Are there abundance differences between flares?

B. Sylwester[1], K.J.H. Phillips[2],
J. Sylwester[1], A. Kepa[1], T. Mrozek[1,3]

[1] Space Research Centre of Polish Academy of Science, Poland
[2] Earth Sciences Department, Natural History Museum, UK
[3]Astronomical Institute, Wrocław University, Poland

RESIK

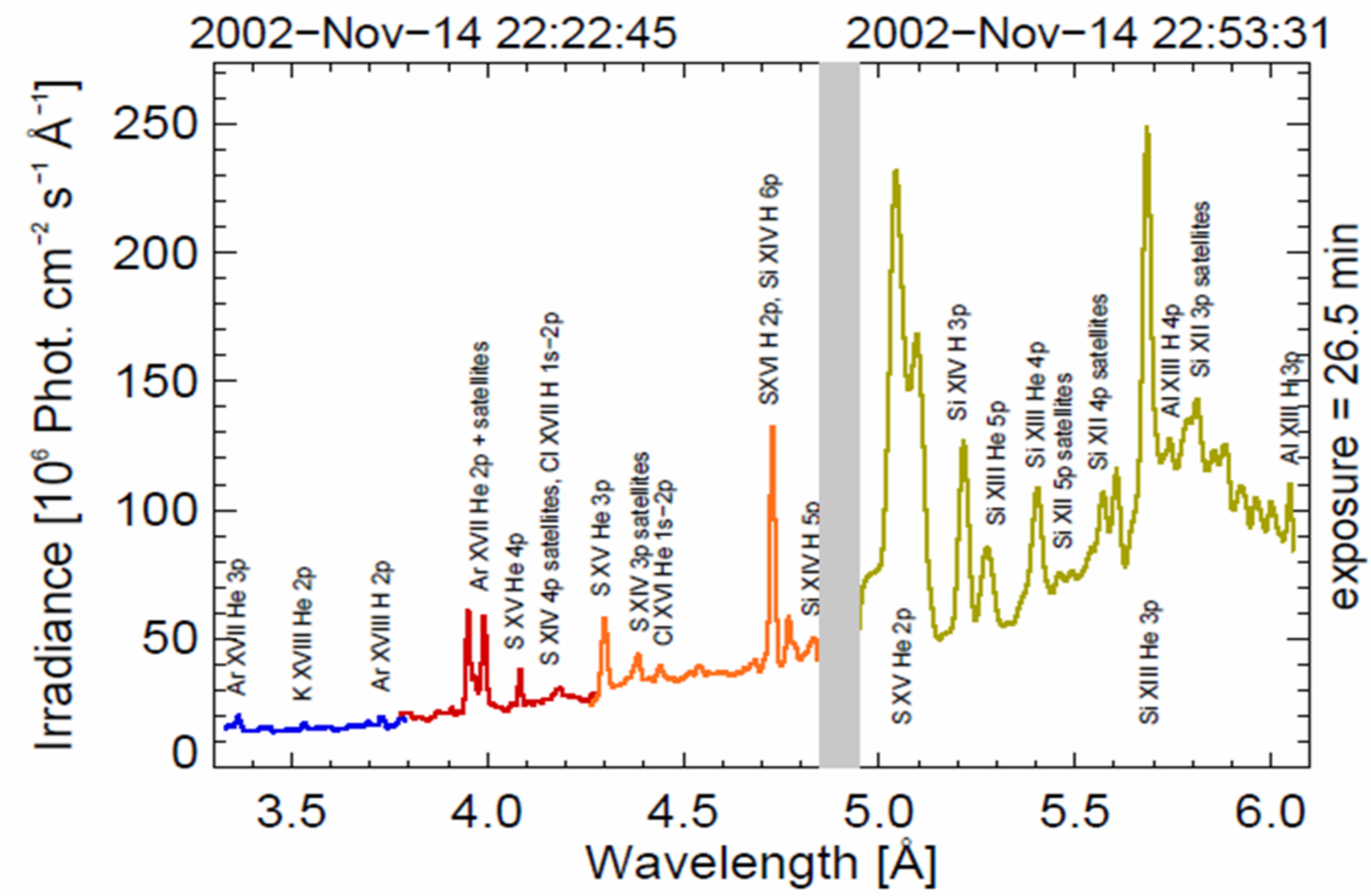
RESIK is Polish-led uncollimated spectrometer placed aboard the CORONAS-F satellite. It was the follow-on of the *Yohkoh* Bent Crystal Spectrometer and used its spare detectors. RESIK observed in the spectral range **3.3–6.1 Å**

with the principal X-ray emission lines of elements with various values of the first ionization potential FIP: **K** (FIP=4.34 eV), **Si** (FIP=8.15 eV),

S (FIP=10.36 eV), **Cl** (FIP=12.97 eV),

Ar (FIP=15.76 eV).

Example spectrum for M1.0 flare



The Aim

Study elemental abundances in the **multithermal approach**

We already introduced an innovative method **AbuOpt** (*Sylwester et al., ApJ 787, 2014*) showing a possibility of determination of **flare abundances** consistent with the observed spectral line and continuum intensities.

Here, abundance determinations obtained for a number of flares observed with RESIK spectrometer are presented and compared with commonly used coronal and photospheric values.

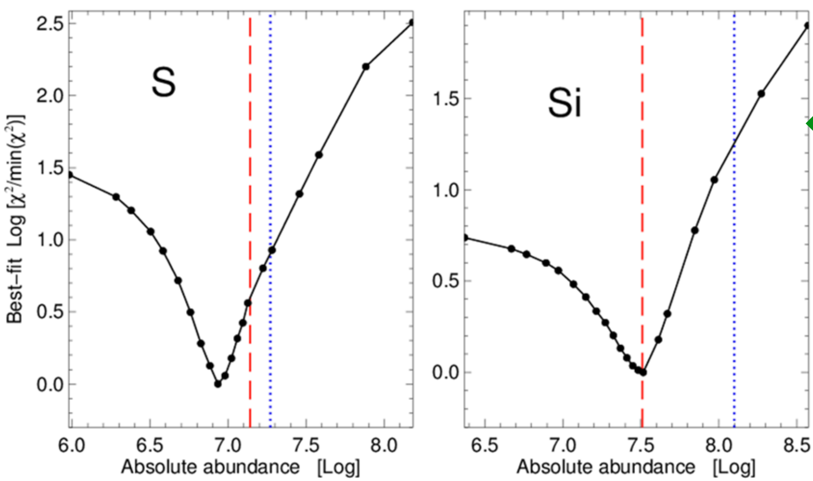
AbuOpt introduction: (fluxes integrated over whole flare duration)

$$F_i = A_i \int_{T=0}^{\infty} f_i(T)\varphi(T)\mathrm{d}T$$

for i=1,2…15 $DEM \equiv \varphi(T) \equiv N_e{}^2 \frac{\mathrm{d}V}{\mathrm{d}T}$

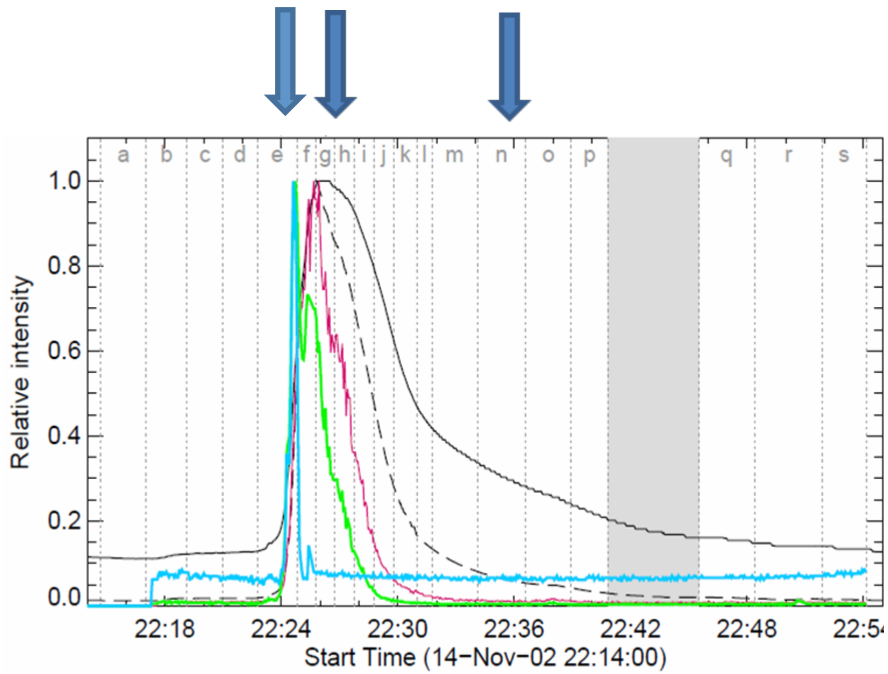
A**$_i$* - an abundance of ***i –th element to be estimated

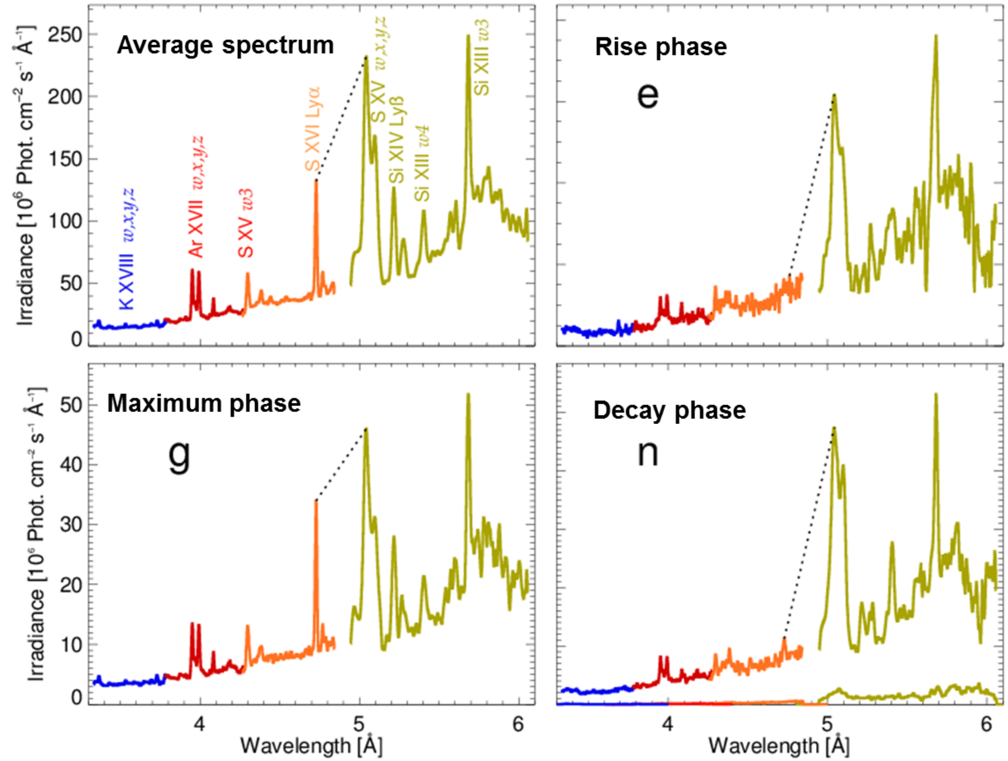
The set of 15 such equations is being solved in order to determine DEM distributions changing value of ***A**$_i$* – we assume **21 values** from the range **0.1 - 16 x coronal value**. We solve the set for the DEM using iterative likelihood procedure and changing the abundance of particular element - abundances of other elements are taken as coronal for the given exercise. For each of 21 exercises, after 1000 iterations we get : A_i, φ_i, and the value χ^2 (for the fit). The relation of **χ^2 on A_i** is analysed and the value of abundance of particular element, which corresponds to the minimum χ^2 value is regarded as the optimum.



An example of χ^2 on A_i dependence as obtained for elements S and Si using the fluxes integrated over the whole flare duration.
Dashed red line denotes the typically assumed photospheric and dotted blue - the coronal abundance.

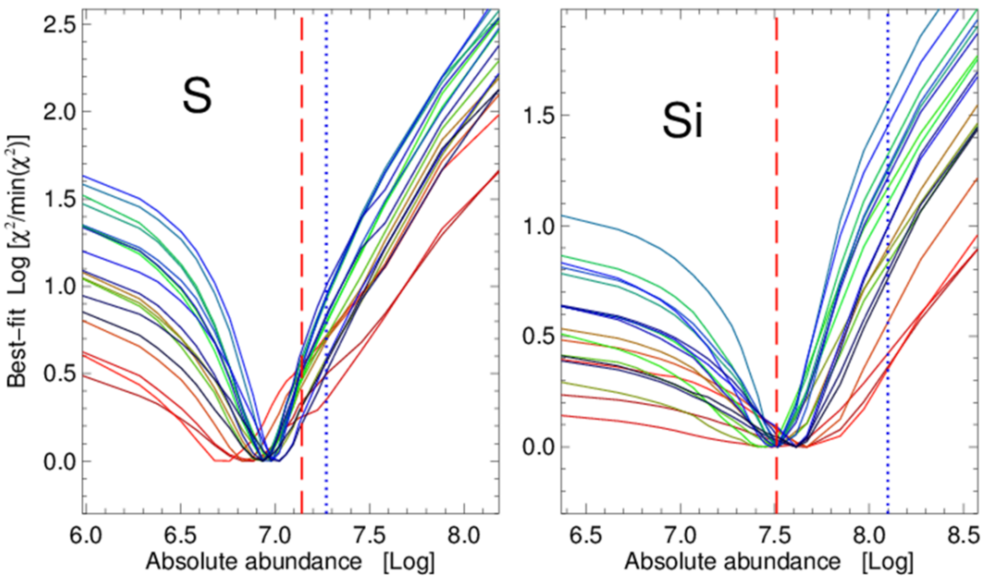
M1 flare on 14 Nov. 2002 at 22:26 UT

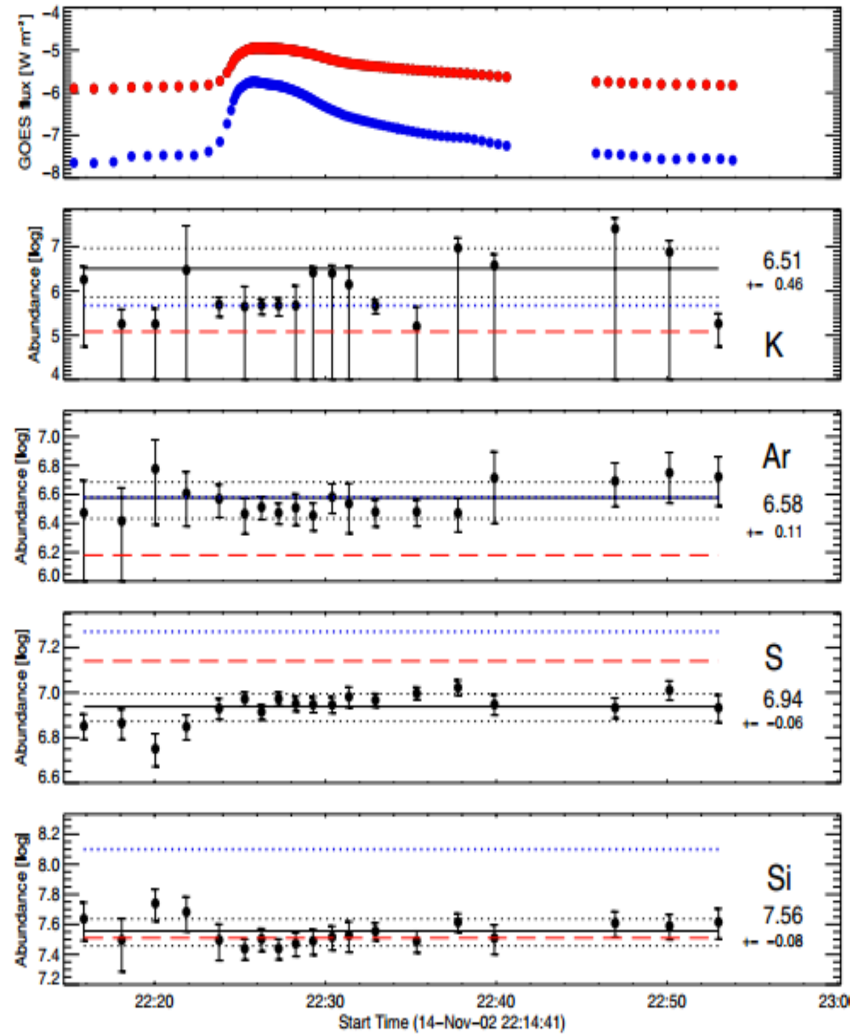




GOES → black
RHESSI → pink (6 - 12 keV)
green (12 - 25 keV)
blue (25 - 50 keV)

14 Nov. 2002; for 19 time intervals

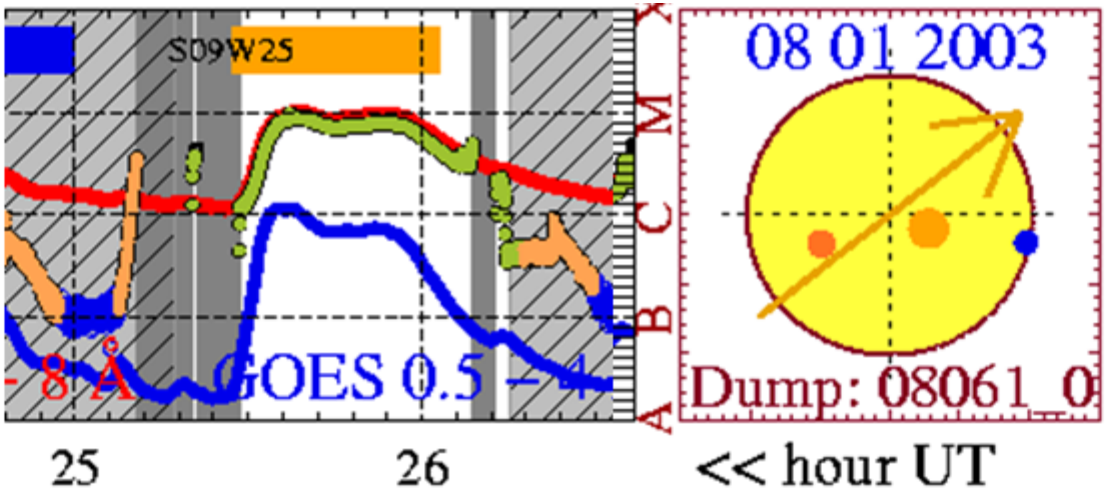


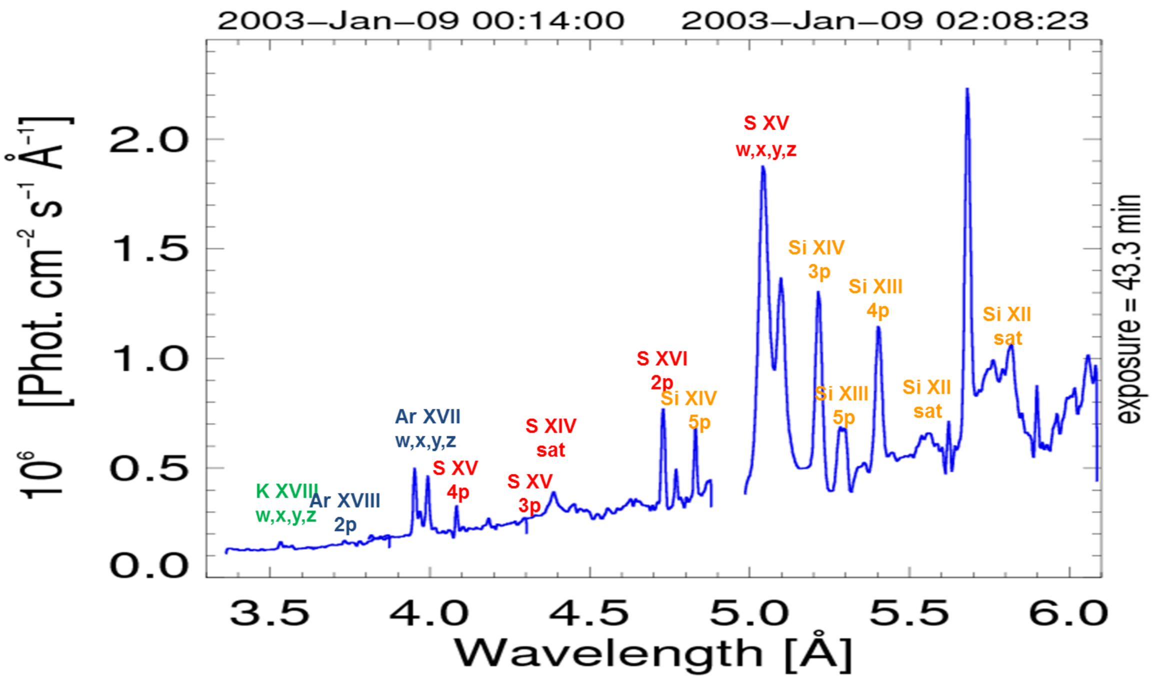


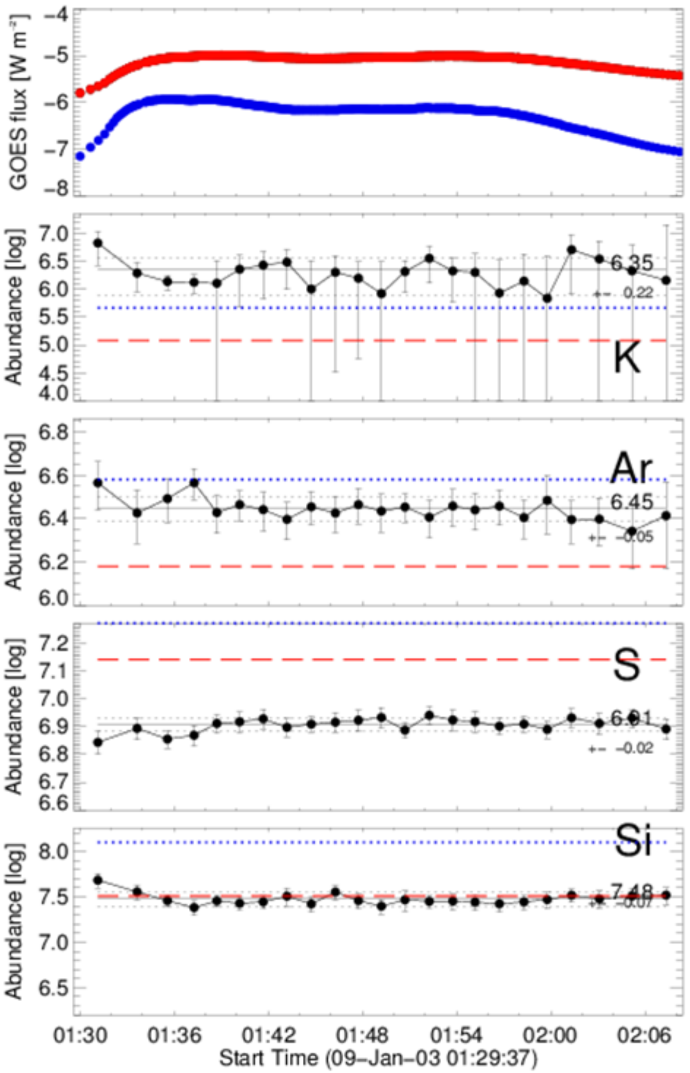
Dashed red line denotes the photospheric and dotted blue the coronal abundances.

Error bars of abundances correspond to values for normalized min(χ^2)+1 (Bevington). **Solid black line** - time averaged values with rms error bars (dotted).

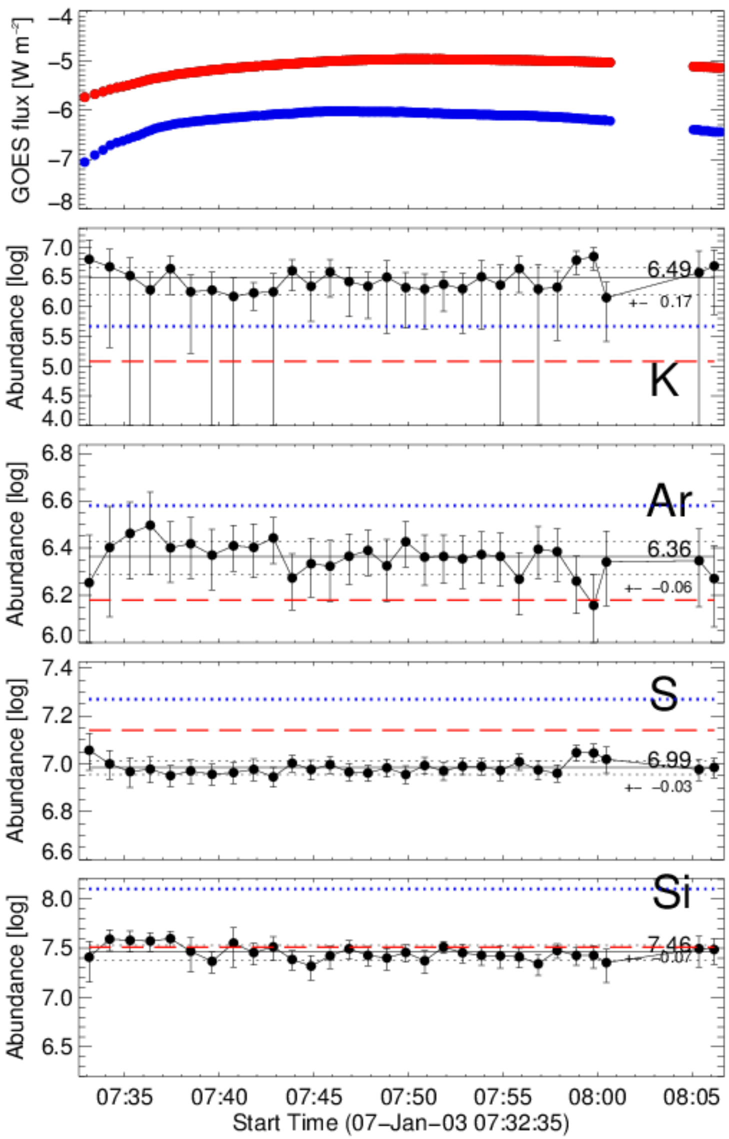
9 Jan 2003 at 01:39 UT; C9.8

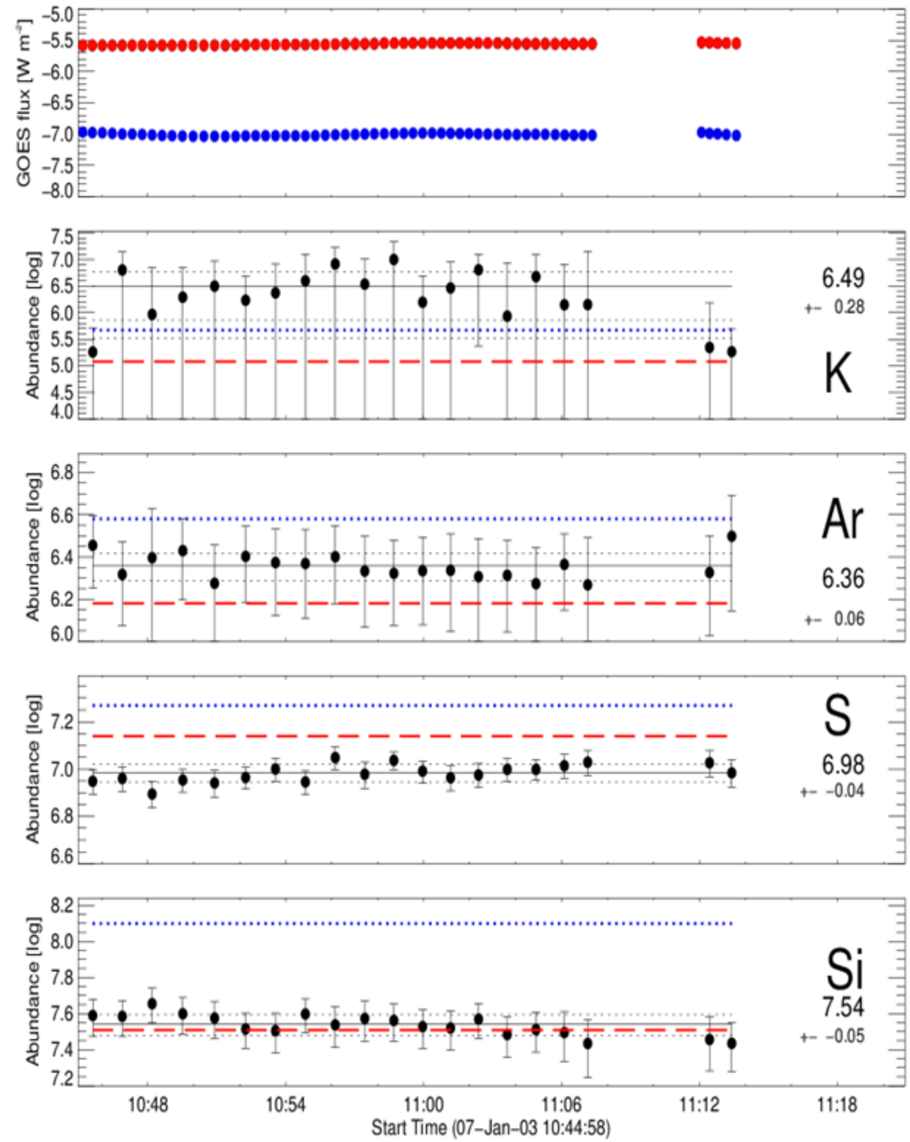






7 Jan. 2003~07:50 UT M1.0 ~11:12 UT C2.9

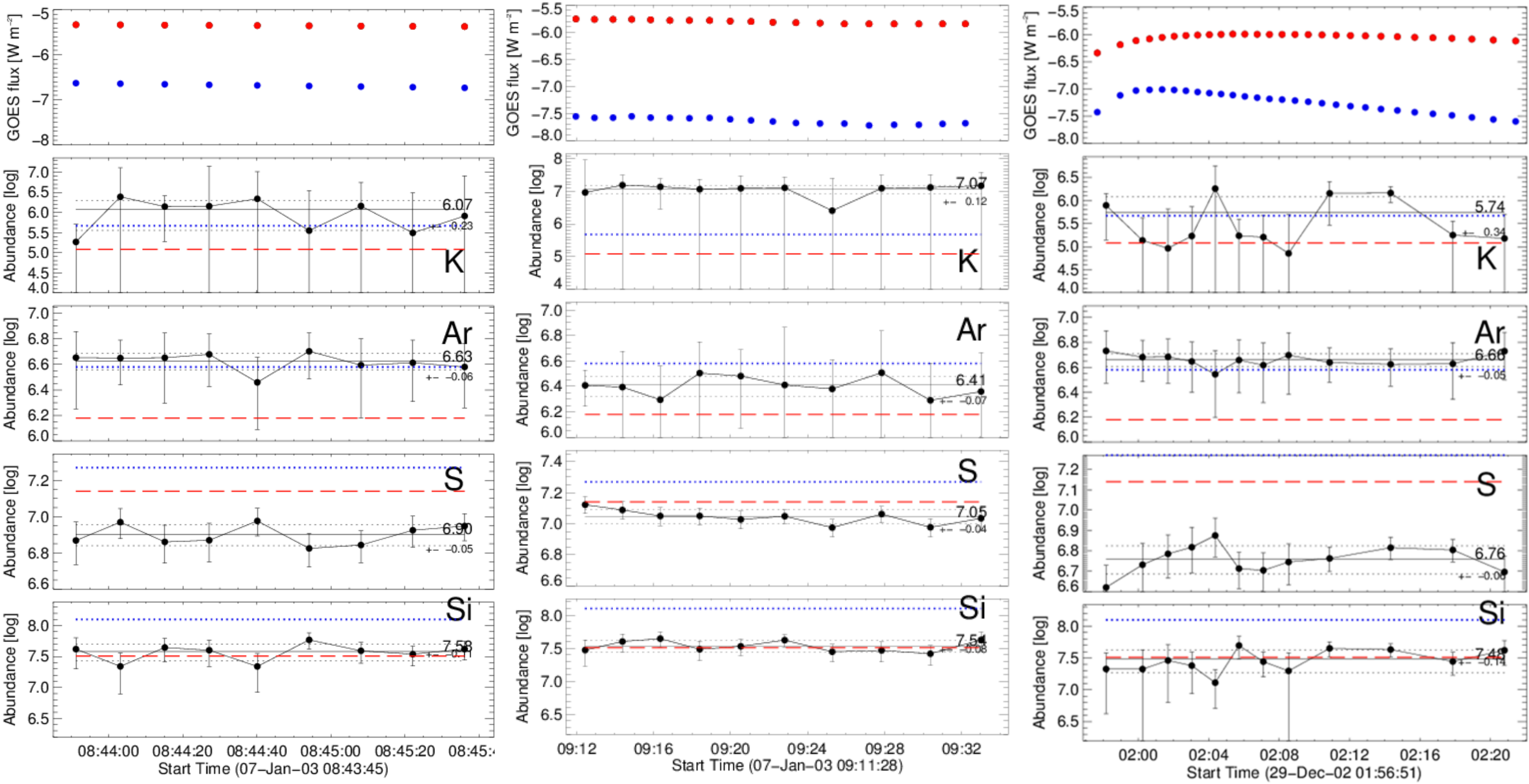




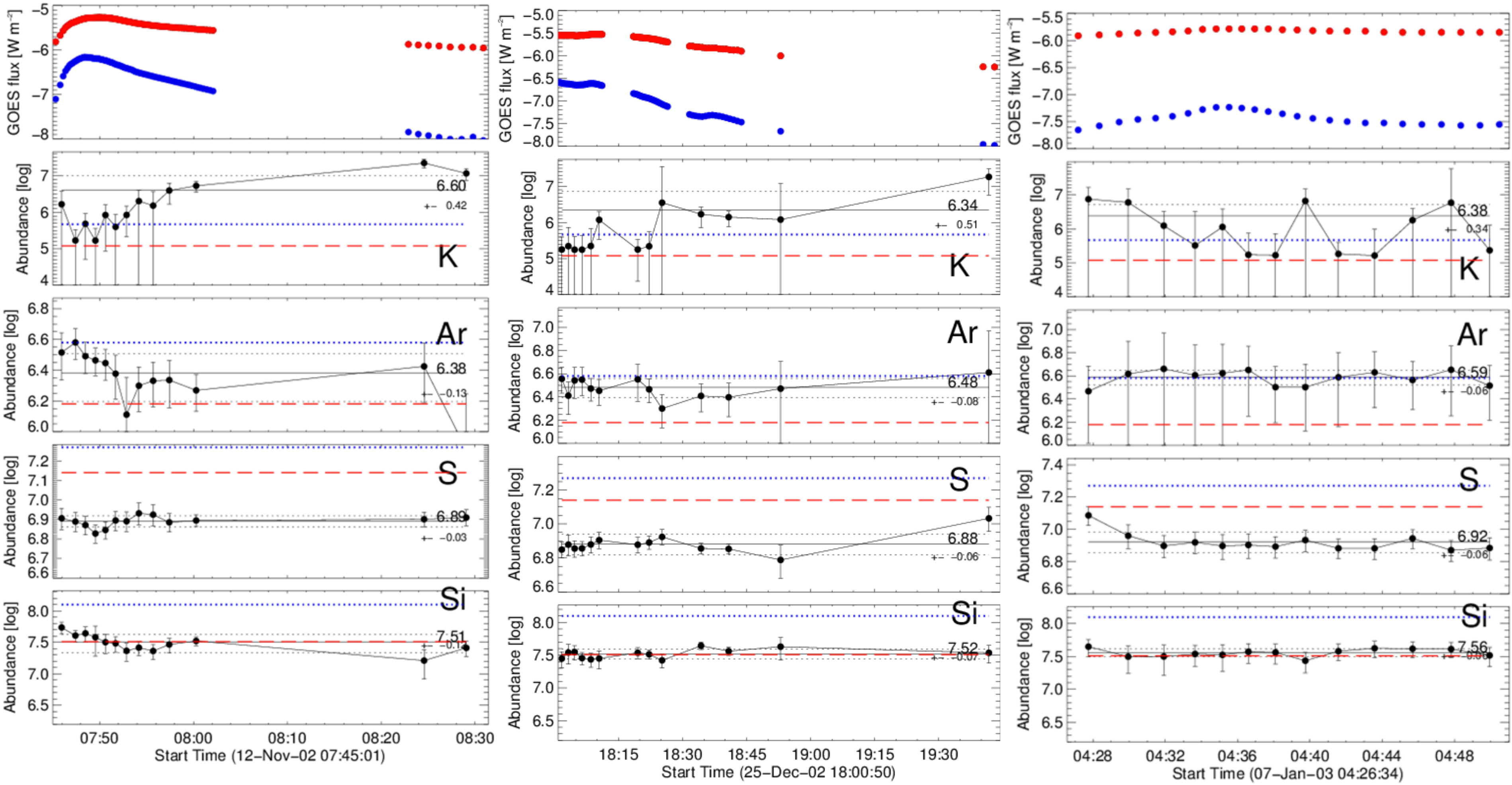
7 Jan. 2003 ~08:33 UT C7.7

7 Jan. 2003 ~09:15 UT C1.7

29 Dec. 2002 : ~02:05 UT B9.9



12 Nov. 2002 ~07:49 UT C5.3   25 Dec. 2002~18:09 UT C2.9   7 Jan. 2003 ~04:35 UT C1.6



The three examples indicated for possible abundance variations during the flare evolution.

Abundances for the analysed (17) flares

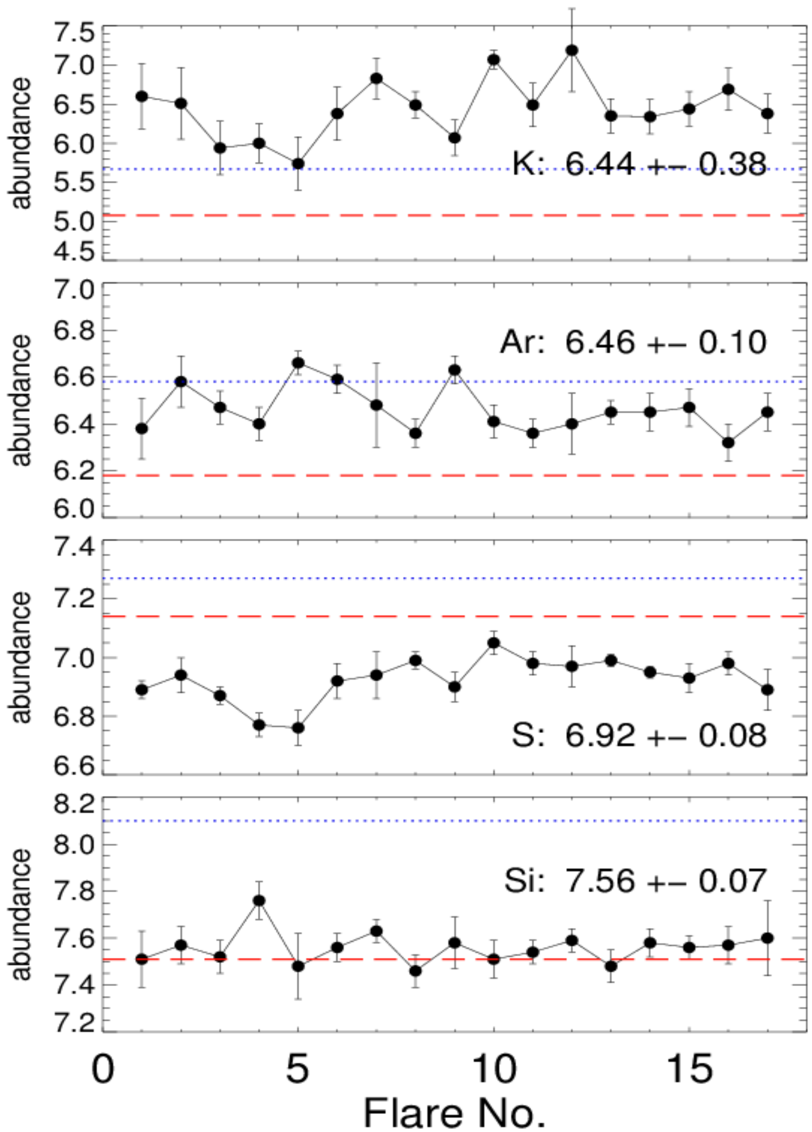
	Data	UT[max]	Class	K	Ar	S	Si
1	07.01.2003	07:50	**M1.0**	6.49±.17	6.36±.06	6.99±.03	7.46±.07
2	07.01.2003	08:33	C7.7	6.07±.23	6.63±.06	6.90±.05	7.58±.11
3	07.01.2003	09:15	C1.7	7.07±.12	6.41±.07	7.05±.04	7.51±.08
4	07.01.2003	11:12	C2.9	6.49±.28	6.36±.06	6.98±.04	7.54±.05
5	07.01.2003	12:35	C1.3	7.19±.53	6.40±.13	6.97±.07	7.59±.05
6	09.01.2003	01:39	C9.8	6.35±.22	6.45±.05	6.99±.02	7.48±.07
7	26.12.2002	08:35	C1.9	6.00±.25	6.40±.07	6.77±.04	7.76±.08
8	14.11.2002	22:26	**M1.0**	6.51±.46	6.58±.11	6.94±.06	7.57±.08
9	29.12.2002	02:05	**B9.9**	5.74±.34	6.66±.05	6.76±.06	7.48±.14
10	12.11.2002	07:49	C5.3	6.60±.42	6.38±.13	6.89±.03	7.51±.12
11	22.02.2003	09:29	C5.8	6.38±.25	6.45±.08	6.89±.07	7.60±.16
12	21.01.2003	15:26	**M1.9**	6.69±.27	6.32±.08	6.98±.04	7.57±.08
13	21.01.2003	02:45	C4.0	6.44±.22	6.47±.08	6.93±.05	7.56±.05

Abundances for the analysed (17) flares

	Data	UT[max]	Class	K	Ar	S	Si
14	07.01.2003	04:35	C1.6	6.38±.34	6.59±.06	6.92±.06	7.56±.06
15	07.01.2003	05:09	C3.2	6.83±.26	6.48±.18	6.94±.08	7.63±.05
16	25.12.2002	18:09	C2.9	5.94±.34	6.47±.07	6.87±.03	7.52±.07
17	21.01.2003	02:28	C8.1	6.34±.22	6.45±.08	6.95±.02	7.58±.06

	K	Ar	S	Si
Averaged values:	**6.44±.38**	**6.46±.10**	**6.92±.08**	**7.56±.07**
Photospheric	5.08	6.18	7.14	7.51
Coronal ext.	5.67	6.58	7.27	8.10
FIP[eV]	**4.34**	**15.76**	**10.36**	**8.15**

Results: Observed regularities



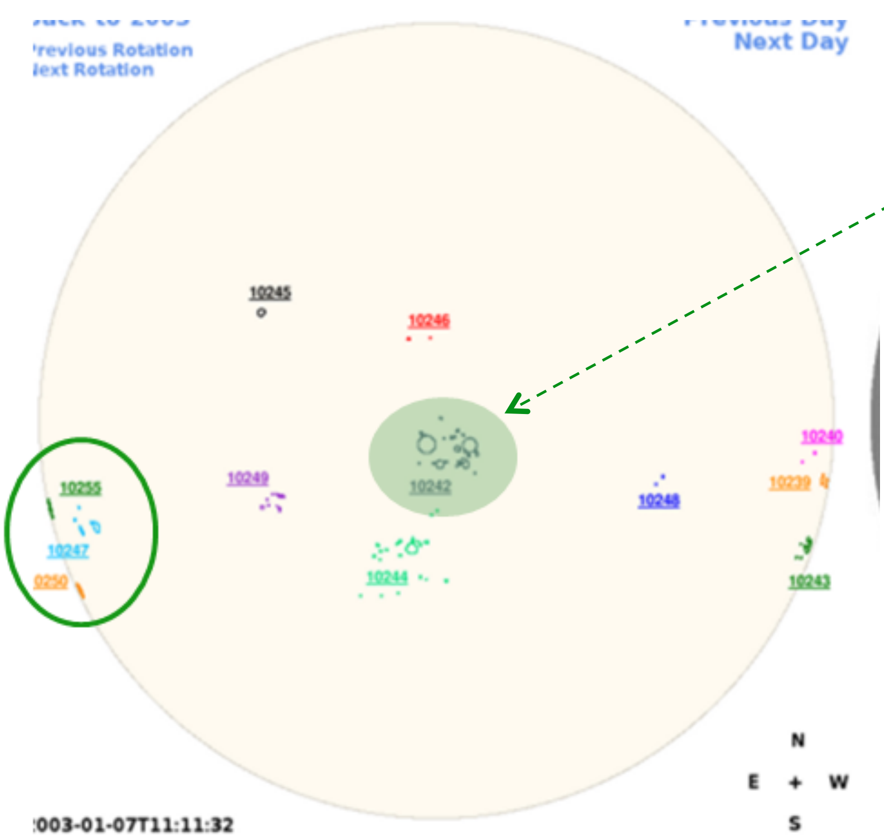
- K (FIP=4.34 eV) abundances usually much above the coronal value; but… should be regarded with caution (?) upper limit is reliable.
- Ar (FIP=15.76 eV) abundances: between the photospheric and coronal values (results in agreement with **isothermal** analysis).
- S (FIP=10.36 eV) abundances always seem to be below photospheric (inverse FIP effect?)
- Si (FIP=8.15 eV) abundances close to the photospheric value.

Time averaged values with rms error bars: small changes from flare to flare are within uncertainties…

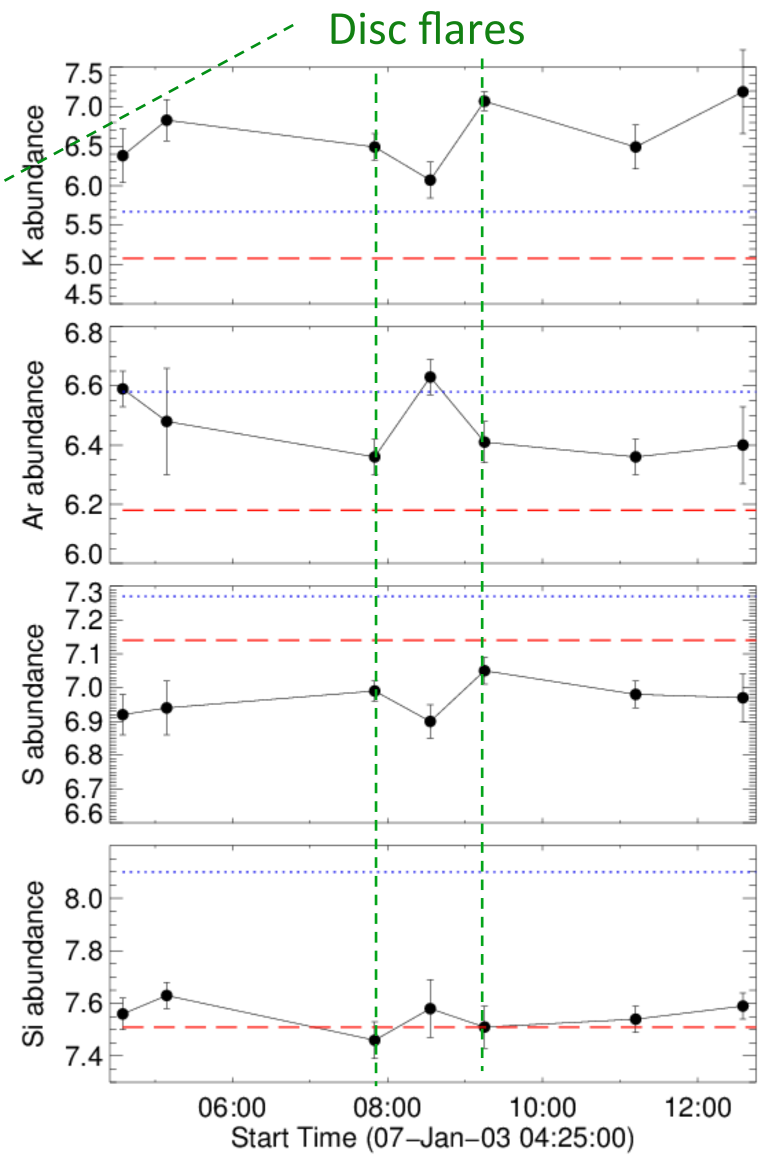
Coronal

Photospheric

7 flares on 7th January 2003



http://fenyi.sci.klte.hu/DPD/2003/index.html



Concluding remarks

- For most of analysed flares the abundances do NOT change significantly during the flare evolution. The variations are within the estimated uncertainties, so the derived abundances seem to be constant over the flare for this sample of investigated moderate RESIK events. (17 flares: 3 of M class, 13 of C class, 1 of B class)
- There is rather little flare to flare variation of estimated values for A(K), A(Ar), A(S) and A(Si) abundances. Mean values ($\log A_H$)=12 with the event to event scatter are:
  A(K) =6.44±0.38
  A(Ar)=6.46±0.10
  A(S) =6.92±0.08
  A(Si)=7.56±0.07
- No conclusive result in respect of abundance dependence on the flare location. Further analysis are needed.

THANK YOU !!!!

References

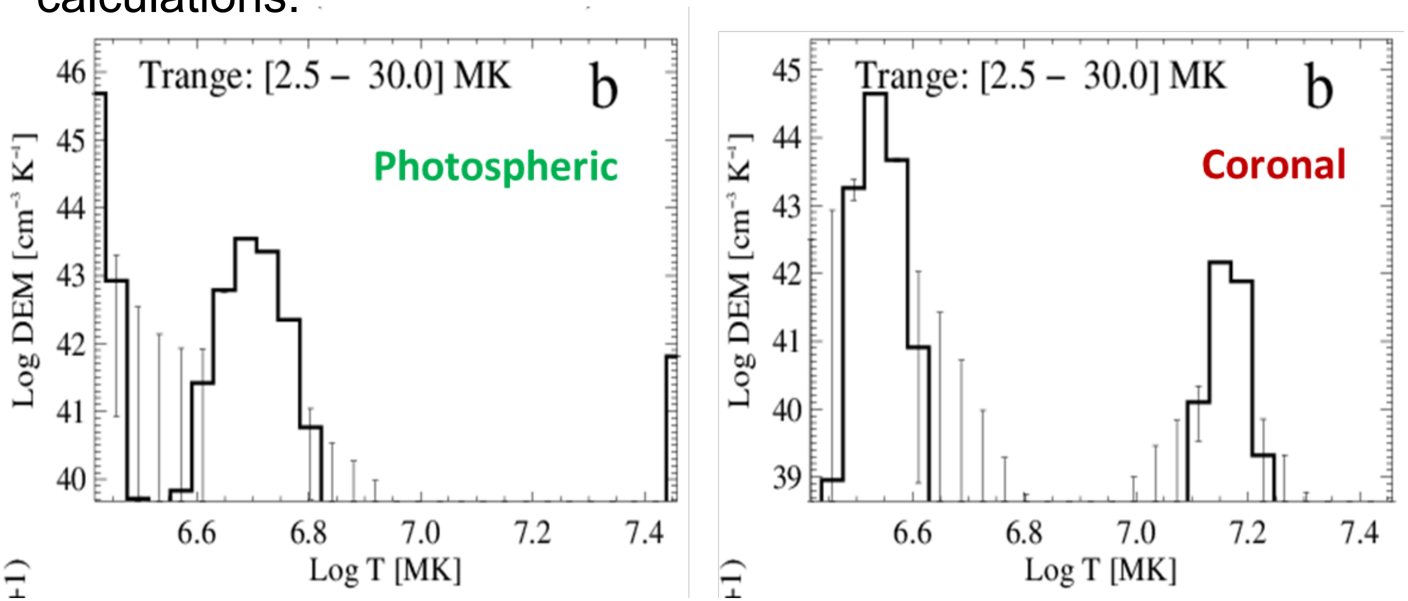
- Measurements of absolute abundances in solar flares; Harry P. Warren, 2014, ApJ, 786
- Solar flare composition and thermodynamics from RESIK X-ray spectra; B. Sylwester, J. Sylwester, K. J. H. Phillips, A. Kępa, and T. Mrozek, 2014, ApJ, 787
- Plasma composition in a sigmoidal anemone active region; D. Baker, D. H. Brooks, P. Demoulin, L. van Driel-Gesztelyi, L. M. Green, K. Steed, and J. Carlyle; 2013, ApJ, 778
- J. Sylwester, J. R. Lemen & R. Mewe; 1984, Nature 310, 665 – 666
- J. Sylwester et al., ApJ. 501, 1998

DEM vs the abundances

$$F_i = A_i \int_{T=0}^{\infty} f_i(T)\varphi(T)\mathrm{d}T$$

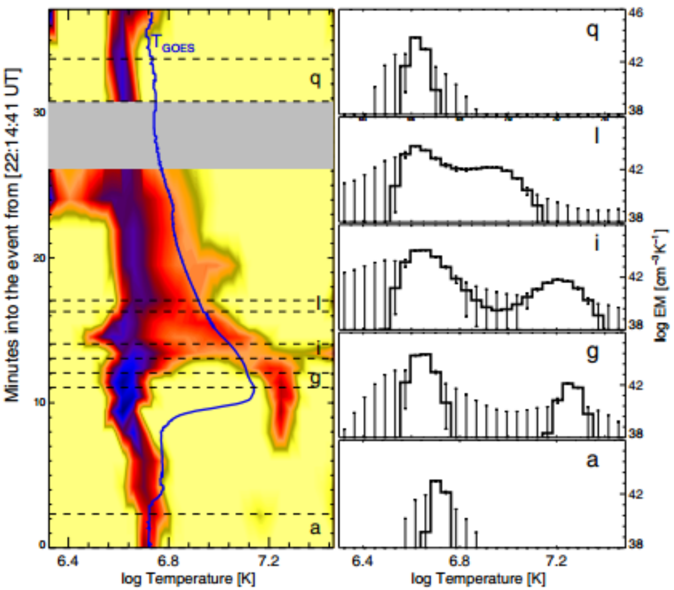
$$DEM \equiv \varphi(T) \equiv {N_e}^2 \frac{\mathrm{d}V}{\mathrm{d}T}$$

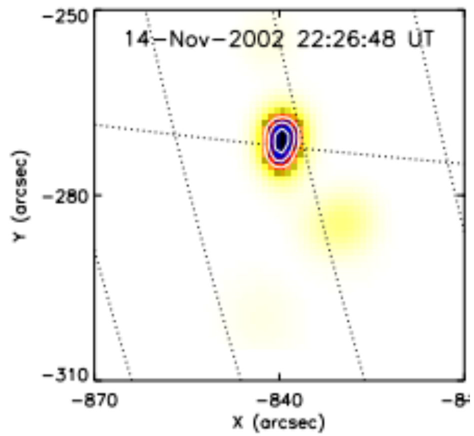
Input: Fluxes in 15 bands (energy intervals containing the most important line and continuum. Theoretical fluxes: calculated based on CHIANTI 7.0 code assuming photospheric and coronal abundances and ionization equilibrium from Bryans (ApJ, 691, 2009).
Method: Withbroe-Sylwester likelihood algorithm (Solar Phys., 67, 1980)→ 10 000 iterations for DEM calculations and 100 Monte Carlo realizations for errors calculations.



DEM distributions obtaained for photospheric and coronal abundances assumed.

Further analysis using determined abundances





Constant volume based on PIXON reconstructed *RHESSI* 6-7 keV images: 5400 km at 50% iso-contour → hot component parameters (N_e, E_{th})