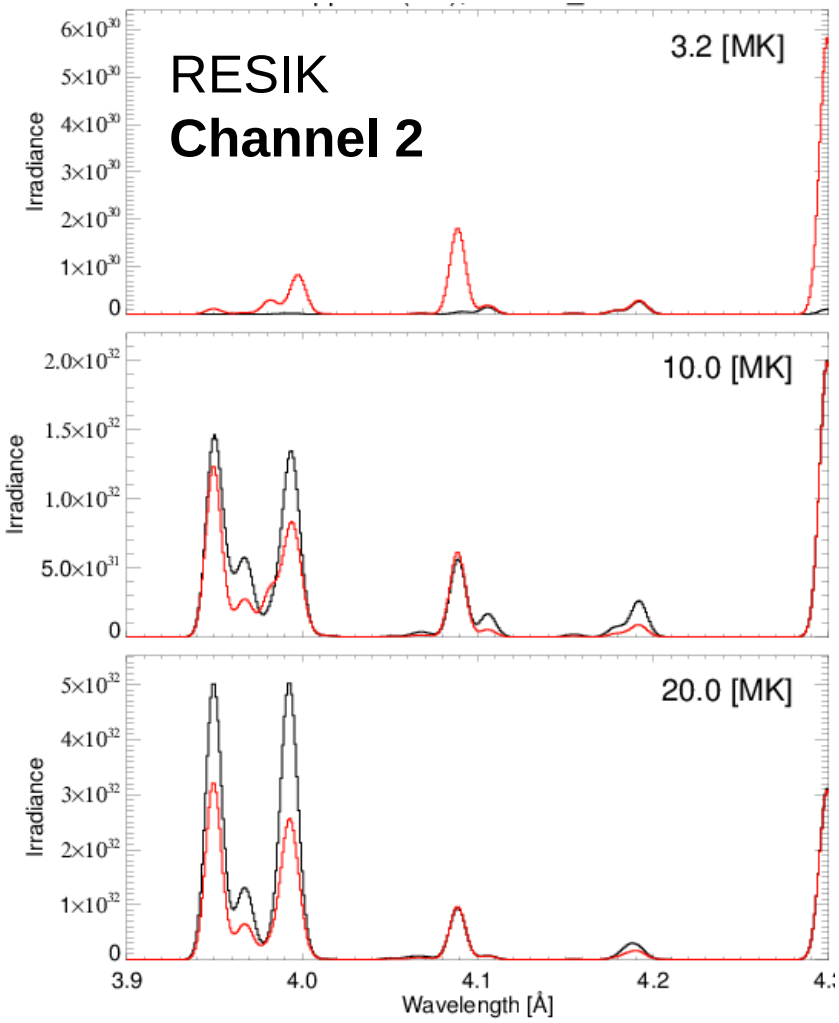
Model appearence of RESIK spectra for **Maxwellian** and **κ** plasmas (whole Δλ range)



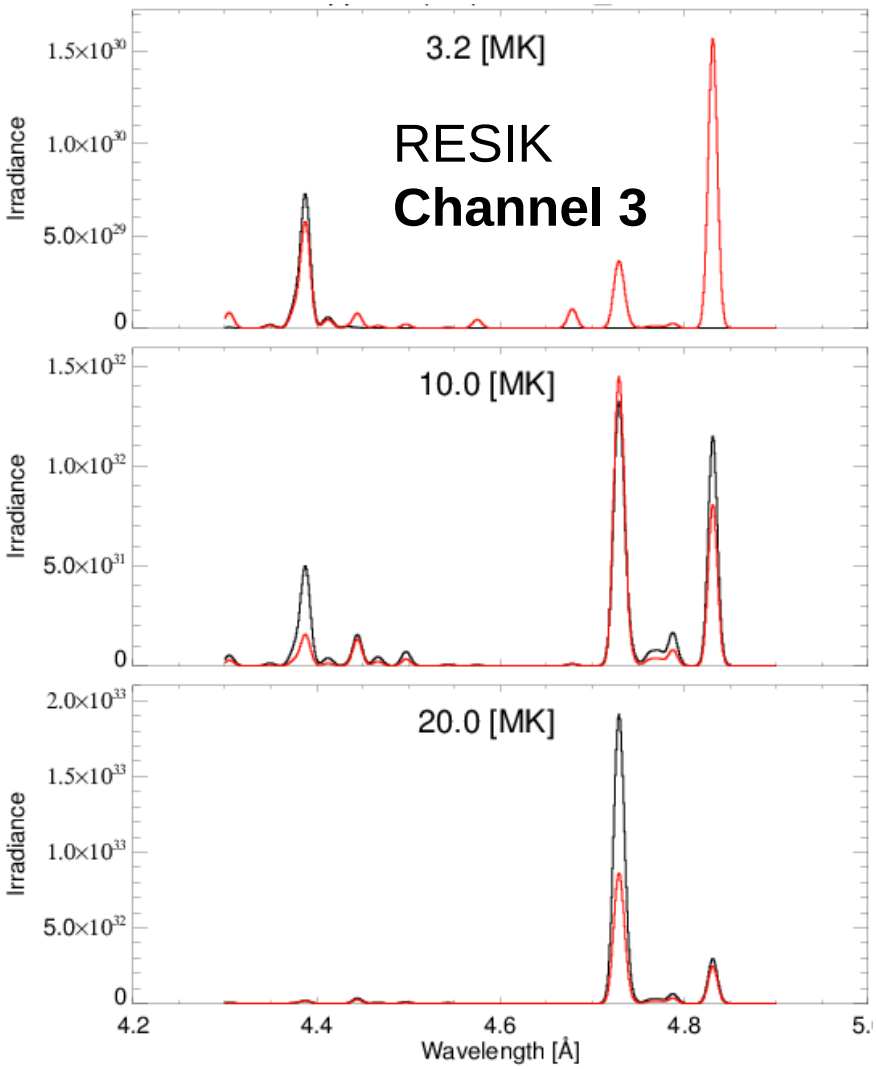
The most of deviations from Maxwellian appearence are seen at lower temperatures.

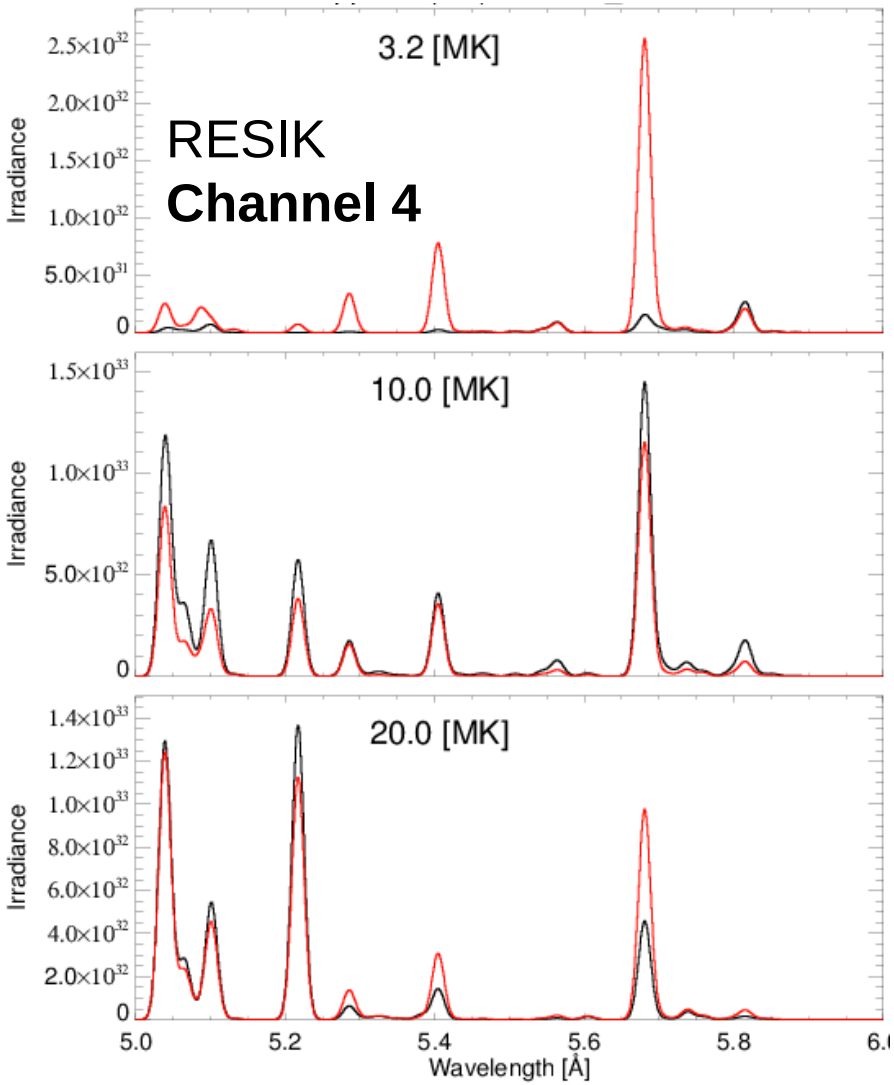
Model appearence of RESIK spectra for **Maxwellian** and **κ=2** plasmas



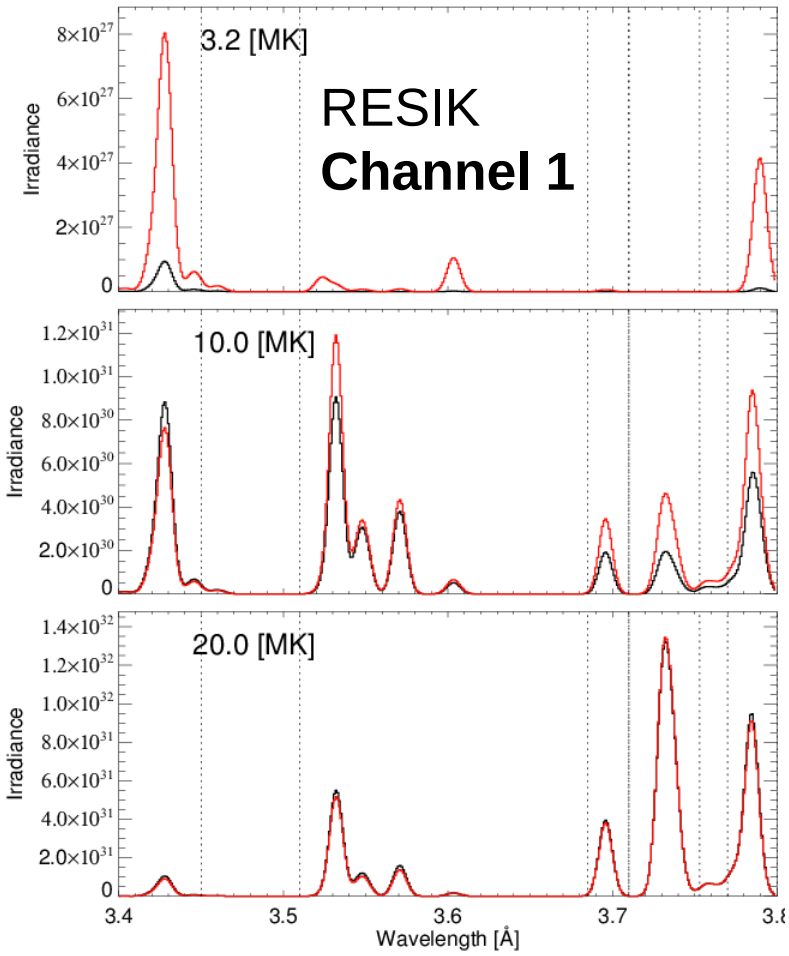


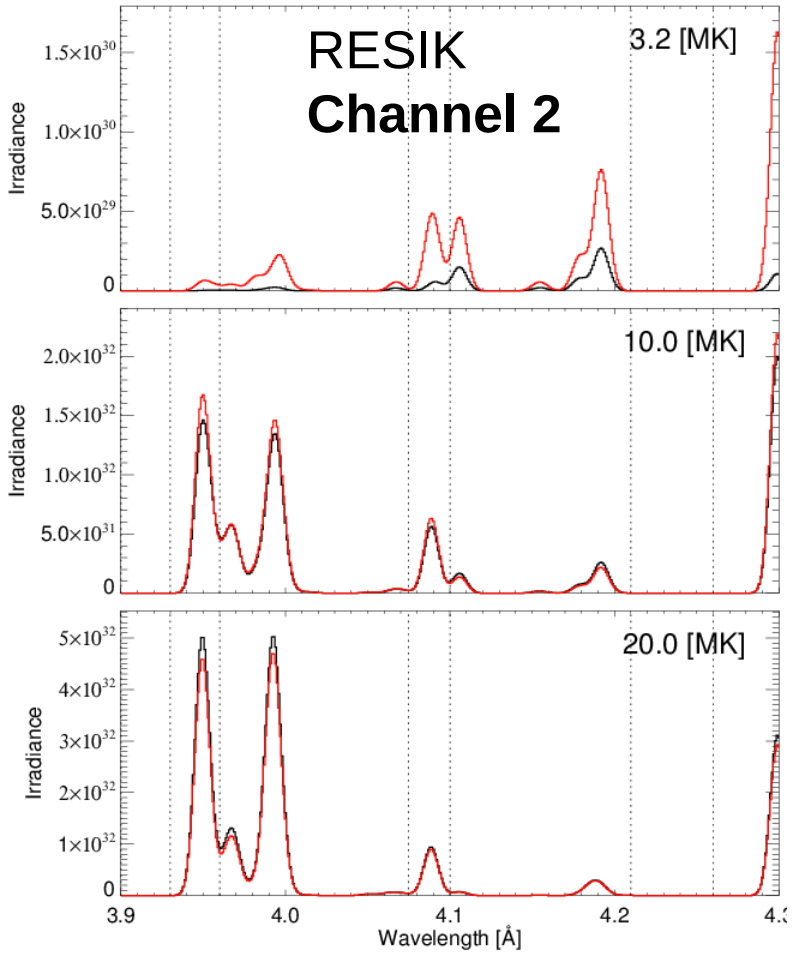
Model appearence of RESIK spectra for **Maxwellian** and **κ=2** plasmas



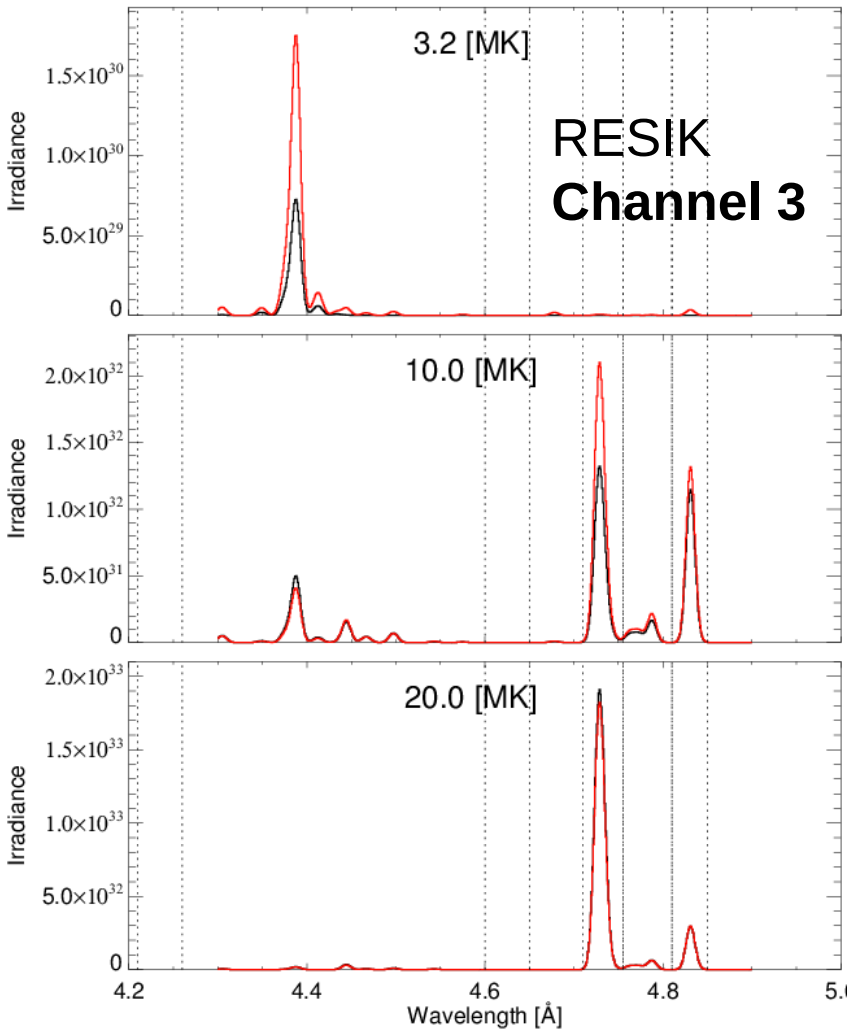


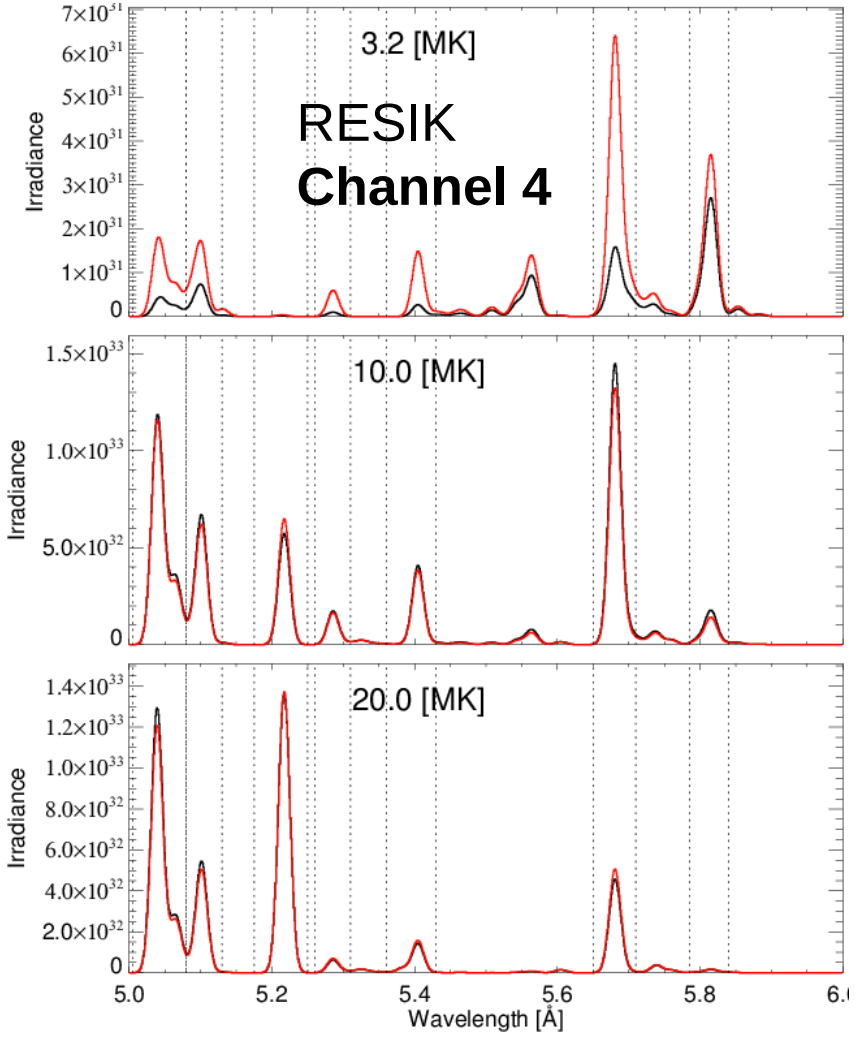
Model appearence of RESIK spectra for **Maxwellian** and **κ=10** plasmas





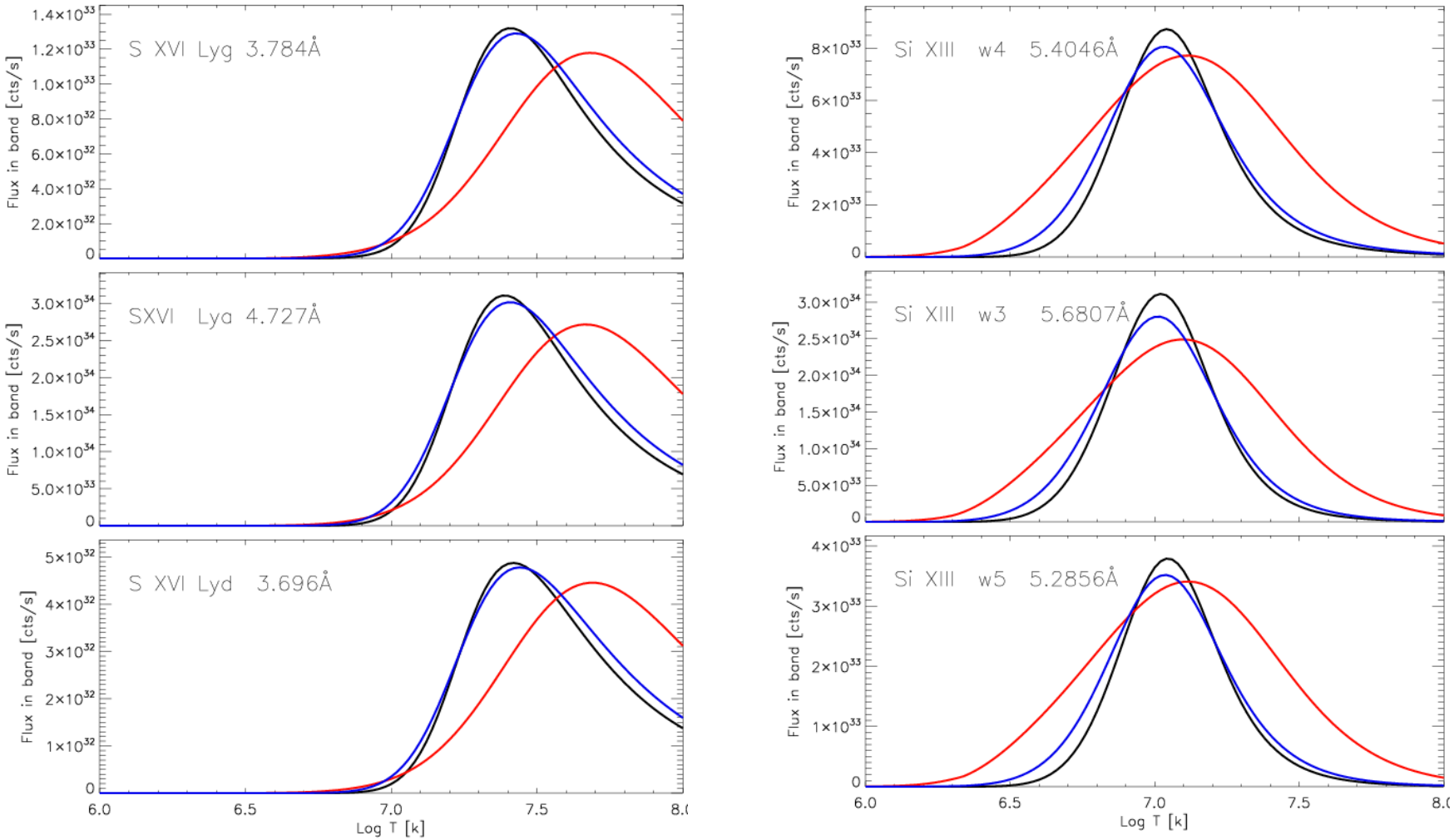
Model appearence of RESIK spectra for **Maxwellian** and **κ=10** plasmas





Equivalent temperature dependence of selected lines' intensities

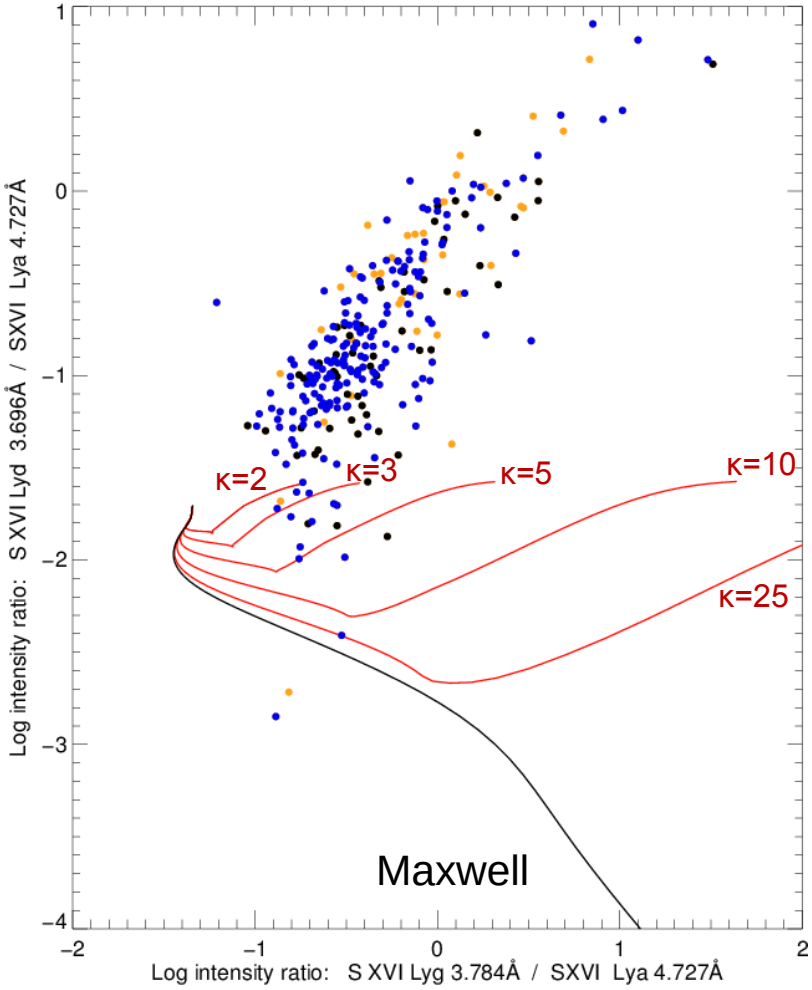
black→ Maxwell, blue→κ=10, red→κ=2



Important are effects on „ionisation equilibrium" and collisional excitations

Do observations support κ–type plasmas?

Case for SOL2002-08-03T19:07



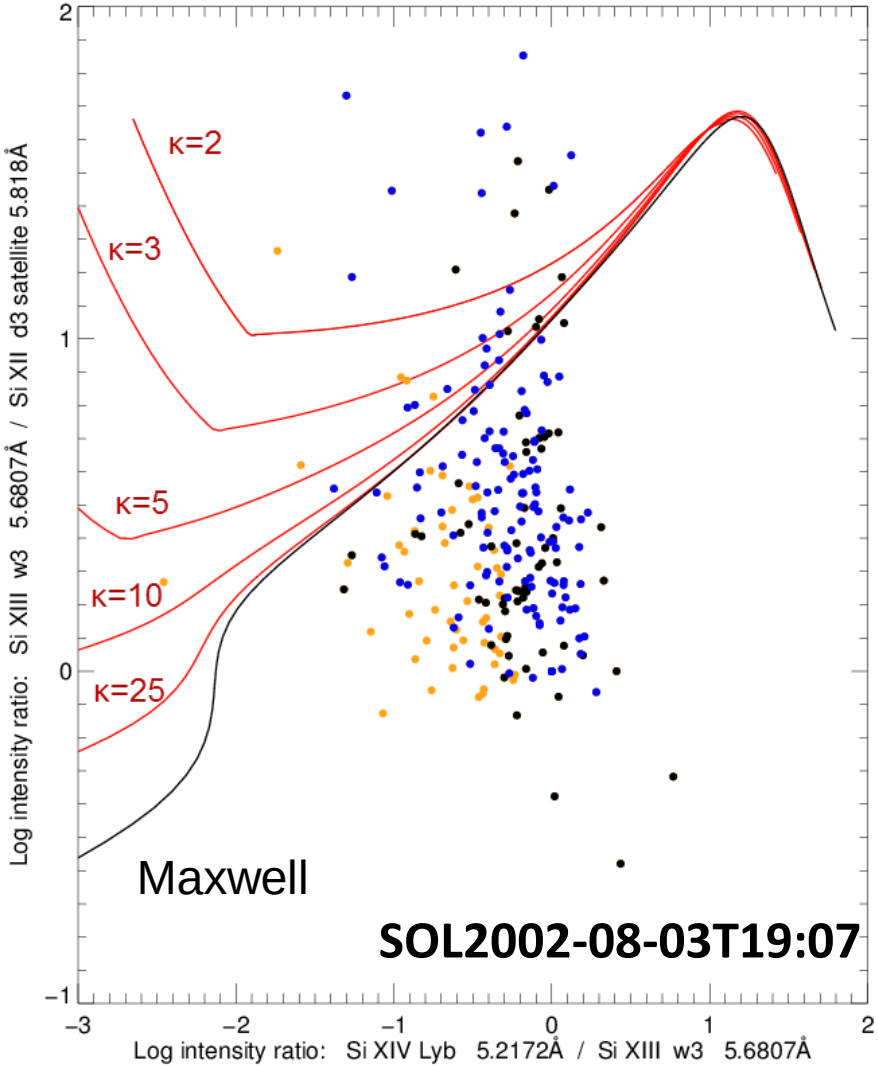
For the comparision, ratios of S XVI Lyδ/S XVI Lyα against S XVI Lyγ/S XVI Lyα have been selected. Red lines correspond to varoious κ-type plasmas with the limit of $\kappa \rightarrow \infty$ (i.e. Maxwellian, thermal plasma). Points represent the observed ratios for individual spectra:

Blue→rise phase

Black→ decay

Orange→late decay

SOL2002-08-03T19:07



Here, ratios of
Si XIII *w3*/S XII *d3* against
Si XIV Lyβ/S XIII *w3* have been selected. Red lines correspond to varoious κ-type plasmas with the limit of
κ→∞
(i.e. Maxwellian, thermal plasma).
Points represent the observed ratios for individual spectra:

Blue→rise phase
Black→ decay
Orange→late decay

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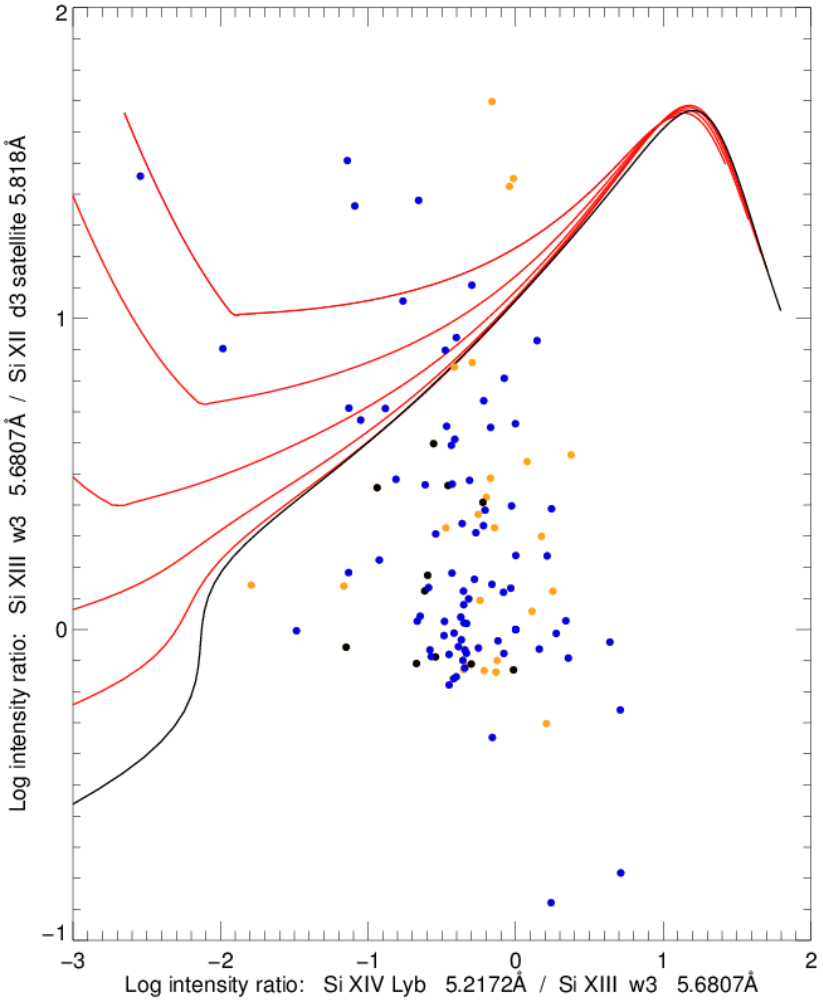

Similar plot for the most impulsive flare studied. Again, ratios of Si XIII *w3*/S XII *d3* against Si XIV Lyβ/S XIII *w3* are considered. Red lines correspond to varoious κ-type plasmas with the limit of $\kappa \rightarrow \infty$ (i.e. Maxwellian, thermal plasma). Points represent the observed ratios for individual spectra:

Blue→rise phase (a)

Orange→maximum (b)

Black→ decay (c)

Take home message

- Observed intensities of higher-n transitions are much higher than for an equilibrium, Maxwellian plasmas. This striking measurements need further reconfirmation (ChemiX). Even assuming the presence of non-Maxwellian κ–type electron distributions does not help in this respect. So, the present state of affairs is that we are not able to account for the observed intensities of higher-*n* (*n*>3) transitions in H- and He-like ions.
- One of the possible explanation may be that there are unresolved blends from yet unknown transitions which contribute to the estimated line fluxes. Better spectral resolution and new theoretical calculations may help to clarify this.
- Another possibility is that constantly recombining transient ionization conditions preveil in the source region causing overpopulation of higher-n levels. The similar idea has been suggested ~45 years ago by A. Dupree:

„Significant departures from thermodynamic eąuilibrium are found for the populations of high levels of coronal ions. These overpopulations can lead to observable effects on the solar emission spectrum”. (Dupree, A.K., ApJ, 152, 1968)

The end

References

- The Formation of Kappa-Distribution
  Accelerated Electron Populations in Solar Flares; Nicolas H. Bian, A. Gordon Emslie, Duncan J. Stackhouse, and Eduard P. Kontar; http://arxiv.org/abs/1410.0819v2, 2014
- Atomic physics algorithms for plasmas undergoing transient ionization and recombination; J Magill; 1977 J. Phys. D: Appl. Phys. 10
- Dielectronic satellite spectra….;A.H. Gabriel; MNRAS_160, 1972
- The population of high atomic levels in the solar corona; Dupree, A.K.; ApJ_152, 1968

Abstract

RESIK data reduction continues; at the time of writing, data for 80 flares have been reduced to science grade (level 2: http://www.cbk.pan.wroc.pl/experiments/resik/RESIK_Level2/index.html).

The spectra include spectral lines formed by H- and He-like ions of Si, S, Ar and K as well as continuum. The lines and continua are formed in the hot coronal plasma corresponding to temperatures T~2-30 MK if interpreted thermally. Nominal spectra data gather interval (DGI) was long (5min) for non-flaring corona, decreasing to 2s for M class events. This makes RESIK spectra uniquely suitable for investigations of the physical conditions of the hotter plasma component of flares and active regions. Many spectra were observed during the rise phase of flares, including the impulsive phases. For some events, anomalous line intensity ratios are evident. Also for “thermal” phases (flare decay), intensities of higher n transitions are generally observed to be above theoretical predictions. We will show examples of such anomalous spectra.

We are not able to account for these observed lines’ intensities in the framework of standard Maxwellian particle distribution function (using isothermal or multi-thermal assumptions). We believed this anomalous line intensity pattern reflects presence of non-equilibrium conditions in flaring plasma, therefore, we compared the observations with kappa-based synthetic spectra. The results will be shown and possible interpretation will be suggested for discussion.