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NON-THERMAL DIAGNOSTICS OF FLARE OBSERVED BY RESIK

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Abstract. The Polish soft X-ray spectrometer RESIK operated on Russian Coronas-F spacecraft during the years 2001 - 2003. It has observed several flares of different classes in a wavelength band of 3.35 - 6.05 Å. We have analysed two flares especially in a region of 5.0 - 6.05 Å which is dominated by allowed lines of Si XIII, Si XIV ions, and satellite lines of Si XII (Si XIId). The flare spectra showed unexpectedly high fluxes of Si XIId satellite lines as compared with fluxes of allowed lines of Si XIII ion which we attempted to explain under the assumption of a non-thermal electron distribution. We have investigated the temporal dependence of the deviation of the non-thermal distribution from the Maxwell distribution during flare. The maximal deviation from thermal distribution correlates with times of observed radio bursts.

Key words: flare - soft X-rays - spectra - non-thermal distribution

1. Introduction

The non-thermal electron distributions can occur in a low density and high temperature plasma, e.g. when beams of accelerated electrons appear in plasma and they are immediately neutralized by the so called return current (Knigth and Sturrock, 1977, Brown and Hayward, 1981, van den Oord, 1990). Such conditions can occur during solar flares when electrons are accelerated at the site of reconnection and penetrate the plasma into magnetic loops below it.

Both the electron beam and the return current modify the electron distribution function and thus influence the ionization and excitation equilibrium. The intensities of spectral lines may therefore differ considerably from those formed under the assumption of Maxwellian distribution of particles (Dzifčáková and Karlický, 2008).

In the present investigation, as the non-thermal distribution we consider the so called n-distribution. It describes the bulk of non-thermal plasma electrons and it does not include the effects of the high-energy tail. The same kind of distribution has been used by Seely*et al.* (1987) for the analysis of several flares from the X-ray iron spectra and also by Dzifčáková *et al.* (2008) for the analysis of silicon spectra of the M4.9 flare observed by RESIK. The n-distribution can be expressed as:

$$f_n(\mathcal{E})d\mathcal{E} = \mathcal{B}^n \frac{2}{\sqrt{\pi}} \mathcal{E}^{\frac{n}{2}} (kT)^{-(\frac{n}{2}+1)} \exp(-\mathcal{E}/kT) d\mathcal{E}, \quad (1)$$

where $\mathcal{B}^n = \pi^{1/2}/(2\Gamma(\frac{n}{2}+1))$ is the normalization constant, $\mathcal{E}$ is the energy of free electrons, k is Boltzmann constant and n and T are the free parameters of the distribution. The n-distribution continuously changes from a Maxwellian distribution ($n = 1$) to a non-Maxwellian distribution ($n > 1$). We would like to point out that T is not thermodynamic temperature although it is given in Kelvin. In order to be able to compare the results with a thermal analysis, we have introduced a pseudo-temperature, τ, which relates the mean energy of the non-thermal plasma distribution to the mean energy of the Maxwellian distribution and is given in Kelvin (Dzifčáková, 1998, Dzifčáková & Kulinová, 2001):

$$\tau = \frac{n+2}{3} T. \quad (2)$$

In the previous paper (Dzifčáková *et al.*, 2008), the possibility to determine the non-thermal shape of the plasma bulk distribution, assuming the n-distribution, have been investigated. The M4.9 flare on 2003 January 7/8 has been used for that analysis and the non-thermal plasma parameters have been determined.

In this paper we have analysed C8.1 flare on 2003 January 21 (02:24 - 02:28 - 02:33 UT) observed by RESIK and we have compared the new results with the previous ones.

2. Synthetic Spectra and Data

The changes in ratios of the spectral line intensities allow us to diagnose the shape of electron distribution. The best diagnostic are the ratios of satellite and allowed lines of ions of one element in different ionization stages. The satellite lines sample the electron distribution function at discrete energies while the intensities of the allowed lines depend on the integral of the product of the collisional cross section with electron velocity over the distribution function extending up from the excitation energy treshold. Using the lines of the same element we can avoid the errors introduced by abundances.

The free parameter n of the n-distribudtion allows us to model various degrees of non-thermal effect. We have calculated a grid of synthetic spectra in the range of 5.0 - 6.0 Å for the values of $n = 1, 3, 5, 7, 9, 11$, $log(\tau) = 6.7$ - 7.3 K with step 0.02, FWHM of 20 mÅ, using RESIK abundances (Chifor *et al.*, 2007), and the ionization equilibrium for n-distributions calculated by Dzifčáková (2005). The used electron density and the column emission measure have no effect on the resulting line ratios.

The synthetic spectra were calculated using the 'non-thermal' modification of CHIANTI package software and the extended database (Dzifčáková, 2006). This modification allows the computation of the excitation equilibrium for non-thermal distributions and involves computation of satellite line intensities.

The strongest silicon spectral lines in the range of 5.0 - 6.0 Å are listed in Table I. The diagnostics of the n-distribution based on Si lines uses Si XIV 5.22 Å, Si XIII 5.68 Å, and Si XIId 5.82 Å lines and it has been proposed by Dzifčáková and Kulinová (2006).

The analysed soft X-ray spectra of the C8.1 class flare from January, 21st, 2003 have been obtained by the Polish Bragg spectrometer: REngenovsky Spektrometr s Izgnutymi Kristalami (RESIK: Sylwester *et al.*, 2005) which operated on board the Russian Coronas-F mission. It was a high-resolution crystal spectrometer observing in four spectral channels (3.40 - 3.80 Å, 3.83 - 4.27 Å, 4.35 - 4.86 Å, 5.00 - 6.05 Å) (Fig. 1). RESIK provided the information on soft X-rays between 2 - 4 keV (1st order) with a dispersion of 2.49 - 4.99 mÅ bin^{-1} (Sylwester *et al.*, 2005).

The 69 individual spectral records of the C8.1 class flare have been time weighted and combined into 13 averaged spectra. The first 3 spectra are not presented here. They map the pre-flare situation mainly. RESIK observes the whole Sun and the pre-flare emission comes from the whole solar disk but during the flare the emission in RESIK channels rises more than 10 times. The other 10 spectra represent each minute within 02:25 - 02:34 UT time interval. The lower, continuous part of the spectrum was removed

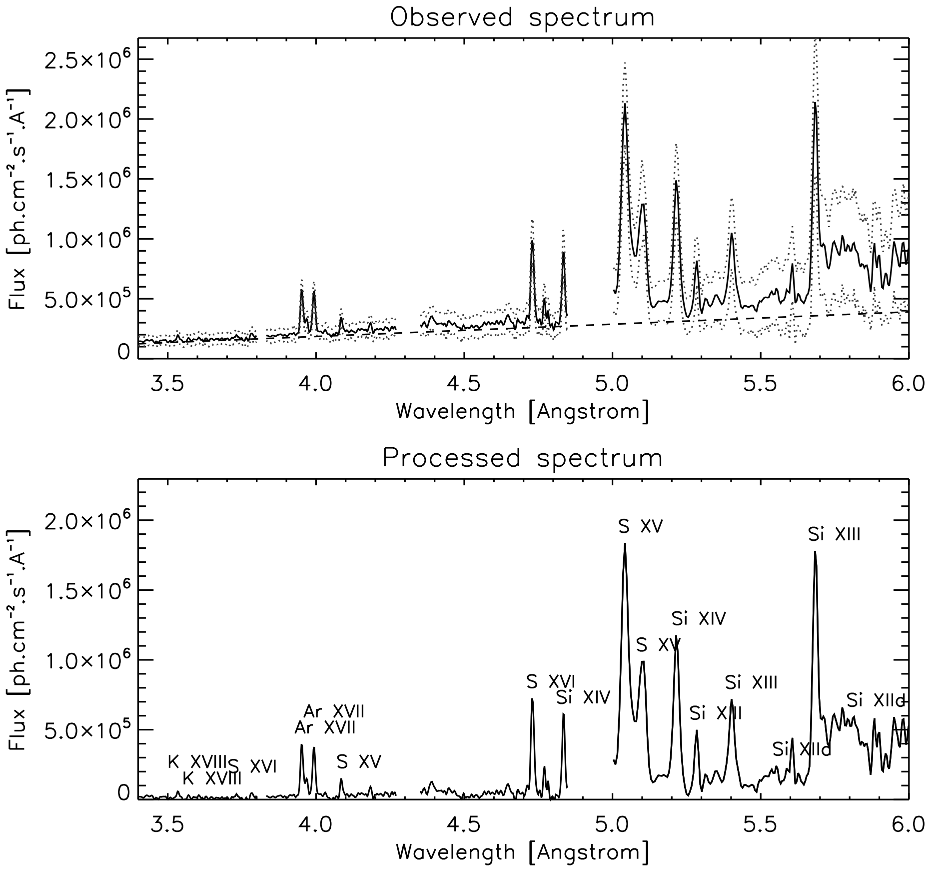

Figure 1: Time weighted RESIK spectrum in all four spectral channels as seen at 02:29 UT. Top: The spectrum with continuum (dashed line) and data errors (thin lines). Bottom: The spectrum as seen after substraction of the continuum. The dominant line in all four channels are labeled.

Table I: The strongest silicon spectral lines observed in fourth RESIK channel. The Si XIId denotes the satellite line excited by dielectronic recombination.

Ion	Wavelength	Transition
Si XIV	5.22	$1s^2\ S_{1/2} - 3p^2\ P_{3/2,1/2}$
Si XIII	5.28	$1s^2\ {}^1S_0 - 1s5p^1\ P_1$
Si XIII	5.40	$1s^2\ {}^1S_0 - 1s4p^1\ P_1$
Si XIII	5.68	$1s^2\ {}^1S_0 - 1s3p^1\ P_1$
Si XIId	5.56	$1s^2 2p\ {}^2P_{1/2,3/2} - 1s2p4p\ {}^2D_{3/2,5/2}$
Si XIId	5.82	$1s^2 2p^2\ P_{1/2,3/2} - 1s2p(3P)\ 3p\ {}^2D_{3/2,5/2}$

from each of the spectrum by subtracting the linear fit through the points where no distinctive lines appeared. The spectral lines were approximated with gaussian profiles and their amplitudes and positions were fitted using *xcfit.pro* routine of SolarSoft package in IDL.

3. Diagnostics

The synthetic line ratios have been compared with the values obtained from X-ray spectra observed by RESIK. The ratios of Si XIV 5.22 Å line to Si XIII 5.68 Å and Si XIII 5.68 Å to Si XIId 5.82 Å have been used for the diagnostics. Figure 2a depicts the diagnostics plot which enables us to estimate the parameter n. The synthetic ratios are plotted as curves and the stars mark the measured ratios. Digits represent number of minutes since 02:25 UT. Figure 2b plot allows us to estimate the $log(\tau)$ value if we assume the values of n from the previous plot. Again the curves represent the theoretical dependence of τ for the different n and blue stars mark the observed values. The time behaviour of parameters n and τ are presented in Figure 3.

The comparison of the observed spectrum at 02:26 UT and 02:34 UT with the synthetic spectrum for the n-distribution and with the synthetic spectrum for the Maxwellian distribution is in the Figure 4 and 5. The observed spectrum in the Figure 4 corresponds to the time of maximum

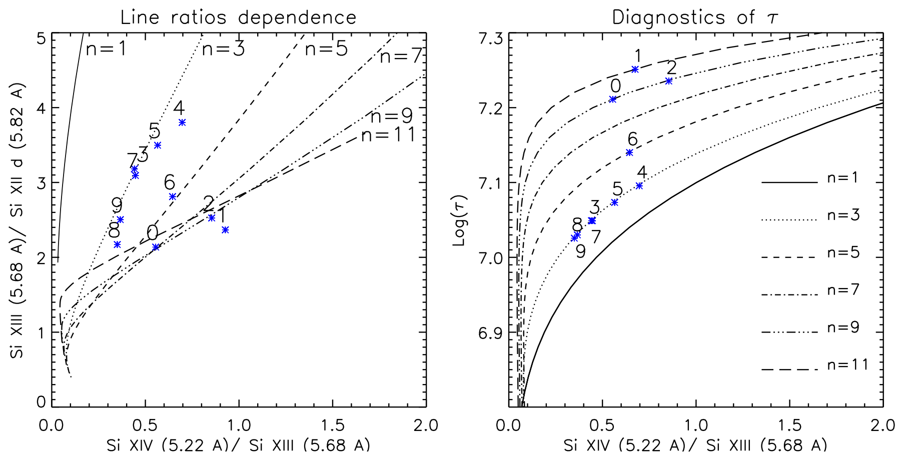

Figure 2: The diagnostics of parameter n (left) and τ (right). Blue stars represent observed line ratios.

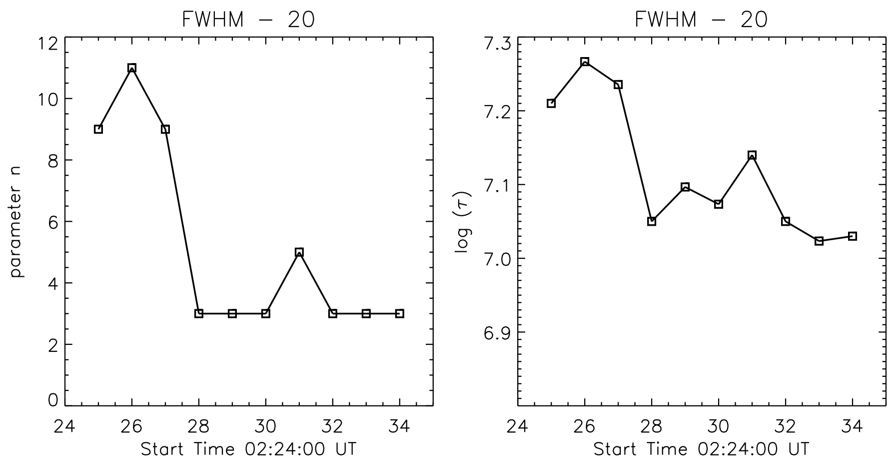

Figure 3: The time behaviour of parameter n (left) and τ (right).

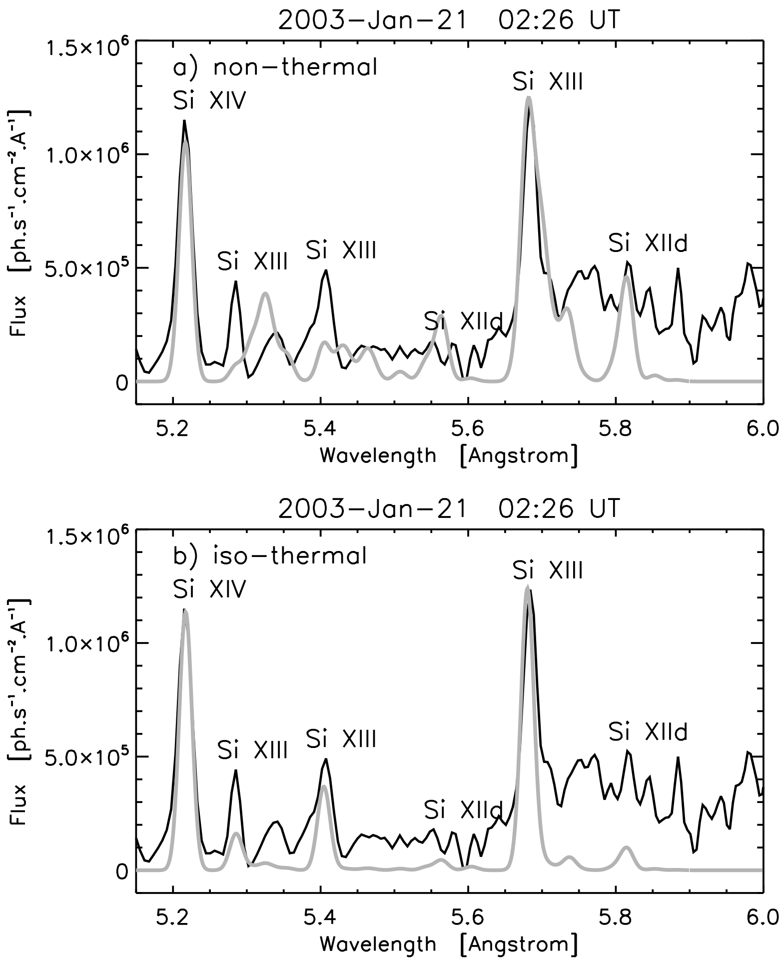

Figure 4: A comparison of the observed spectrum at 02:26 UT with the synthetic spectrum for the n-distribution with $n = 11$ (above) and with the synthetic spectrum for the Maxwellian distribution.

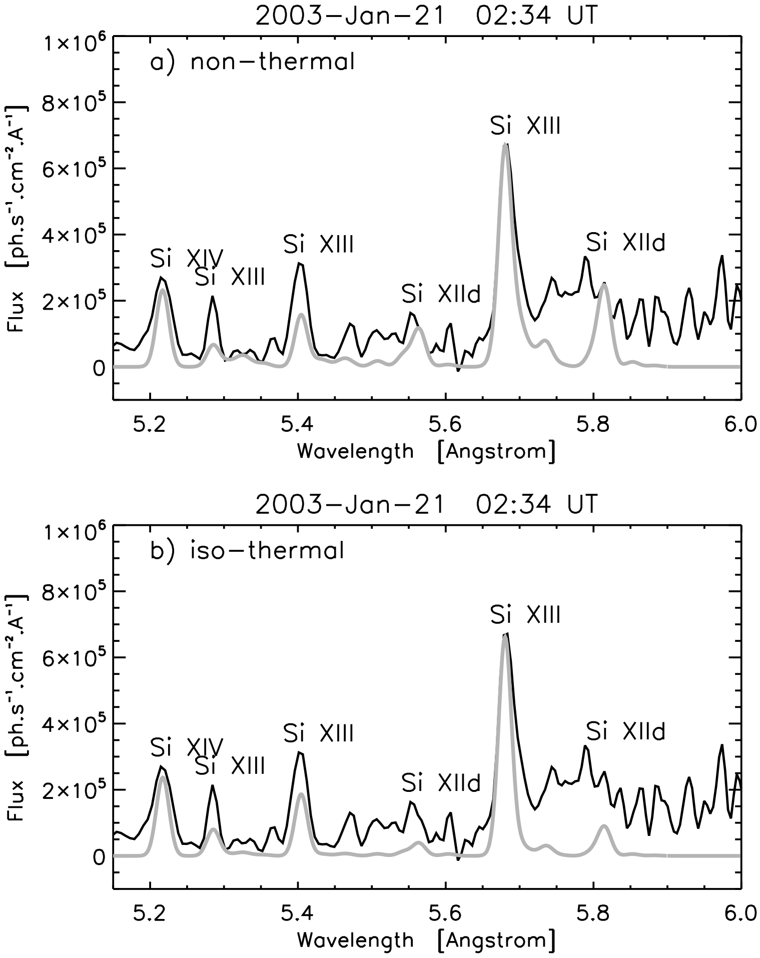

Figure 5: A comparison of the observed spectrum at 02:34 UT with the synthetic spectrum for the n-distribution with $n = 3$ (above) and with the synthetic spectrum for the Maxwellian distribution.

deviation of the distribution from the Maxwellian one and the spectrum in Figure 5 represents the early decay phase of the flare. It is clear that the non-thermal spectra are able to estimate the fluxes in satellite lines much better than Maxwellian spectra but the fluxes in Si XIII 5.28 Å and Si XIII 5.40 Å are underestimated for the non-thermal spectra. The fluxes in these two lines are sensitive to the presence of the high tail in the distribution (Dzifčáková and Karlický, 2008) and the presence of such high energy tail has not been included in our analysis.

4. Results

The plasma starts to be non-thermal since the rise phase up to the maximum of the flares and later becomes Maxwellian. Figure 3 shows that the maximum deviation ($n = 11$) of diagnosed distribution from the Maxwellian one appeared 2 minutes before the maximum of the flare. It is different from the results for the previously analysed M4.9, Jan 7, 2003 flare where the maximum deviation from the Maxwellian distribution occurred about the flare maximum. In both cases the non-thermality correlates well with radio emission (Figure 6) or RHESSI 25 - 50 keV non-thermal emission for M4.9 flare. In the case of C8.1 flare the type III radio bursts were observed at 02:25 - 02:29 UT.

For the decay phase spectra - better said post maximum spectra - the points of measured ratios in the Figure 2a are distributed about the $n = 3$ curve what still predicts departure from Maxwellian distribution. The timing of the last analysed spectrum for C8.1 flare is about 6 minutes after the maximum of the flare. Moreover, in the GOES measurements (1 - 8 Å), the enhanced soft X-ray emission has been observed after the maximum. The spectra from late decay phase of this flare were not obtained. On the contrary, for the previously analyzed M4.9 flare we missed the spectra from early post maximum flare. The spectra which corresponded to Maxwellian distribution ($n = 1$) for M4.9 flare were observed more than 30 minutes after the maximum.

5. Summary

We can conclude that it is possible to probe the non-thermality of the free electron distribution of plasma bulk in flaring plasma.

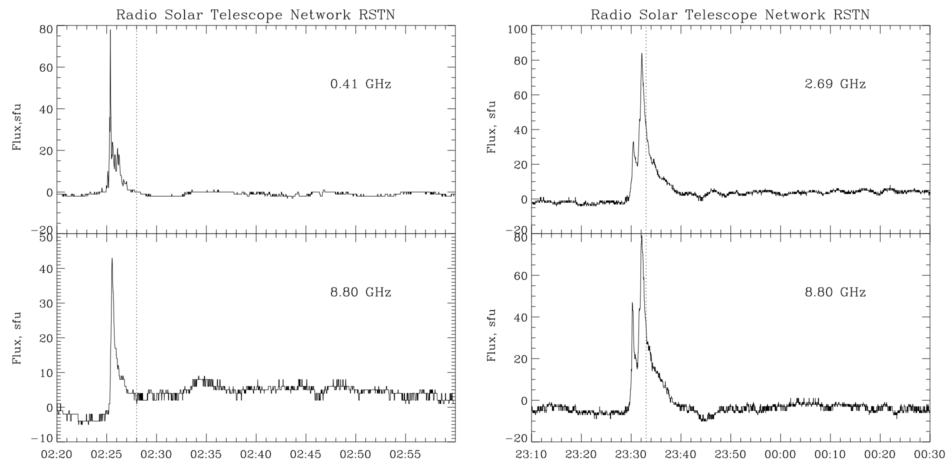

Figure 6: Radio emission of C8.1 (left) and M4.9 flare (right). Thin vertical lines mark the positions of the maximum of the flare by GOES.

The plasma starts to be non-thermal during the rise phase up to the maximum of the flares and then thermalizes. In both analysed flares (present and previous), the maximum of the non-thermality correlates well with radio emission, so it is connected with acceleration of the particles.

The synthetic spectra modelled under the assumption of n-distribution with diagnosed parameters n and $log(\tau)$ rather satisfactorily mimic the observed ones. However, they failed to model higher fluxes of Si XIII lines $1s^2\,{}^1S_0 - 1s\,np\,{}^{1,3}P_1$, where $n \geq 4$. We suppose that this can be due to presence of high energy tail of electron distribution affected by electron beams.

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