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Determination of flaring plasma characteristics from RESIK X-ray spectra

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Abstract. We present spectral analysis methods suitable for diagnostics of flaring plasma from RESIK spectra. RESIK is the uncollimated bent crystal spectrometer aboard the Russian *CORONAS-F* solar mission. It collected many flare and active region spectra in the wavelength range 3.3 Å–6.1 Å, where strong emission lines of Si, S, Ar, and K are present. Based on a careful instrument calibration the absolute fluxes in the individual spectral lines have been obtained. These fluxes have been used for determination of a set of thermodynamic parameters characterizing the emitting plasma and for studies their time behavior during selected flares.

Keywords. Sun: flares, X-rays, spectroscopic plasma diagnostic

1. Introduction

The RESIK consists of two double-channel X-ray spectrometers, designed to observe solar active region and flare plasmas. The nominal wavelength coverage of RESIK is 3.35 Å–6.1 Å. The detailed description of the instrument, its operation and calibration is presented in the paper by Sylwester, Gaicki, Kordylewski, *et al.* (2005). We have calibrated the measured spectra, establishing an absolute wavelength scale and determining the absolute photon fluxes. This made it possible to identify several spectral features, some of which were observed for the first time from astrophysical plasmas. In particular we have detected lines due to highly ionized chlorine (see Sylwester, Sylwester, Siarkowski, *et al.* (2004)). The observed line intensities can be used in order to study the physical conditions in the flaring plasma as well as to investigate its composition. It is now generally accepted that the coronal abundances of elements with first ionization potential (FIP) less than 10 eV (low-FIP) can reach the values much higher than photospheric values relative to those of high-FIP (so called FIP effect). The evidence of diversified FIP effect in the other stars is presented in the paper by Garcia-Alvarez, *et al.* (2006). In the RESIK spectra one can find lines belonging to the elements with substantially different values of FIP (from K with FIP = 4.34 eV through S with FIP = 10.36 eV to Ar with FIP = 15.75 eV). In the present analysis, we consider in more details the determination of basic flaring plasma characteristics in preparation for the subsequent study of the plasma composition and detailed role of FIP effect in this respect.

2. Analysis and results

In order to present an outline of our diagnostic roadmap we have selected a small disc (N16 W05) flare (optical SF, *GOES* class C5.8) seen on 2003 February 22 at 09:29 UT. This event was of short duration (10 min.). In figure 1 we show reduced absolute RESIK

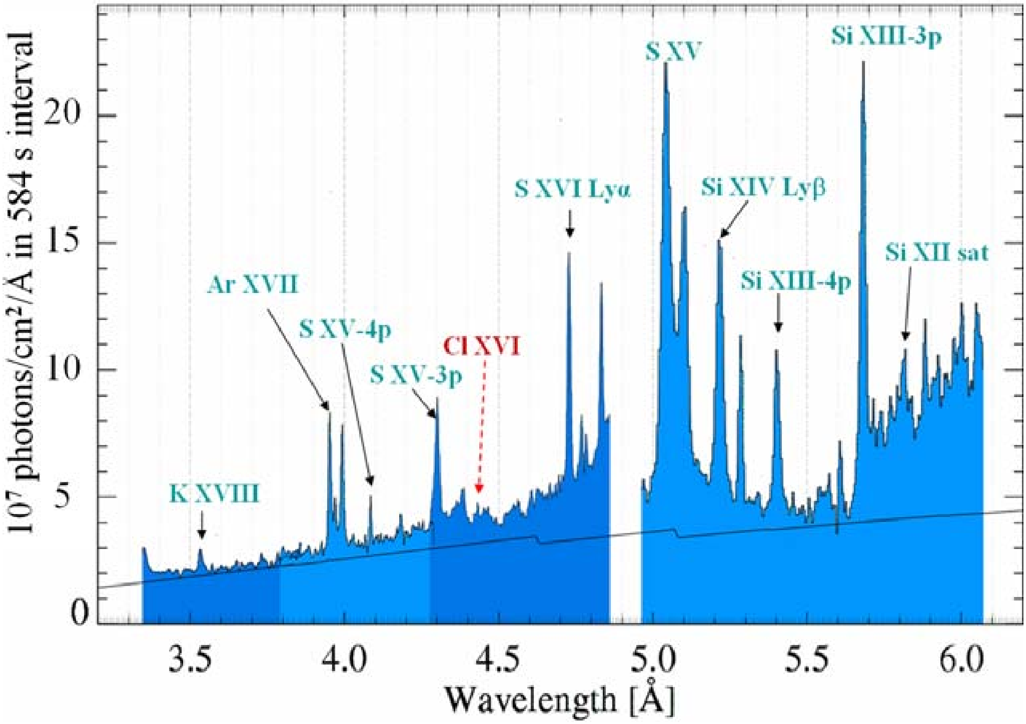

Figure 1. The absolute RESIK spectrum of the 2003 February 22 flare. The most prominent lines are marked. Individual spectral channels are shown in slightly different semi-tones. The thin line at the base of the lines represents the real continuum as calculated based on the temperature and emission measure determined in the isothermal approximation based on channel 1 and channel 4 flux ratio ($T = 8.9$ MK, $EM = 8 \times 10^{48}$ cm^{-3}). The spectrum has been integrated over 584 s, covering the entire flare.

spectrum for this flare integrated over the event duration. The main spectral features characteristic for individual channels are identified. In the first RESIK channel it is K XVIII triplet in the range 3.53 Å–3.58 Å. At the wavelength of 3.73 Å the weak Lyα line of Ar XVIII is seen. In the second channel, prominent line features in the range 3.94 Å–4.05 Å are identified as belonging to the Ar XVII triplet and to $1s^2$–$1s4p$ transition in S XV ion at 4.08 Å . In the third channel a strong line seen at the edge (4.3 Å) corresponds to $1s^2$–$1s3p$ transition in S XV He-like ion. Near the other edge of this channel (at 4.7 Å) the S XVI Lyα line appears. In the fourth channel the S XV triplet lines are seen in the range 5.0 Å–5.12 Å , as do the strong lines of Si XIII ($1s^2$–$1s3p$ and $1s^2$–$1s4p$ transitions at 5.68 Å and 5.4 Å). In addition, one can see in this channel a line corresponding to the transition $1s$-$3p$ (Lyβ) in Si XIV ion at 5.21 Å. In the analyzed spectral region many strong dielectronic lines formed in He-like ions are evident. These lines have not often been discussed in the literature as diagnostics of the solar flare plasma. They include, in particular, the 5.818 Å and 5.565 Å satellite lines of Li-like ion Si XII. For more details about these lines' diagnostic use see Phillips, *et al.* (2006). Having so many lines and the continuum at our disposal, we can select a number of suitable pairs of lines (or bands) fluxes in order to investigate the temperature of the plasma under isothermal approximation. Example results are presented in the left lower panel of figure 2. In this figure, the temperatures (lower left plot) obtained from 3 s *GOES* data are shown also for the comparison (densely packed full points). The top plot with dark grey points presents the temperature changes as determined from the flux ratio of the strongest

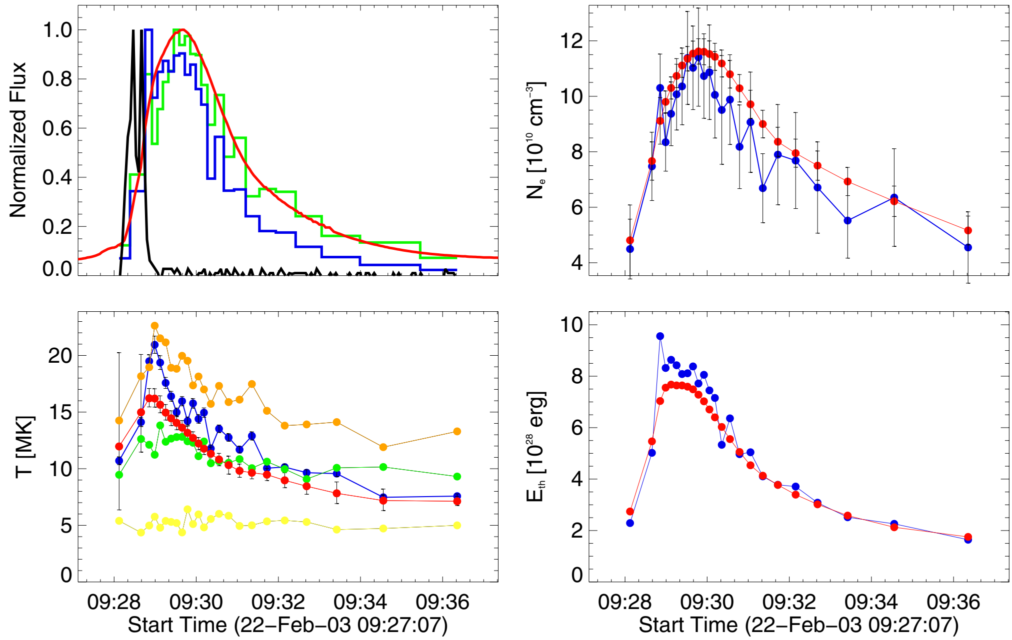

Figure 2. Upper left: The normalized lightcurves for the flare on 2003 February 22. The *GOES* 1 - 8 Å, lightcurve is shown as smooth solid line, the *RHESSI* 25–50 keV as heavy, the RESIK short wavelength (3.35–3.8 Å) and long wavelength ($5.0-6.05$ Å) channels are shown as darker and lighter gray histograms respectively. **Lower left**: The time variability of the temperature as determined in the isothermal approximation based on the flux ratio technique from different pairs of fluxes (see the text). **Upper right**: The corresponding plots of density variations (open and full circles for *GOES* and RESIK respectively) as determined using the estimate of the source extend from *RHESSI* reconstructed image. **Lower right**: Plot of plasma thermal energy content for the analyzed flare obtained from *GOES* (open circles) and RESIK.

S XVI and S XV lines, while the second from bottom plot is the temperature from the flux ratio of the strongest Si XIV and Si XIII lines. The second from the top plot represents temperature as determined from the ratio of wavelength-integrated fluxes measured in the first and fourth RESIK channels. The bottom plot is that of temperatures derived from the flux ratio of dielectronic (Si XII) to parent (Si XIII) lines. This line ratio is a good indicator of the temperature for a cooler plasma component (Phillips, *et al.* (2006)). From the emission measures corresponding to each of the temperature determinations, plasma densities can be derived based on the spatial extent of the source (taken in this case from *RHESSI* images to be FWHM $= 3.8 \times 10^8$ cm). These derived densities are plotted in the right upper panel of the Figure for *GOES* and RESIK. It is seen that the density values obtained are consistent between these two instruments. From this plot, it follows that the flare hot plasma source was rather dense ($\sim 10^{11}$cm^{-3}), especially during the maximum phase.

Based on the temperature, emission measure and the volume of the emitting region one can calculate the thermal energy content (see the lower right panel in figure 2) using the following equation:

$$E_{\rm th} = 3\,k\,V^{1/2}\,T(EM)^{1/2}$$

Using a full set of line fluxes (several) observed instantaneously by RESIK one can calculate momentary distributions of the plasma with temperature (i.e. DEM – differential emission measure distributions) for particular flare phases. In figure 3 the results of

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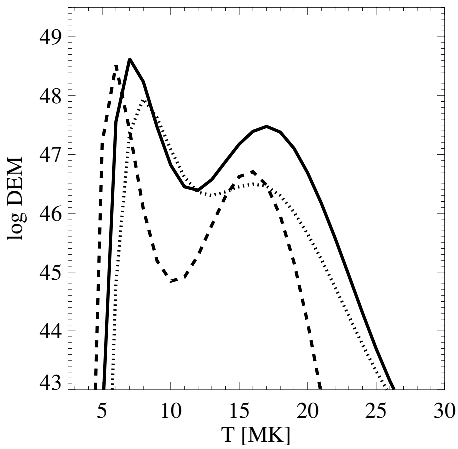

Figure 3. The temperature distribution of the differential emission measure (DEM) for the analyzed flare on 2003 February 22. Dotted, solid and dashed lines correspond to the rise, maximum and the decay phases respectively.

such calculations are presented for the rise, maximum and decay phase of the analyzed flare of 2003 February 22 at 09:39 UT. DEM calculations have been performed using Withbroe-Sylwester maximum likelihood algorithm. It is seen that the flaring plasma is concentrated into two distinguishable temperature components. Notice that the ratios of emission measure in the hotter and cooler components vary markedly depending on the phase of the flare.

3. Concluding remarks

The RESIK spectra are suitable for a number of studies aimed in determination of basic plasma characteristics such as the total energy content variability. Among others, evolution of the flaring plasma temperature, emission measure and density can be made for a number of temperature bands using suitable line pairs. The emission measure values obtained under the isothermal assumption may be compared with the "true" DEM profiles obtained from the analysis of a full set of lines. Use of flare images obtained in similar spectral energy bands (*RHESSI*) leads to estimates of the source volume and thus provides a way to look for the density variability in the hotter multimillion Kelvin flaring plasma. Determinations of these important plasma characteristics will pave the way for detailed studies of flaring plasma composition, especially as concerns its possible FIP and time dependence.

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