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Corresponding Author: Dr. J. Sylwester,

Corresponding Author's Institution: Space Research Center

First Author: J. Sylwester

Order of Authors: J. Sylwester; Barbara Sylwester, Dr.; Enrico Landi, Dr.; Kenneth J Phillips, Dr.; Vladimir D Kuznetsov, Prof.

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Determination of K, Ar, Cl, S, Si and Al flare abundances from RESIK soft X-ray spectra

J. Sylwester [a,*], B. Sylwester [a],

[a] *Space Research Centre, Polish Academy of Sciences,ul. Kopernika 11, PL-51-622 Wroclaw, Poland*

E. Landi [b],

[b] *Artep, Inc. at Naval Research Laboratory, USA*

K.J.H. Phillips [c],

[c] *Mullard Space Science Laboratory, University College London, U.K.*

V.D. Kuznetsov [d],

[d] *IZMIRAN, Russian Academy of Sciences, Troitsk, Russia*

Abstract

The RESIK is a high sensitivity, uncollimated bent crystal spectrometer which successfully operated aboard Russian *CORONAS-F* solar mission between 2001 and 2003. It measured for the first time in a systematic way solar soft X-ray spectra in the four wavelength channels from 3.3 Å to 6.1 Å. This range includes characteristic strong lines of H- and He-like ions of K, Ar, Cl, Si, S and Al in the respective spectral channels. A distinguishing feature of RESIK is its possibility of making reliable measurements of the continuum radiation in flares. Interpretation of line and the continuum intensities observed in vicinity of these triplets provides diagnostics of plasma temperature and absolute abundances of K, Ar, Cl, S, Si and Al in several flares. We analyzed the observed intensities of spectral lines and the nearby continuum using the CHIANTI v5.2 atomic data package. A specific, so-called "locally isothermal" approach has been used in this respect allowing us to make not only flare-averaged abundance estimates, but also to look into a possible variability of plasma composition during the course of flares.

Key words: solar physics, X-ray flares, spectroscopy, abundances

* Corresponding author
Email address: `js@cbk.pan.wroc.pl` (J. Sylwester).

1 RESIK Bent Crystal Spectrometer

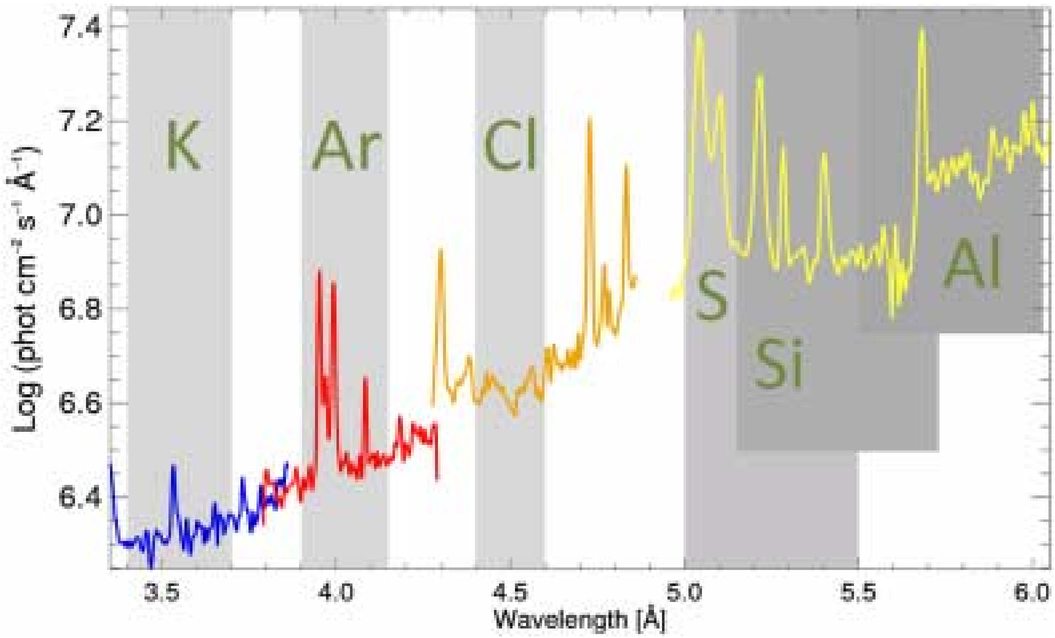

Fig. 1. An example of a calibrated RESIK spectrum. This spectrum was accumulated over entire 2003 February 22 flare which took place around 09:30 UT. In gray, several spectral bands are marked, selected to study the absolute abundance of indicated respective elements.

The RESIK consists of two double-channel X-ray spectrometers equipped with bent crystals, a design similar to the BCS spectrometers aboard *SMM* and *Yohkoh*. RESIK was designed to observe hot solar plasmas. It was included in the scientific payload of the Russian solar satellite mission *CORONAS-F*. The detailed description of the RESIK instrument, its operation and calibration are presented in the paper by Sylwester et al. (2005). Here we summarize a number of instrument characteristics important for the present study. The nominal wavelength coverage of RESIK was 3.35 Å - 6.1 Å . This range contains several spectral features useful for the X-ray plasma diagnostics. The observed line intensities can be used in order to study the physical conditions in the flaring plasma as well as to investigate its relative (element-to-element) composition. Inclusion of the continuum, also reliable measured, allows us to measure the absolute (relative to hydrogen) abundances, as substantial contribution to the continuum comes from bremsstrahlung emission. In the RESIK spectra one can find lines belonging to the elements with substantially different values of FIP: from the lowest being 4.34 eV (K), the highest being 15.75 eV (Ar). Other lines are identified by Sylwester et al. (2006) and Kepa et al. (2006). They include the triplets of He-like ions (K XVIII, Ar XVII, Cl XVI and S XV) as well as lines corresponding to $(n > 3) \rightarrow (1)$ transitions in Si and Al.

2 Spectra observed and new abundance analysis approach

For the purpose of the present analysis we have selected 7 typical flares, well observed by RESIK. The flares selected represent short and longer duration events seen on the disk and/or at the limb. All flares were observed early

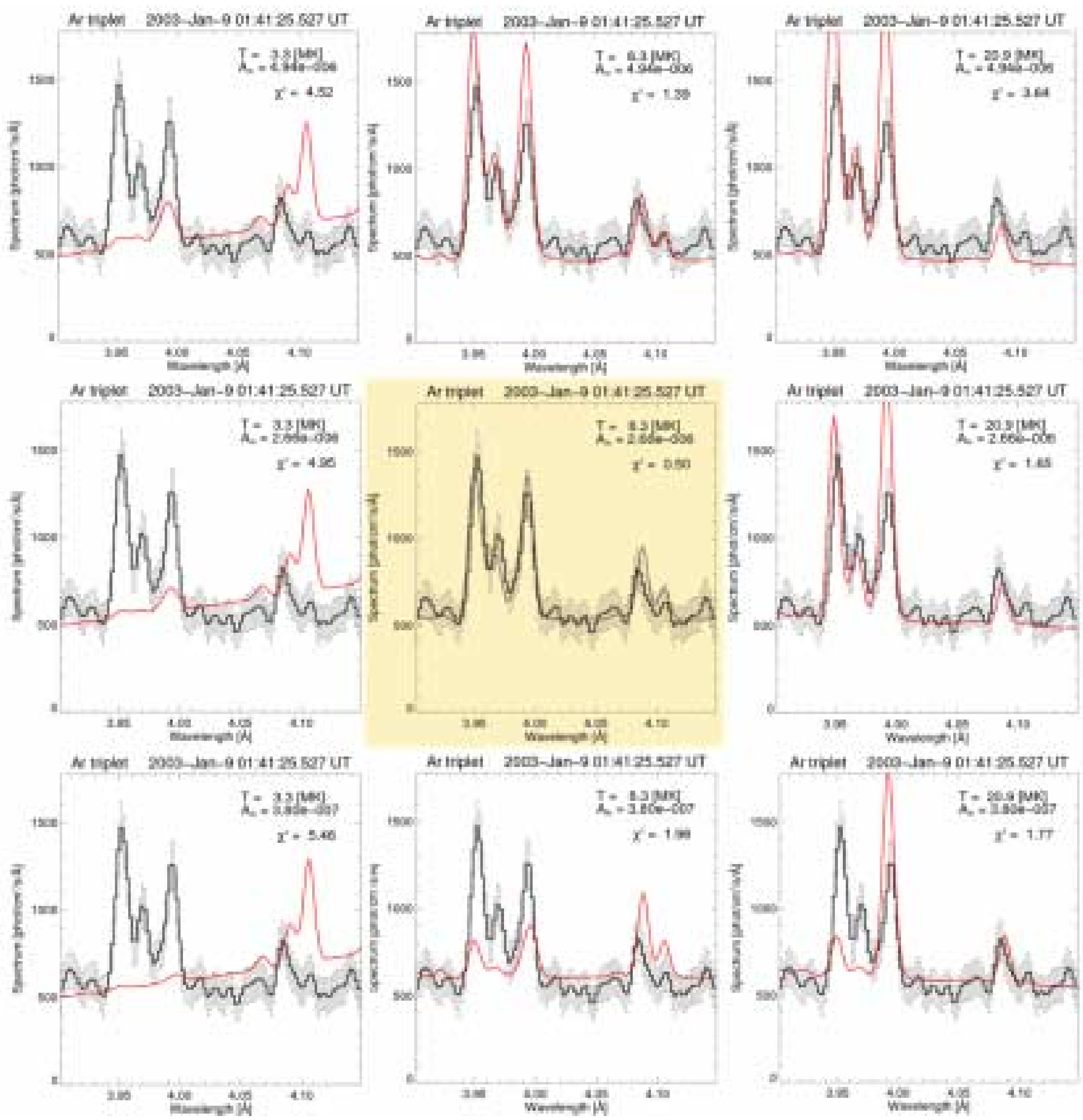

Fig. 2. Nine examples of the fit between observed (histogram) and synthetic spectra. In each row, the abundance of the element of interest (Ar) is kept constant and the plasma temperatures correspond to three different values. In each column, the plasma temperature is constant and the abundance of Ar is set to three different values. In the central panel, the optimum fit is shown, characterized by the smallest value of χ^2 parameter. Such an optimum fit has been obtained for each of the spectra recorded throughout the flare.

in 2003, when the instrument settings were optimised (cf. Table 1). We have carefully calibrated the observed spectra, establishing an absolute wavelength scale and determining the absolute spectral photon fluxes. We incorporated all known corrections which essentially remove the instrumental fluorescence radiation from the RESIK bent crystals material. This leads us to believe that the level of the continuum seen in the longer wavelength channels of RESIK is not contaminated. For the two shorter wavelength bands, the contribution of this fluorescence to the continuum is found not to be a problem as it amounts to less than one percent.

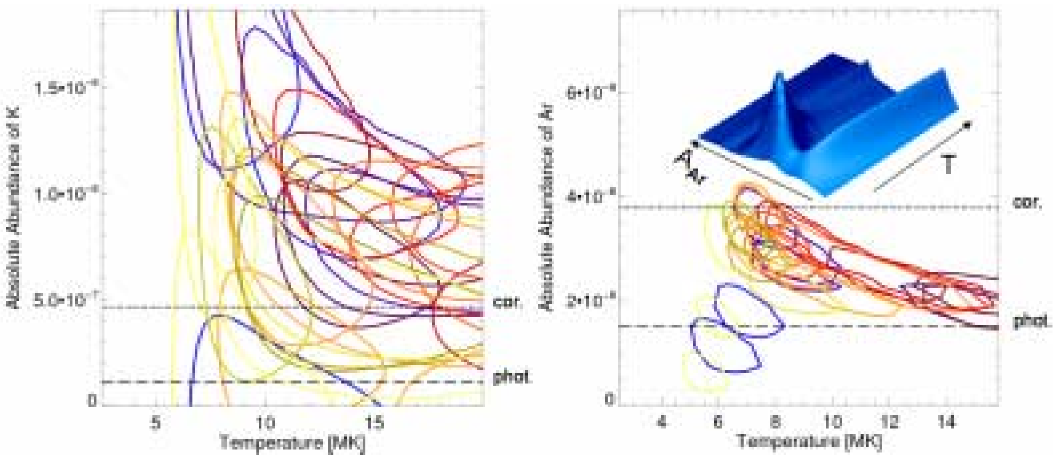

Fig. 3. **left: potassium** Contours of $min(\chi^2) + 1\sigma$ for the 2003 February 22, 09:30 UT flare. Individual shades of the contours represent the time-in-flare, with dark shades representing fits to the spectra observed earlier on in the rise phase. The light gray contours represent the decay phase of the flare. The "phot. " and "cor." horizontal lines designate the photospheric and coronal abundance levels for potassium as taken from Asplund et al. (2005) and Feldman & Laming (2000) respectively. **right: argon** A corresponding diagram shown for more abundant element Ar. Here the $min(\chi^2) + 1\sigma$ contours are more compact which indicates that respective abundance uncertainties are much smaller. The inset in the upper right shows the actual shape of the $1/\chi^2$ surface at one time corresponding to flare maximum.

In the analysis, we have used a novel "locally isothermal" (LI) approach in order to separate the impact of abundance variability from the temperature (multitemperature-DEM) effects on the spectra as much as possible. In the LI approach we make "implicit use" of somewhat similar temperature dependence of the line and the nearby continuum emission functions in the region of the effective line formation. This similarity causes the abundance effects to dominate over DEM effects in the Line-to-Continuum (L/C) ratio variability. Our non-standard determination technique is based on converging iterative scheme, where we start from the measured value of a total (wavelength integrated) flux in entire selected wavelength band including the lines of the element of interest and substantial part of near-by continuum. A counterpart,

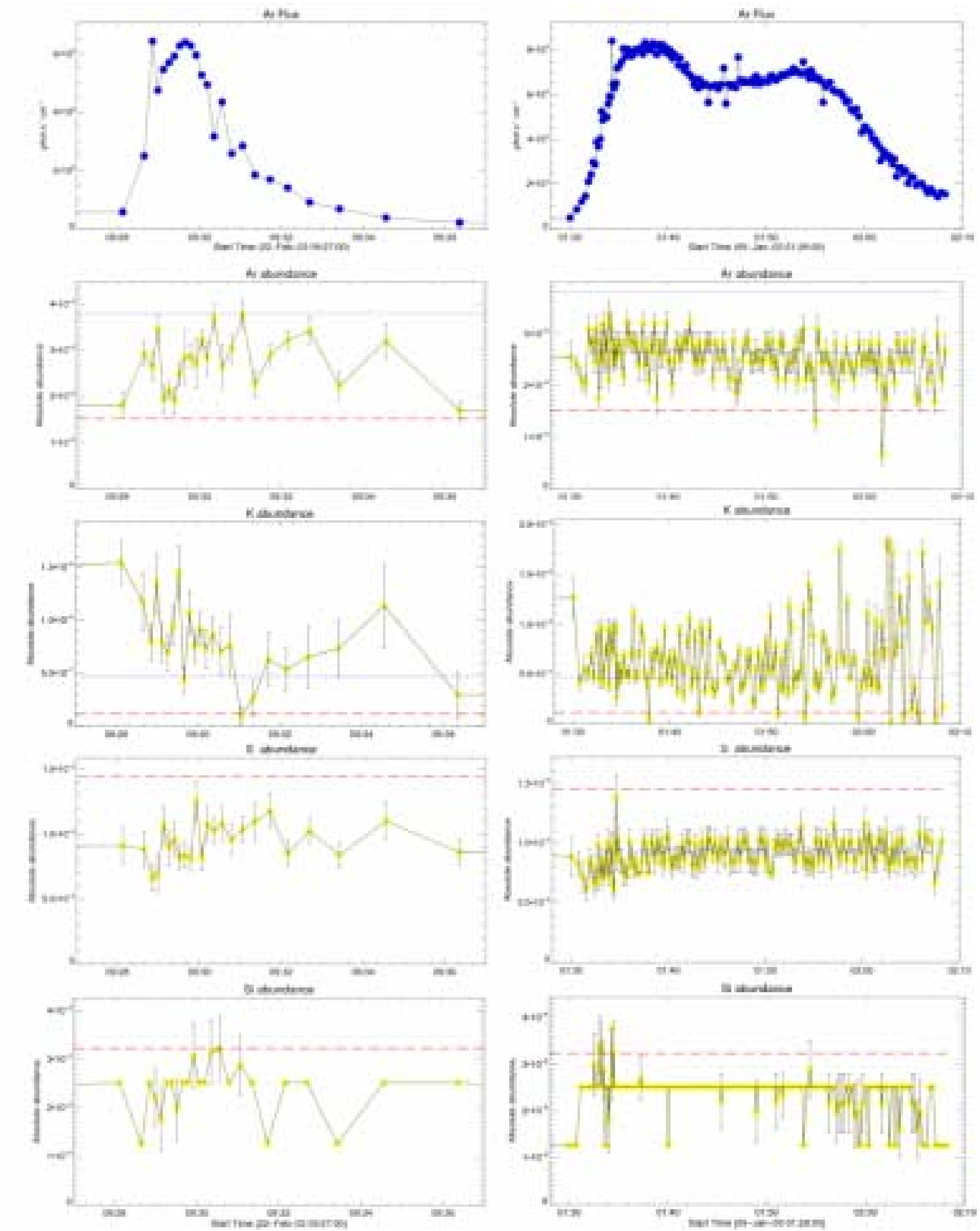

Fig. 4. Time dependence of derived flare abundances. Two flares are shown in the figure in respective columns: a fast evolving flare on 2003 February 22 (left), and a “double” flare of 2003 January 9. In the upper part, the flare flux in the Ar spectral band is plotted for each flare. The uncertainties plotted correspond to the vertical extension of the iso-contours shown in Figure 3. Respective coronal and photospheric abundance levels are given for each element as dotted and dashed lines respectively.

theoretically predicted fluxes in the same selected band depend on the assumed plasma temperature, emission measure and the composition. By varying values of the two parameters within the calculation cube, i.e. for a set of selected temperatures and particular element abundances (40 linearly separated values from "zero" up to four times the coronal abundance value of Feldman & Laming, 2000), we determine respective emission measure values from the measured band fluxes. These values are next used to calculate the shape of synthetic spectrum in each of the observed individual spectral bins contained in the analyzed band. Such synthetic spectra are then compared with the observed spectra in terms of the χ^2 statistics. This comparison makes use of the measurement uncertainties in each spectral bin separately. By performing the calculations for each of the mesh values of the 2D parameters temperature–abundance ($T - \mathrm{A}_{\mathrm{El}}$) grid, we construct the χ^2 surface, identify the position of its local minimum in the parameter space, and determine the 1σ contours according to the classical approach of Bevington (1969). Example result of the described procedure is illustrated in Figure 2. As mentioned, the quality of the spectral fits between the observed and synthetic spectra was characterized by the value of χ^2 statistics which in the temperature ($T - \mathrm{A}_{\mathrm{El}}$) parameter space is represented as a surface. The position of the minimum and the shape of the χ^2 contour provide a realistic estimate of the instantaneous value of average temperature of formation for the line *and* nearby continuum for each measured spectrum, as it evolves throughout the flare. It is also possible to estimate the uncertainty of both the temperature and abundance. For purposes of the spectral synthesis task, we pre-calculated an extensive ~10 GB-database consisting of a grid of theoretical spectra, with $\delta\lambda = 0.001$Å, for 101 temperatures between 1 - 100 MK, for 6 elements: K, Ar, Cl, S, Si and Al, and for 41 abundance value of each element. The calculations were based on CHIANTI v5.2 spectral code, a part of *SolarSoft*. The important free-free and free-bound processes have all been included in the calculations of the continuum. As checked by Chifor et al. (2006) the continuum calculations following from CHIANTI are in very good agreement (few percent) with the earlier results of Mewe et al. (1986). As these two sets of calculations depend on independent approximations for the basic atomic cross-sections, such a good agreement increases our confidence in derived values of the abundances discussed in the present study.

3 The Results

In Figure 4 we show examples of time dependence of best-fit abundance determinations for two flares observed by RESIK in contiguous manner. One flare was of a fast rise and decay and have fallen entirely within the 20 min observation window. However it was a rather faint event, and therefore the statistically reliable spectra collection time was necessarily longer for the early rise and late decay phases. The other flare was much stronger with the two pronounced maxima. It was possible to study its spectral variability each few

Table 1
Average absolute flare abundances [10^{-6}]

FIP [eV]⇒	4.34	15.76	12.97	10.36	8.15	5.99
Flare⇓ Element⇒	K	Ar	Cl	S	Si	Al
2003-Jan-04 06:30	0.53	2.28	0.52	8.96	17.5	13.3
B9.2 S23 E50	±0.4	±0.5	±0.2	±1.6	±6.1	±5.8
2003-Jan-07 07:50	0.52	2.26	0.35	10.1	30.5	7.26
M1.0 S24 E08	±0.4	±0.6	±0.3	±1.4	±17	±9.4
2003-Jan-07 23:30	0.66	2.38	0.41	9.46	19.8	11.3
M4.9 S11 E08	±0.4	±0.9	±0.3	±1.5	±6.6	±10
2003-Jan-09 01:39	0.65	2.53	0.25	9.12	23.8	5.04
C9.8 S09 W25	±0.4	±0.4	±0.3	±1.2	±4.2	±4.7
2003-Jan-21 15:26	0.43	2.69	0.36	11.3	26.2	7.45
M1.9 S07 E90	±0.3	±0.7	±0.4	±2.1	±13	±8.5
2003-Jan-25 18:55	0.70	2.79	0.32	9.81	24.9	9.68
C4.4 N13 W27	±0.5	±0.8	±0.3	±3.6	±23	±9.1
2003-Feb-22 09:30	0.76	2.60	0.28	9.41	23.0	13.3
C5.8 N16 W05	±0.4	±0.8	±0.2	±1.5	±6.0	±7.1
A_{El} photospheric[a] ⇒	0.115	1.51	0.170	14.45	32.36	2.69
A_{El} coronal[b] ⇒	0.468	3.80	0.316	18.62	125.9	10.96

[a] - from Asplund, Grevese and Sauval, (2005)
[b] - from Feldman and Lamming, (2000)

seconds. In the Figure we plot the abundance values for each element in question together with respective $\pm 1\sigma$ uncertainties. These uncertainties represent the size of the $min(\chi^2)+1\sigma$ contour from Figure 3, as projected onto the abundance axis. It is worth noting that the results presented in Figure 3 show for the first time the plasma composition variability *during* flares, as determined from spectroscopic data.
Examination of Figure 4 and similar plots constructed for the other flares studied, allows us to draw a number of conclusions.

- For many events the plasma composition is approximately constant in time.
- For some events like 2003 February 22, A_{Ar} appears to anticorrelate with A_K; these two elements have the largest FIP contrast among those studied.
- For the events shown in Figure 4, it is highly improbable that the time variability pattern observed occurs by chance, and therefore, we conclude that substantial plasma composition variability takes place during flares.

If the above conclusions are confirmed in a following larger study covering many tens of flares observed by RESIK, the physical consequences are expected to be profound for considerations concerning the origin (source) of matter contributing to soft X-ray flaring plasma. It is possible, that such matter may be characterized by a highly non-uniform composition probably influenced by plasma-magnetic field mechanisms acting selectively on semi-ionized gas over longer periods.

Based on the observed composition variability pattern for the analyzed flares, it was possible to determine seven flare-averaged plasma abundance sets for the six elements studied. These average values are given in Table 1, together with formal $\pm 1\sigma$ uncertainties. The uncertainties were calculated taking into account the scatter about the mean value. The uncertainties are large for cases where the abundance appears to be time dependent.

4 Summary and Conclusions

In this study we present analysis of RESIK bent crystal spectrometer soft X-ray spectra for seven well-observed flares. The novel nature of the spectral analysis applied, as well as unprecedented quality of the spectra measured, have allowed us to study time-variability of absolute elemental composition for the following elements: K, Ar, Cl, S, Si and Al. The results shown in Figure 4 indicate possible changes in flaring plasma composition as the flare progress. The flare-averaged composition for seven analyzed flares (presented in Table 1) is seen to vary from event-to-event. The amplitude of variability is the largest for the low-FIP elements like potassium. Derived average abundances of sulphur and silicon are significantly below, at the level of ($\sim$60%) of the photospheric values taken from Asplund et al. (2005). Abundances of Ar are between the photospheric and coronal (Feldman & Laming , 2000) values, while for potassium and aluminum the derived values are significantly above the assumed coronal level. Notwithstanding of a careful analysis of the instrumental fluorescence contribution, there is still a possibility of some uncounted contamination of fluorescence in the RESIK channel where S, Si and Al lines are observed. Work is in progress and we hope to present completely unbiased estimates for these elements in the subsequent extended study following the outline presented here.

Acknowledgements

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