Analysis of X-ray flare spectra seen by RESIK

B. Sylwester[a], J. Sylwester[a], A. Kępa[a], T. Mrozek[a,b] K.J.H.Phillips[c] and V.D.Kuznetsov[d]

[a] Solar Physics Division, Space Research Centre PAS, Wrocław, Poland
[b] Astronomical Institute, University of Wrocław, Poland
[c] Visiting Professor, University College London, UK
[d] IZMIRAN, Russian Academy of Scinces, Moscow

We present results of **differential emission measure** (**DEM**) analysis of flaring plasma. In this respect we use the X-ray spectra obtained with Polish-led spectrometer RESIK placed aboard the Russian *CORONAS-F* satellite. RESIK was an uncollimated bent crystal spectrometer taking instant measurements in four spectral channels covering the soft X-ray range between 3.3 Å and 6.1 Å. On the recorded spectra many spectral lines are seen formed in H- and He-like ions of elements: K, Ar, S and Si. Below the lines, the continuum is clearly perceived in most cases. The line and continuum emissions are formed in thermal coronal plasma from the temperature range **3 MK ÷ 30 MK**. The overall shape of the spectrum depends strongly on the amount of plasma being at different temperatures. This makes RESIK spectra uniquely suitable for investigations of the temperature structure of the source (DEM) as well as the plasma elemental composition.

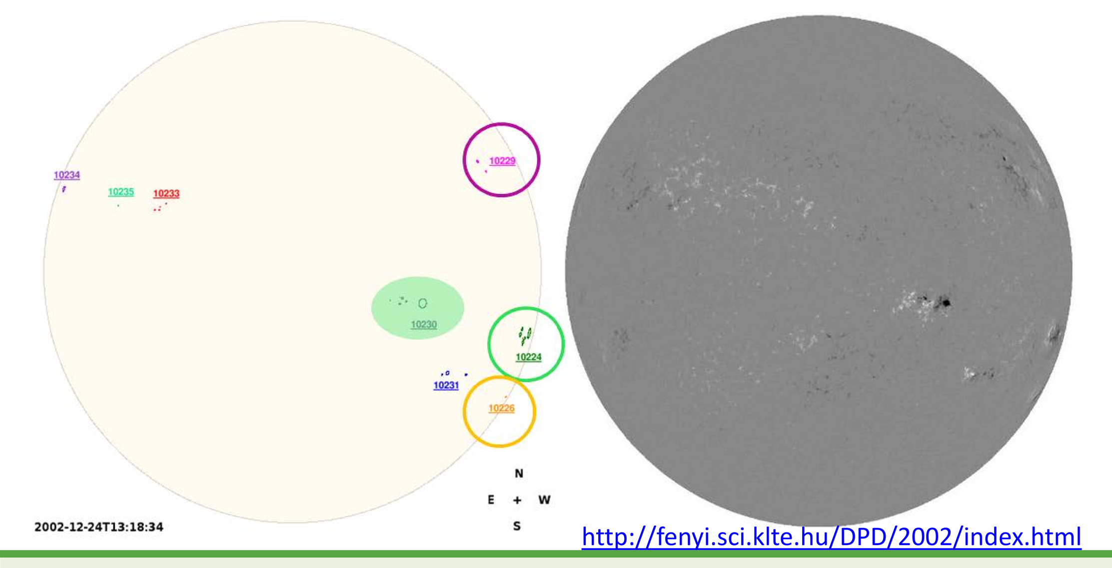
For the present study, an extended analysis has been made for **10 flares** observed on 25 and 26 Dec. 2002. List of flares studied is presented in the Table below.

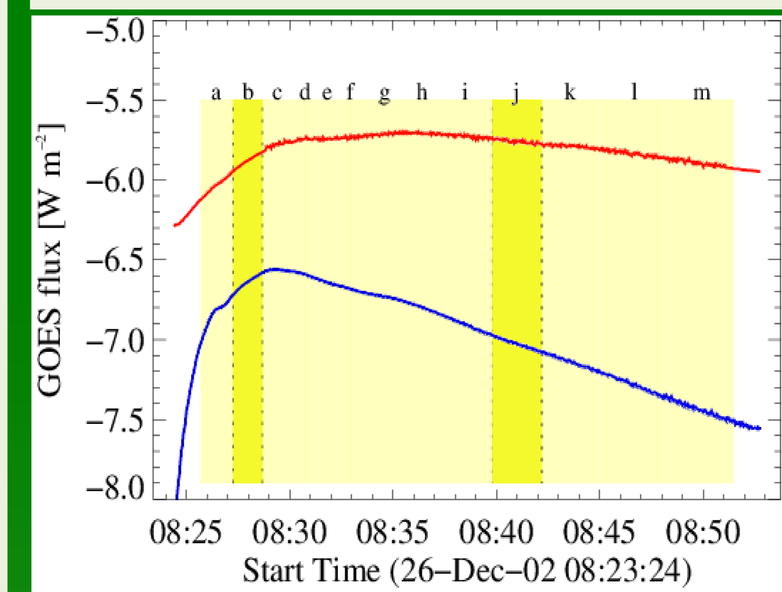
Locations of ARs to which flares has been assigned are indicated as circles on Debrecen Photoheliographic map below the Table.

Spectra of flares observed close to the Western limb show a prominent S XV w3 line ($1s^2$-$1s3p$) in RESIK channel No. 2.

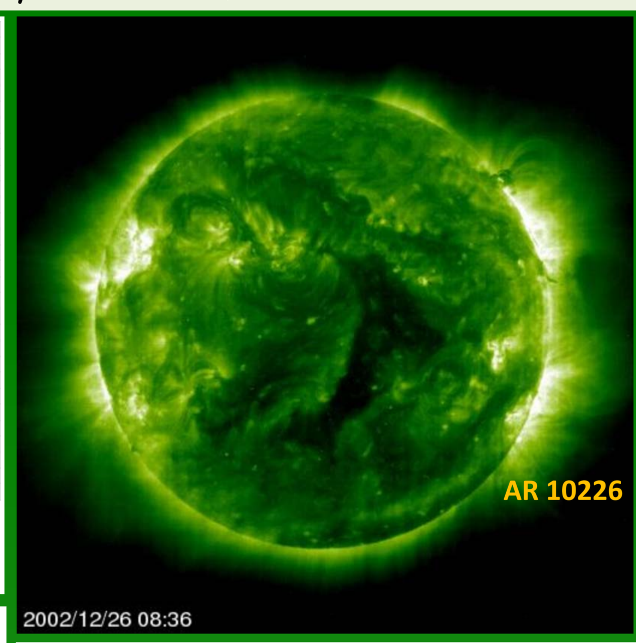
No.	Time max. [UT]	No. of spectra	*GOES* class	NOAA AR No.	A_{Ar}	A_S	A_{Si}
1	25-Dec-2002 05:46	115	C4.8	10224	6.49	6.86	7.56
2	25-Dec-2002 07:34	21	C1.4	10226	6.52	6.59	7.58
3	25-Dec-2002 10:41	14	C1.0	10226	6.52	6.85	7.53
4	25-Dec-2002 12:07	60	C3.5	10226	6.52	6.89	7.41
5	25-Dec-2002 13:55	19	C1.1	10224	6.60	6.84	7.57
6	25-Dec-2002 18:09	82	C2.9	10226	6.48	6.88	7.52
7	**25-Dec-2002 21:32**	**22**	**C1.7**	**10230**	**6.41**	**6.96**	**7.50**
8	25-Dec-2002 22:48	6	C1.1	10229	6.28	6.93	7.58
9	25-Dec-2002 23:10	9	B8.0	10224	6.58	6.83	7.67
10	26-Dec-2002 08:35	53	C1.9	10226	6.44	6.84	7.48

Except event No 7, all flares were located in the active regions above the Westen limb. Colors denote individual active regions

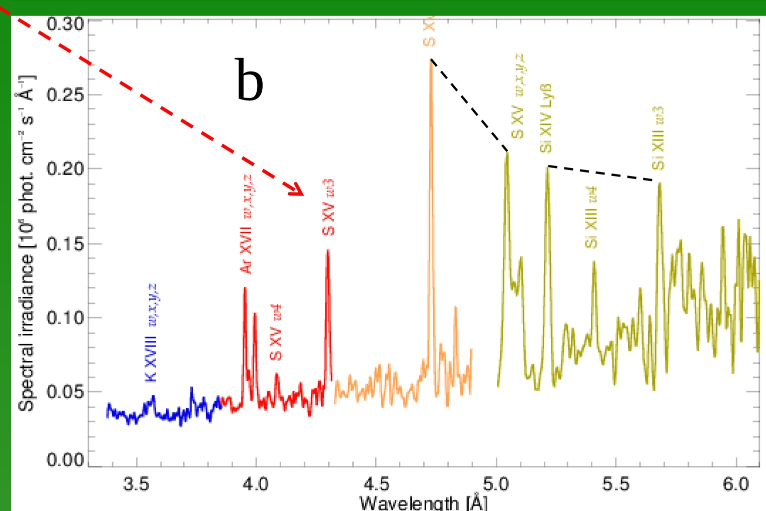


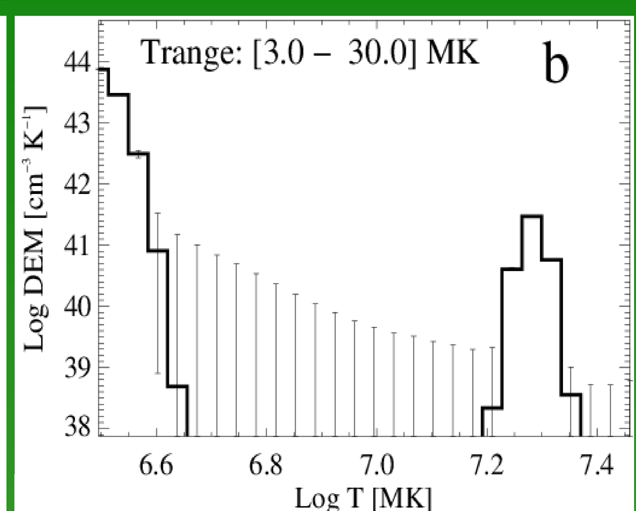


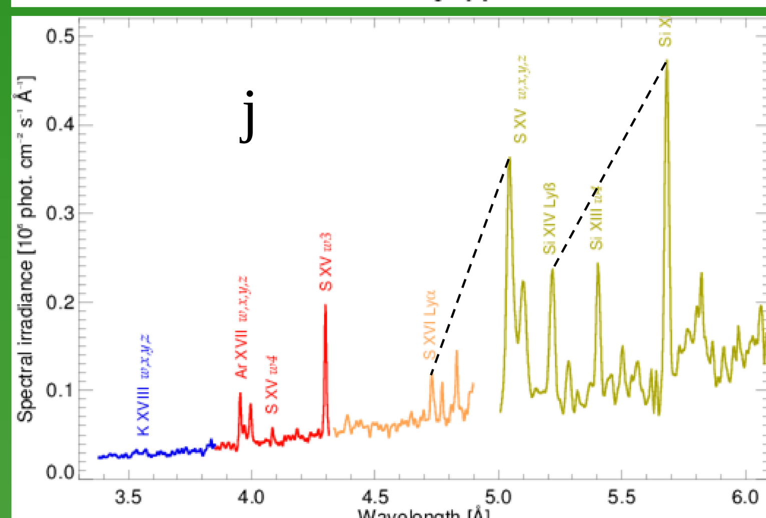
GOES lightcurves in 0.5-4 Å and 1-8 Å bands. RESIK spectra shown below were collected during the rise phase (b) and decay (j)

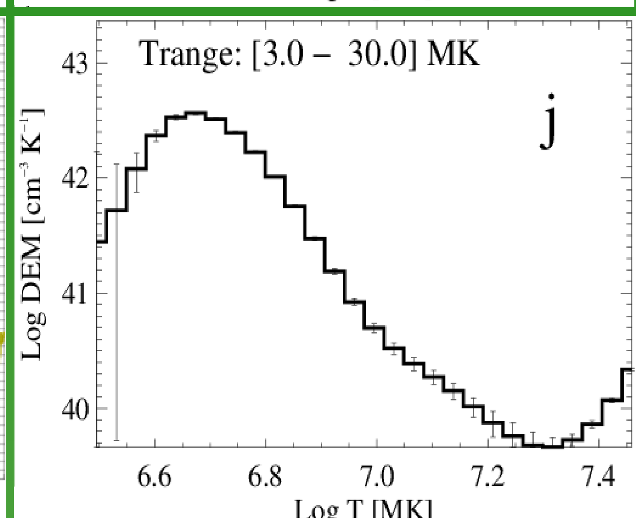


SOHO EIT 195 Å image of the Sun taken at the maximum of the considered flare





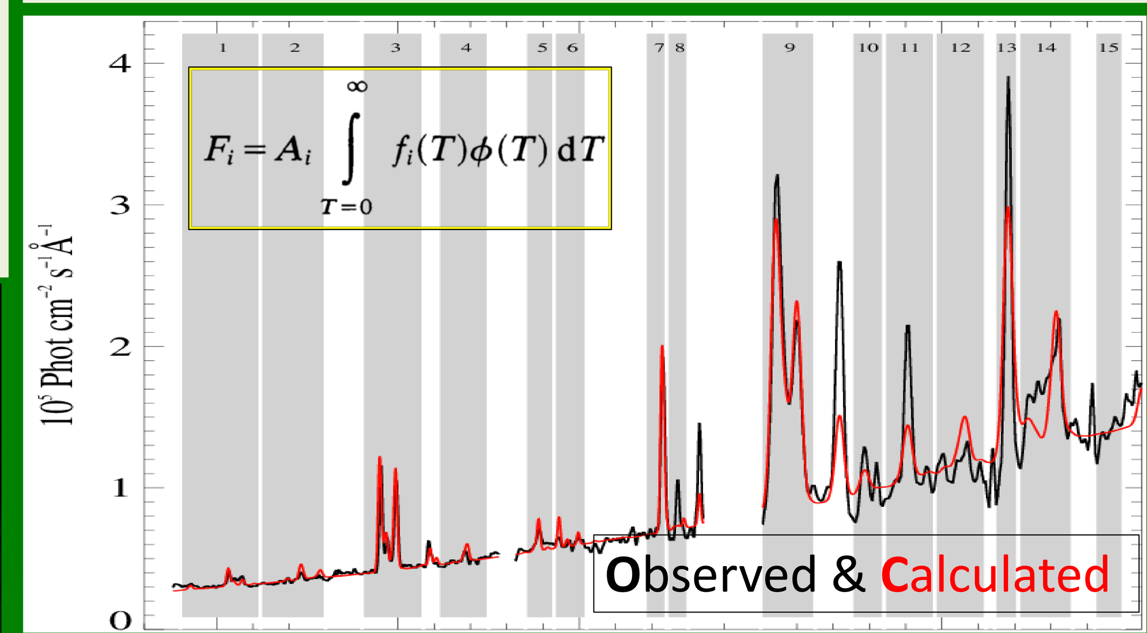


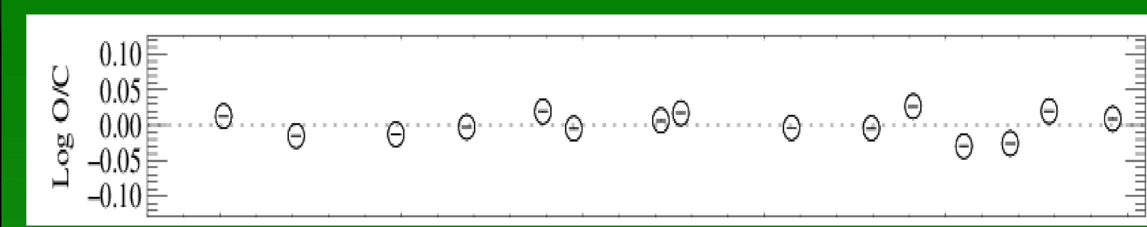


Different line ratios and spectral shapes are clearly seen between the rise and decay phases of the flare. The plasma is multithermal (as seen to the right)

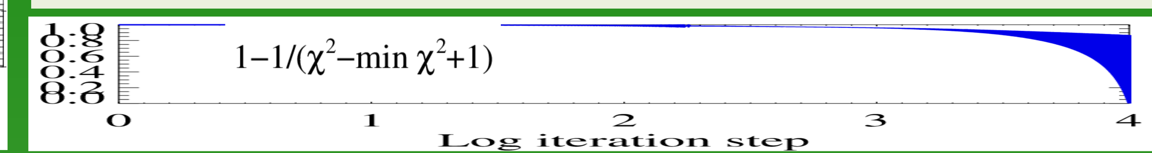
Calculated DEM distributions reflect pronounced differences of plasma thermal structure between rise and decay

From reduced absolute RESIK spectra we have selected 15 narrow spectral bands (in gray) embracing the most intense lines and the continuum below. We determined the time-changing fluxes in these bands for flares selected in this research. These fluxes constitute the input set for the differential emission measure (DEM) inversion

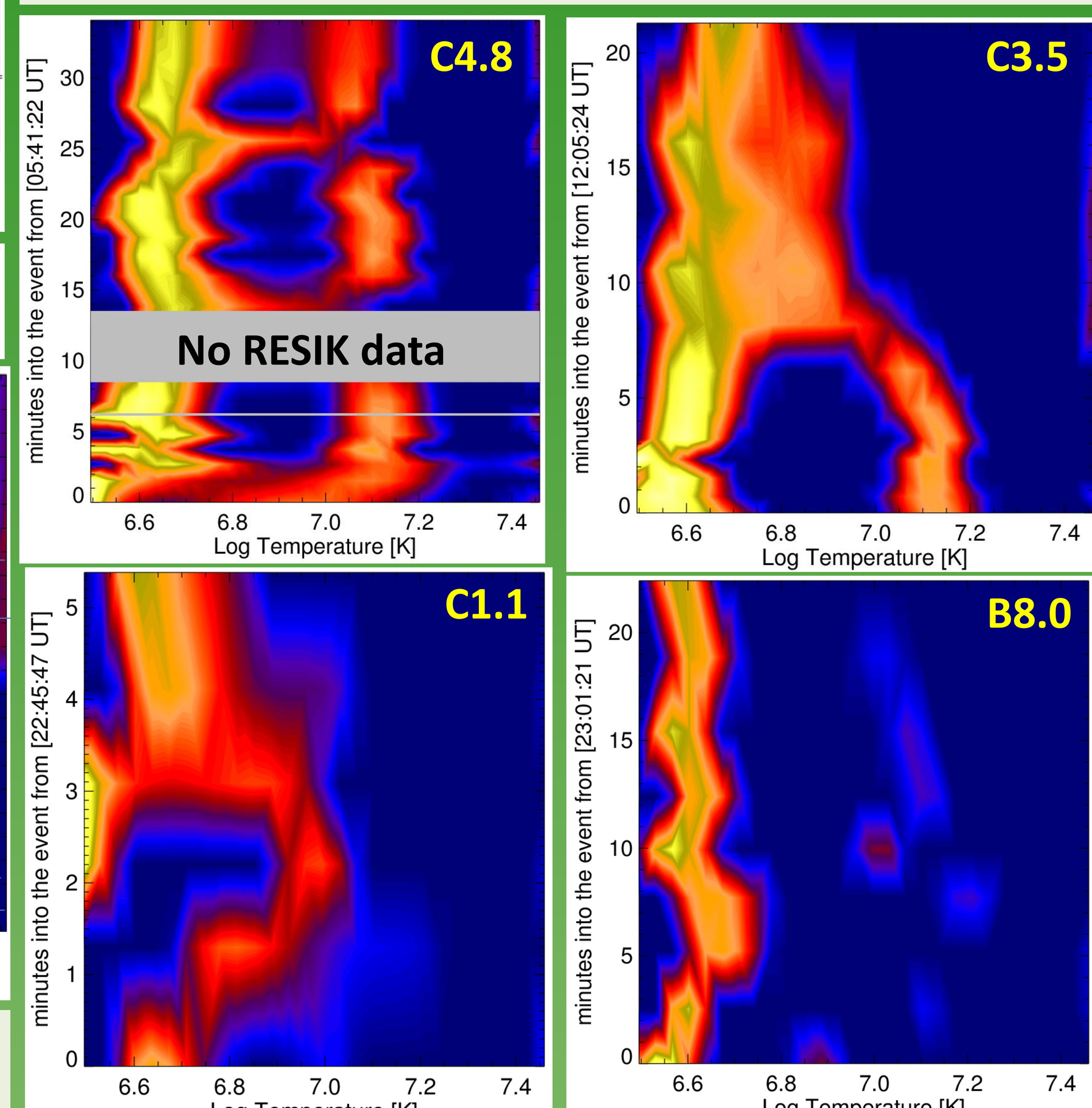




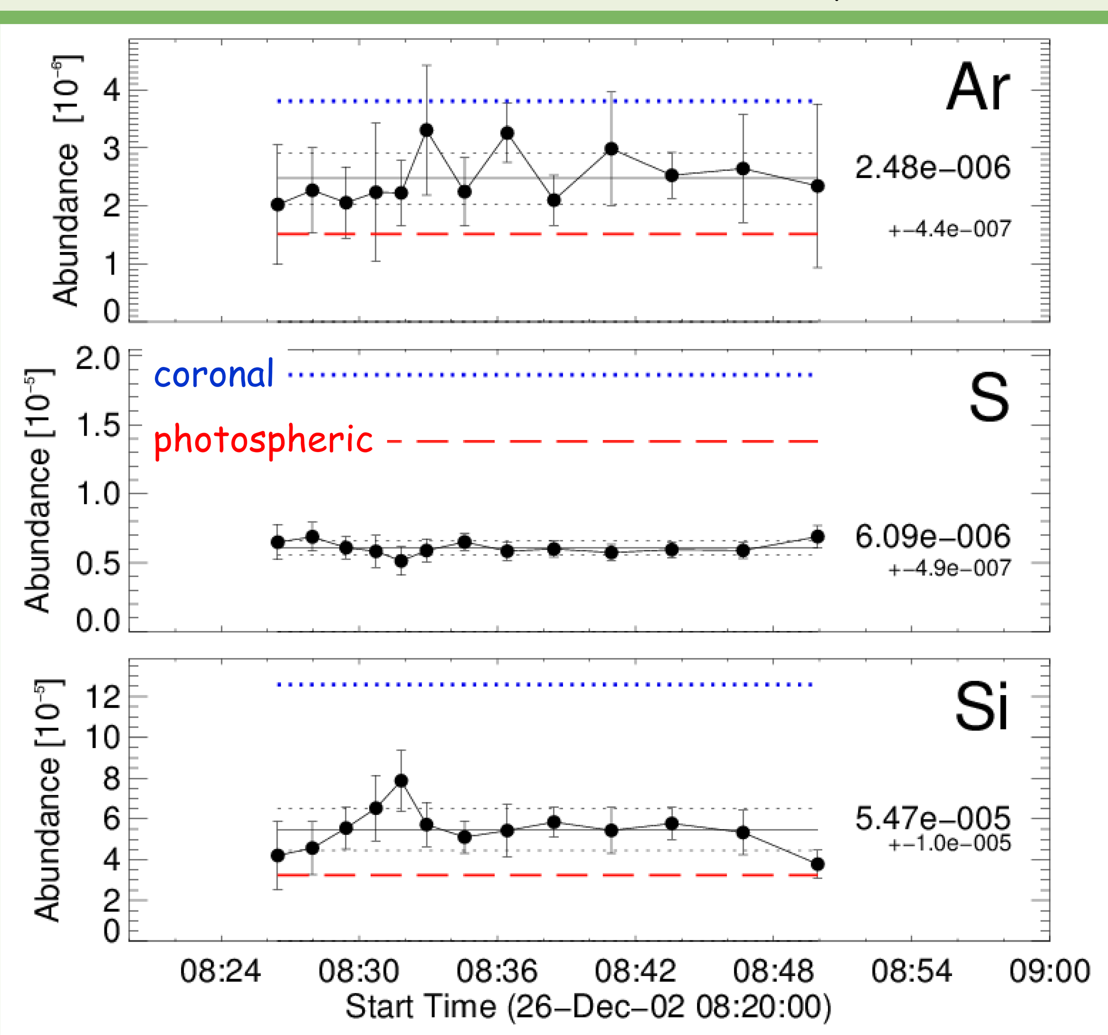
The theoretical fluxes have been calculated using the CHIANTI 7.0 code (http://www.chiantidatabase.org) with appropriately selected plasma composition – representative (optimum) for each selected event for the elements: Ar, S, Si, (see discussion in the right ppanel). In the spectral calculations, Bryans, Landi & Savin (ApJ, 691,2009) ionization equilibrium has been adopted. For inversion, we used the Withbroe-Sylwester algorithm (W-S) which follows the Bayesian approach (described in detail by Sylwester, Schrijver & Mewe, Solar Phys., 67, 1980). Typically, better than 5 % agreement between observed and DEM predicted fluxes in every spectral bands is reached (see above).



The inversions have been carried out over the temperature range 3 MK - 30 MK. 10 000 iterations were performed on each inversion run in the accelerated scenario. The inversion uncertainties were determined from 100 Monte Carlo exercises, where the input fluxes for time-frame of interest were randomly perturbed with corresponding measurement uncertainties.

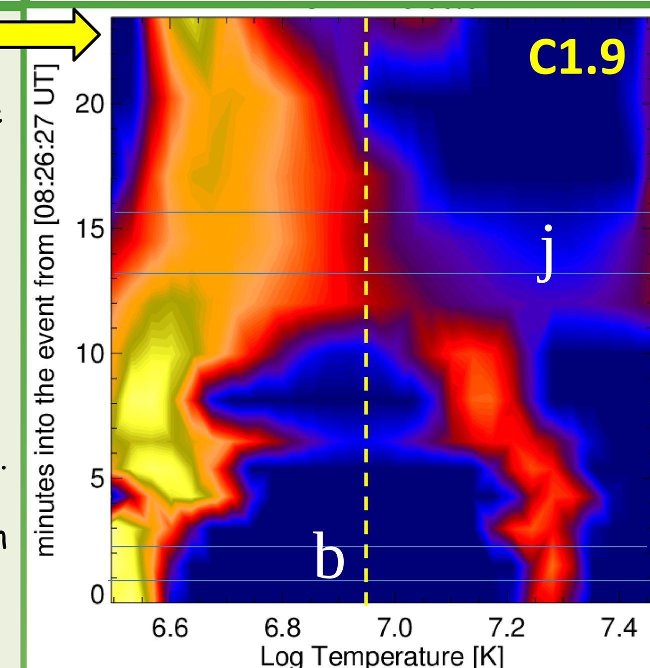


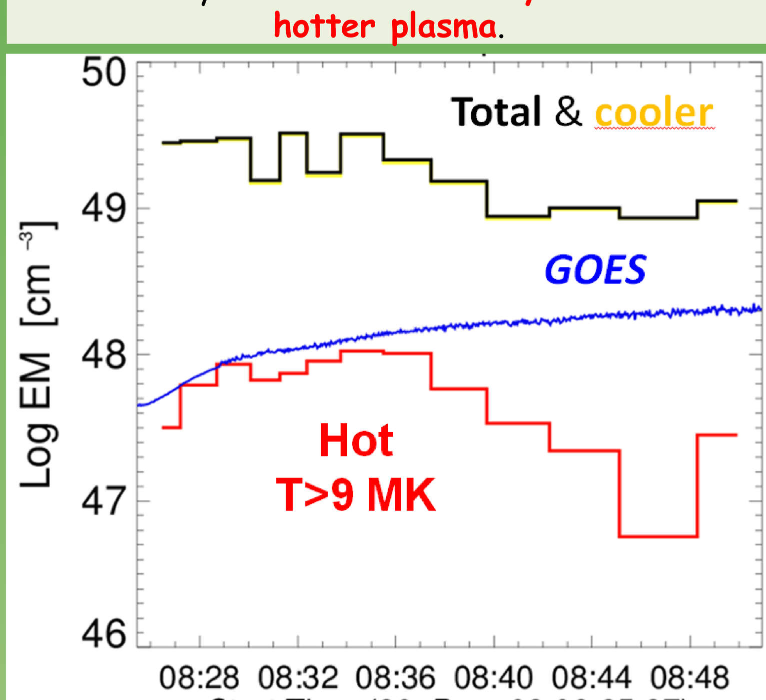
It turned out that neither the photospheric nor the coronal abundance models can be used to describe the observed set of spectral intensities at the same time. We thus concluded that in order to determine reliable estimates of the DEM shape we should finely adjust the plasma composition in order to optimize the fit between the observed and calculated spectral band fluxes. To do so we generated spectral look-up cube containing spectra synthesized using RESIK instrumental profiles. In these look-up cubes the spectra were calculated for a wide range of changing abundances of elements: Ar, S and Si. The range of particular element variability was taken to cover the range from 0.1 up to 20 times the standard coronal abundance value of every element. By using this spectral look-up cube it has been relatively easy to optimize the flaring plasma elemental composition, i.e. minimize the χ^2 difference between observed and calculated fluxes in selected 15 spectral bands.



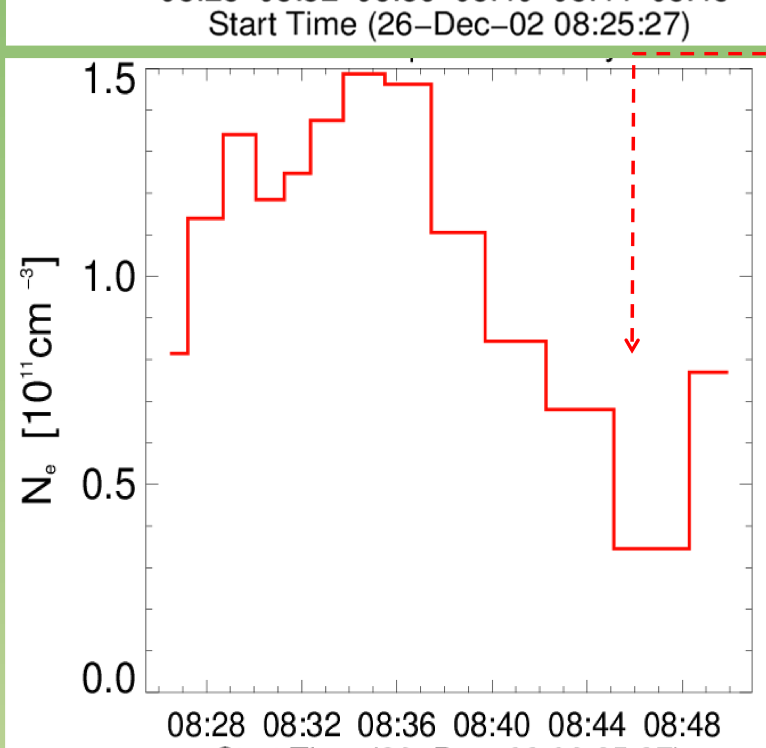
Above, the time variability of adjusted abundances as obtained for the flare No. 10 are presented. Dashed red lines denote the photospheric abundances while the dotted blue stand for the coronal ones. We performed the DEM calculations using an average optimum abundance values for each flare.

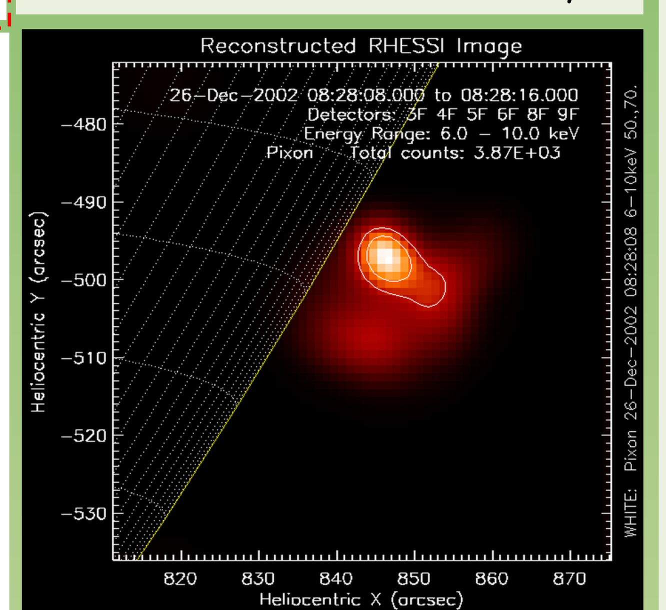
DEM evolution is clearly seen in the diagram. On the horizontal axis the log of plasma temperature is shown and on the vertical one the time elapsed from the flare start (indicated). The dashed vertical yellow line at 9 MK marks the division between cooler and hoter plasma. It is observed that the hot plasma quickly vanishes. The evolution of total emission measure (EM) of **hot**, **cooler** and **total** components are shown underneath. For the comparison, the EM as determined from GOES flux ratio in the isothermal approximation (**blue line**) is presented. The total EM is dominated by the cooler plasma component. However, in order to explain the observed shape of the spectrum it is necessary to allow for the **tiny amount of hotter plasma**.





We can safely assume that the EM of the hot component is contained within the RHESSI bright kernel. From assumed spherical shape of the source as seen on the PIXON reconstructed image (at 70% max D=4.2 x 10^8 cm, not changing much in time), the evolution of **the hotter plasma density** component is determined. Similar results for the other flares indicate that the plasma density of the hotter component is typically ~10^{11} cm^{-3} around the flare maximum and ~10^{10} cm^{-3} towards late decay.





RHESSI image of the flaring source reconstructed using PIXON algorithm. Contours are plotted at 50% and 70% max

Concluding remarks

- Absolutely calibrated RESIK spectra are suitable for determination of DEM. We identified multiple (15) spectral bands convenient for the inversion.
- It is essential to adjust the plasma composition before final DEM inversion is performed - otherwise, the outcome may result in strongly biased solutions. For the analysed flares values of adjusted abundances for elements: Si, S and Ar are lower than their typical coronal values (Feldman et al., ApJ, 81, 1992).
- Calculated DEM distributions indicate for presence of two plasma components in flaring plasma: the cooler component being present at temperature below 9 MK, and the hotter one above 9 MK. The cooler component is probably related to the bulk of active region and the hotter one to this part of flaring plasma which is directly connected to the energy deposition region.
- The total amount of the hotter plasma is orders of magnitude lower in comparison with the cooler component emission measure. The EM of the hotter component rapidly falls off as the flare progress. Nevertheless of its tiny amount, presence of this hot plasma is essential in order to reproduce the observed shape of RESIK spectra.
- The results of abundance optimization indicates that for analyzed flares, the abundances of Ar, Si and S are about the same, independent of their AR assignement. Further analysis of other flares seen by RESIK is necessary to confirm this result in general.

We acknowledge financial support from the Polish Ministry of Education and Science grant 2011/01/B/ST9/05861, the European Commissions grant FP7/2007-2013: eHEROES, project No. 284461. The data analysis have been performed using the CHIANTI atomic code, a collaborative project involving George Mason University, the University of Michigan (USA) and the University of Cambridge (UK).