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Observations of $1s^2$–1s np and 1s–np lines in RESIK soft X-ray spectra

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Abstract

RESIK is the X-ray bent crystal spectrometer on the *CORONAS-F* satellite. Between 2002 and 2003, RESIK collected numerous spectra of active regions and flares in the wavelength range from 3.37 to 6.09 Å. This range includes many strong emission lines due to transitions $1s^2$–1s np and 1s–np, in He-like and H-like ions, respectively; the $n = 2$ and 3 lines are routinely observed for Si, S and Ar ions. For some flares RESIK has observed enhanced emission in spectral features coinciding with lines due to transitions for n up to 9 or 10. Identifications of these features, not previously observed in astrophysical spectra, are presented in this paper. Their observed intensities are compared with those from theory.

Keywords: Sun; X-ray; Spectra; High-n transitions

1. Introduction

The RESIK (in Russian – REntgenovsky Spektrometers Izognutymi Kristalami) spectrometer (Sylwester et al., 2005) aboard the *CORONAS-F* solar observatory collected spectra during hundreds of solar flares in the highly interesting spectral range 3.37–6.09 Å. In this wavelength range the high n Rydberg series for Al XIII, Si XIV, Si XIII, S XVI and S XV are observed (Sylwester et al., 2004). In this paper observed line intensities are compared with theory. In previous observations, the emission line ratio of the higher-n soft X-ray transitions of the type $1s^2$–1s np, have been reported by Keenan et al. (1985, 1986, 1987) for $n = 2, 3$ in O VII, Ne IX and Mg XI ions. The results of their observations are in good general agreement with the theory. Keenan et al. (1990) compared observed Si XIII emission lines ratios [$1s^2$–1s np]/[$1s^2$–1s 2p] ($n = 3$–5) recorded by flat crystal spectrometer (FCS) aboard *Solar Maximum Mission* and obtained substantial discrepancy between the observed (too low) and calculated line intensity ratios only in case of $n = 4$ line for Si XIII. They ascribe this discrepancy to problems with the calibration of FCS Channel 4 sensitivity.

Generally, in previous observations, including the early data from *OV 1–17* (Walker et al., 1974) and *OSO-8* (Parkinson et al., 1978), the line intensity ratios corresponding to $1s^2$–1s np transitions appear in agreement with predictions of the theory, even in a simple isothermal approach.

In this work, we investigate the relative line intensity ratios again using data collected by RESIK. We use spectra obtained for 14 selected flares, where the higher-n lines are particularly well seen. For the theory, we calculate the

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respective emission functions from the work of Mewe and Gronenschild (1981) and Mewe et al. (1985).

2. The observed spectra

For the study of relative line intensities within particular resonance series – so-called "line decrements", we use the RESIK spectra collected during 14 flares (eight of them of *GOES* C class, six of *GOES* M class). All these spectra have been measured between 2003 January 1 and 2003 March 14. In this period, all important RESIK instrument settings (i.e., the high voltage and the energy discrimination thresholds) were set to optimum values. The relative accuracy of RESIK wavelength sensitivity calibration is expected to be better than 10% over this time. Our event selection criterion was that the higher-n transitions should be discernible by eye in respective spectral plots. The overall 14-event average spectra in individual RESIK channels with descriptions of important lines and marked positions of respective ionisation limits of important line series are shown in Fig. 1. In Channel 1, the K XVIII triplet, lines from Ar XVII, Ar XVIII and the lines of H-like ion S XVI corresponding to transition from $n \geqslant 4$ are observed. In Channel 2, one can see the Ar XVII triplet and lines of S XV He-like ions (from $n \geqslant 4$). In Channel 3, the lines of sulphur are prominent: S XVI 1s–2p (Lyα), S XV 1s^2–1s 3p and the lines of H-like Si XIV ion corresponding to transitions from $n \geqslant 5$ are noticeable. In Channel 4, the S XV triplet and the lines of H-like ions (Si XIV and Al XIII) corresponding to the transitions from $n \geqslant 3$ are seen. In Table 1, we present the theoretical wavelengths for the corresponding transitions expected to be present within the spectral range covered by RESIK.

The wavelengths for Ar XVIII were taken from Rice et al. (1999), while for the remaining elements we used atomic data from Verner's tabulations (Verner et al.,

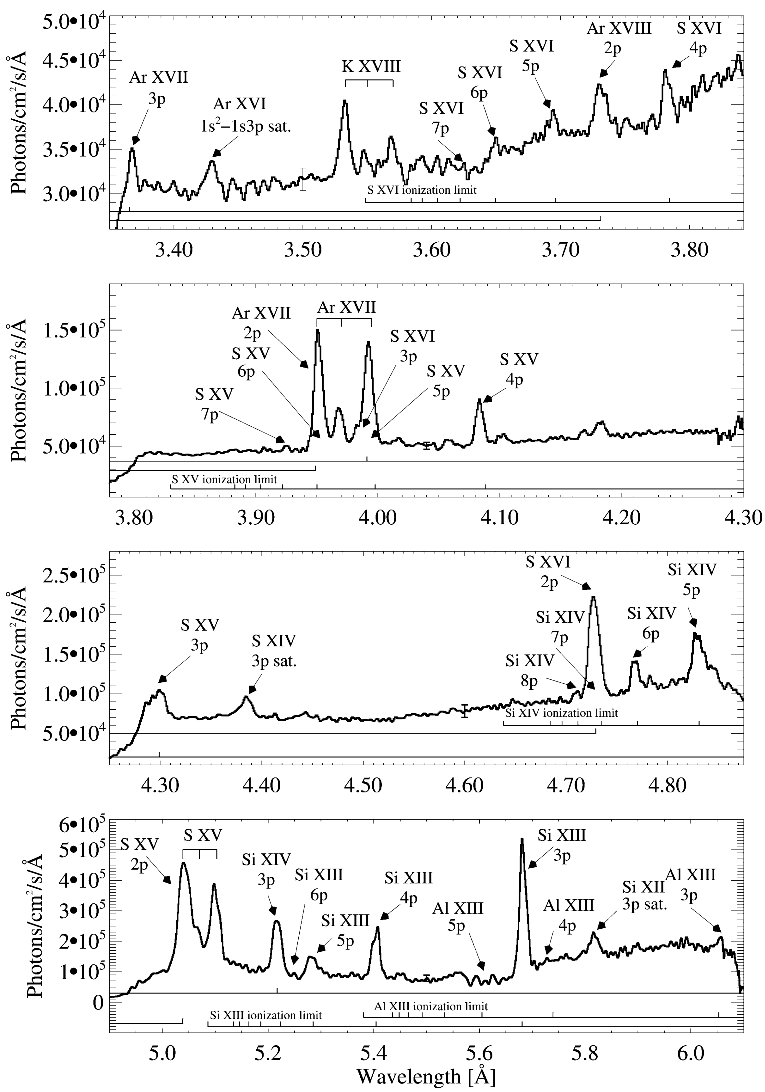

Fig. 1. Average spectra observed by RESIK for 14 flares (the total integration time amounts approximately to 9 h). In each panel, the formal, example uncertainty is presented, corresponding to r.m.s. error of the average for a given spectral bin.

Table 1
Theoretical wavelengths (Å) for indicated transitions

Transition	H-like ions			Transition	He-like ions		
1s–np	Al XIII	Si XIV	S XVI	$1s^2$–1s np	Si XIII	S XV	Ar XVII
2p	7.1727	6.1822	4.7292	2p	6.6480	5.0387	3.9488
3p	6.0529	5.2172	3.9912	3p	5.6807	4.2991	3.3654
4p	5.7393	4.9469	3.7845	4p	5.4046	4.0885	3.1996
5p	5.6049	4.8311	3.6959	5p	5.2856	3.9978	3.1281
6p	5.5345	4.7704	3.6496	6p	5.2231	3.9501	3.0950
7p	5.4929	4.7346	3.6221	7p	5.1861	3.9219	3.0686
8p	5.4662	4.7116	3.6045	8p	5.1623	3.9039	3.0544
9p	5.4481	4.6960	3.5926	9p	5.1462	3.8916	3.0447
10p	5.4352	4.6849	3.5841	10p	5.1347	3.8828	3.0378

1996). The wavelengths corresponding to ionisation limits for Al XIII, Si XIV, Si XIII, S XVI, S XV and Ar XVII ions we took (Allen, 1973) to be 5.3811, 4.6382, 5.0862, 3.5484, 3.8302 and 3.0088 Å, respectively.

3. Line radiation processes

We calculated the temperature dependence of line intensities from formulas given by Mewe et al. (1985), by taking the necessary values of the absorption oscillator strength from Mewe and Schrijver (1977). For the calculations of emission functions we have used the ionisation balance computations by Mazzotta et al. (1998). We took line wavelengths from Verner et al. (1996) and for Ar XVII from Rice et al. (1999). In Fig. 2, we present our calculations of the emission functions. The emission functions represent the temperature variations of the photon flux (i.e., power in line) emitted from a plasma with a unit element abundance and emission

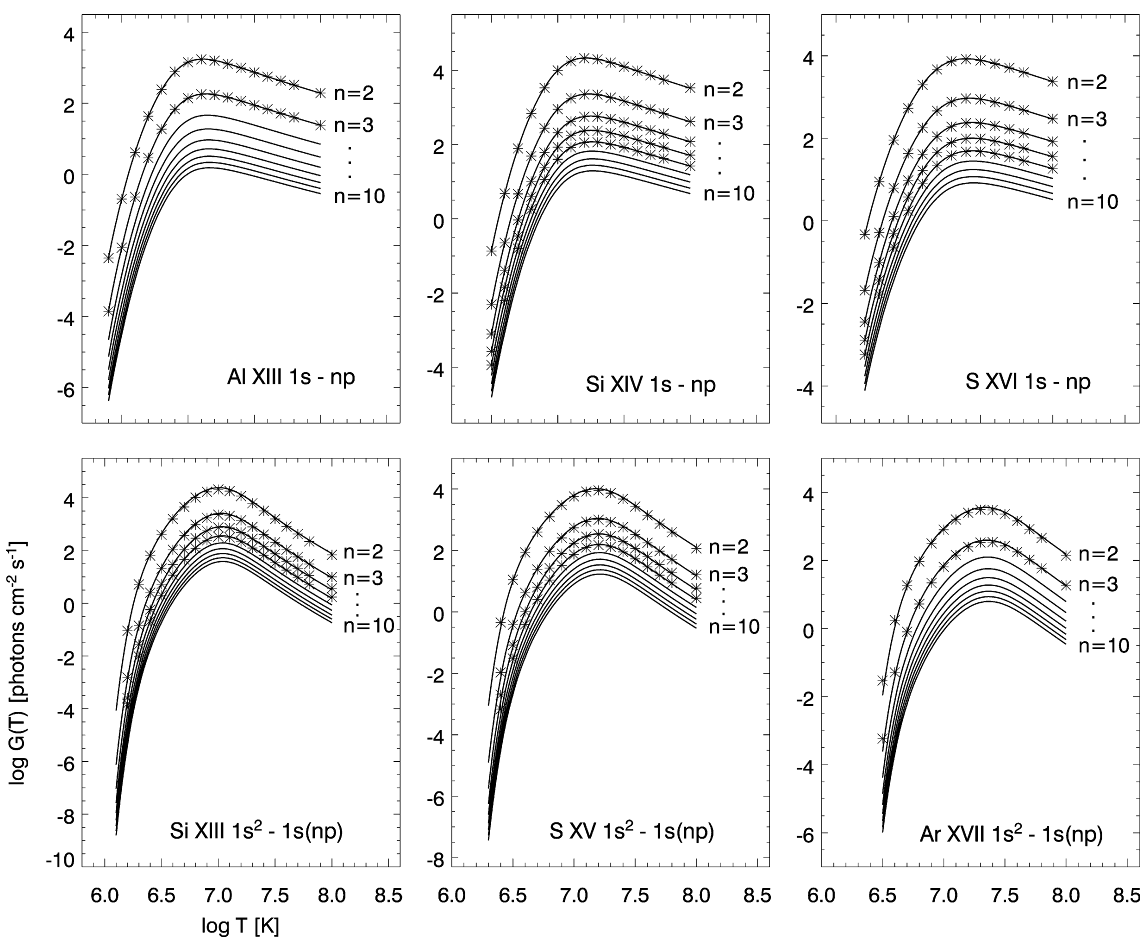

Fig. 2. The calculated emission functions for H-like and He-like ions. Lines represent temperature dependence calculated using Mewe theory and ionisation equilibrium according to Mazzotta et al. (1998), while stars are the actual tabulated values given by Mewe and Gronenschild (1981) and Mewe et al. (1985).

measure $\mathrm{EM} = 10^{48}\ \mathrm{cm}^{-3}$. Asterisks in the plots represent the values tabulated by Mewe et al. (1985) while underlying lines correspond to our results.

4. Comparison of observed and theoretical decrements

From the set of 14 flares selected for analysis, 10 have been measured during the fast rise part of the soft X-ray light curve. The average spectrum obtained for these events we call *impulsive* phase (IP). For the remaining four flares, the spectra observed by RESIK have been recorded during flare decay phases and their average represents the *decay* phase (DP). In order to compare the observed line intensity ratios with those predicted by the theory, we scaled the measured line intensities to the strength of these members of the line series which *always* stand out the most clearly in the observed spectra. These *reference* line transitions are given in Table 2 in the denominators of respective headers. For H-like ions and for He-like ions the reference transitions are: 1s–3p, 1s–4p and $1s^2$–1s 3p, respectively. The observed values of intensity ratios represent those obtained with the contribution of the continuum emission removed. In the column "IP" and "DP" we present values obtained from the average impulsive and decay phases, respectively. In the column "Theory" we present values of the corresponding ratios calculated for the indicated set of temperatures, i.e., $T = 5$, 10, 15 and 25 MK.

We found a large discrepancy between the observed and theoretical ratios for spectra collected during the *impulsive* phase. The observed values are definitely out of the range expected for thermal equilibrium plasma. The observed discrepancies are generally larger for lines of H-like series than those for lines of He-like series. This effect may be linked to differences in the respective line excitation threshold energies. Thermal excitation (isothermal or multi-temperature) models fail to explain such a large observed inconsistency present during the flare impulsive phase, even by assuming unrealistically high values of the plasma temperature.

By contrast, the values of ratios observed during the decay phase of flares appear to be in agreement with multi-thermal interpretation as has been observed in the previous experiments (characterized by a long spectra integration times). In order to check for the accuracy of the thermal excitation model used, we cross-checked the ratios calculated using Mewe approximations with these obtained from the CHIANTI atomic code (Young et al., 2003). For lines where this comparison was possible (CHIANTI includes line intensities for transitions up to $n = 5$), we found the agreement to be within 5%.

Table 2
Comparison of observed and calculated intensity ratios

Line		Observed		Theory			
		IP	DP	$T = 5$ MK	$T = 10$ MK	$T = 15$ MK	$T = 25$ MK
H-like ions							
				Intensity ratio [1s–*n*p]/[1s–3p]			
Al XIII	4p	0.460	–	0.206	0.240	0.254	0.268
	5p	0.069	–	0.078	0.097	0.105	0.112
Si XIV	4p	–	–	0.197	0.234	0.249	0.264
	5p	0.166	0.110	0.074	0.093	0.102	0.110
	6p	0.083	0.058	0.034	0.045	0.050	0.055
	7p	–	–	0.018	0.025	0.028	0.031
	8p	0.048	0.015	0.011	0.015	0.017	0.019
	9p	0.041	0.009	0.007	0.010	0.012	0.013
	10p	0.038	0.006	0.005	0.007	0.008	0.009
				Intensity ratio [1s–*n*p]/[1s–4p]			
S XVI	2p	8.333	42	127.8	56.4	43.7	35.4
	5p	0.611	0.400	0.353	0.391	0.403	0.414
He-like ions							
				Intensity ratio [$1s^2$–1s *n*p]/[$1s^2$–1s 3p]			
Si XIII	4p	0.448	0.280	0.272	0.308	0.322	0.333
	5p	0.205	0.131	0.115	0.138	0.147	0.154
	6p	0.089	0.071	0.060	0.074	0.080	0.085
S XV	2p	11.57	10.5	16.3	10.6	9.3	8.553
	4p	0.912	0.270	0.250	0.296	0.314	0.328
	5p	–	–	0.101	0.130	0.141	0.151
	6p	–	–	0.052	0.069	0.076	0.083
	7p	0.417	0.045	0.030	0.042	0.046	0.051
	8p	0.167	0.028	0.019	0.027	0.030	0.033
	9p	0.142	0.020	0.013	0.019	0.021	0.023
Ar XVII	2p	12.0	9.6	21.5	12.0	10.1	9.01

Therefore, for the decay phase, the actual value of the temperature corresponding to a given observed line ratio may be found somewhat different depending on the atomic approximation used and may substantially differ from one ratio to the other. This can be explained by the presence of a *non-isothermal* plasma, i.e., one with a differential emission measure distribution.

After eliminating possible known instrumental factors, and taking into account a good agreement of the observed and thermally predicted intensity ratios during flare decay phases, we suggest that the unusual values of the investigated ratios observed during the impulsive flare phases may be due to the line excitation by non-thermal (non-Maxwellian) populations of the electrons possibly present during this phase of flare. We will continue the analysis of RESIK spectra having in mind this possible excitation model.

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