RESIK OBSERVATIONS OF HIGHLY IONIZED ARGON AND POTASSIUM X-RAY EMISSION LINES IN SOLAR FLARES

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ABSTRACT

The first detailed solar X-ray spectra obtained by the RESIK bent crystal spectrometer aboard the *CORONAS-F* observatory are presented and instrument performance discussed. RESIK is a bent crystal spectrometer covering four soft X-ray spectral ranges (3.369–3.879 Å, 3.821–4.326 Å, 4.307–4.890 Å, 4.960–6.086 Å), some of which have not been well covered by previous instruments. RESIK forms spectra in each of these ranges in 250 bins simultaneously in intervals of 10 s or so. Many flares, including several of *GOES* X-class, and bright active regions have now been observed in detail. (See http://www.cbk.pan.wroc.pl/2002.htm for examples.) In this paper, observations of spectral lines due to K XVIII, Ar XVIII, Ar XVII, S XV, Si XIV and Si XIII ions will be shown and the time evolution of their intensities will be discussed. These observations will eventually allow for precise determination of differential emission measure (DEM) and chemical composition of the hot flare plasma, and should, alongside data from the *RHESSI*, *TRACE*, and *SOHO* spacecraft, enable new and detailed insight into solar flare mechanisms.

Key words: solar physics; flares; X-ray spectroscopy.

1. INTRODUCTION

Observations of soft X-ray line spectra by high-resolution spectrometers in the past, such as SOLFLEX on the *P-78* satellite (Doschek et al., 1979), the Bent Crystal Spectrometer on *Solar Maximum Mission* (Culhane et al., 1981), the spectrometer on *Hinotori* (Tanaka et al., 1983), and the Bragg Crystal Spectrometer on the Yohkoh satellite (Culhane et al., 1991), have given important insights into the nature of the hot plasmas which are formed at the onset of solar flares. Temperatures, emission measures or differential emission measures, turbulent velocities, plasma motions, and chemical composition have all been derived from particular observations made by these instruments. The highest-temperature ion observed in detail so far is H-like Fe, but many more observations have been made of He-like Fe (Fe XXV), Ca (Ca XIX), and S (S XV). In the case of the He-like ions, the observed line emission is due to $1s^2 - 1s2l$ $(l = s, p)$ transitions and consists of the resonance line; w: notation of (Gabriel, 1972) and on its long-wavelength side intercombination (x, y) and forbidden (z) lines, as well as dielectronic satellite lines due to the Li-like stage, the intensities of which give information about temperature, ionization conditions etc. Other elements have large abundances in the solar corona and are therefore suitable for similar analysis.

Table 1. RESIK characteristcs.

Chan.	#1	#2	#3	#4
Spectr.	A	B	A	B
Crystal plane	Si 111	Si 111	Qu $10\bar{1}0$	Qu $10\bar{1}0$
λ (Å) range	3.369 3.879	3.821 4.326	4.307 4.890	4.960 6.086
X-ray lines & trans.	K XVIII $1s^2$- 1s2p	Ar XVII $1s^2$- 1s2p	S XVI 1s-2p	S XV $1s^2$- 1s2p

The RESIK (REntgenowsky Spektrometr s Izognutymi Kristalami) spectrometer on the *CORONAS-F* mission which was launched in July 2001 has been routinely observing line emission due to He-like Ar (Ar XVII) and K (K XVIII) as well as other ions such as S XV. The elements Ar and K are of interest because they have widely differing first ionization potentials (FIPs); it has been suggested that the ratio of coronal to photospheric abundances for each element depends on the value of the element's FIP. Observations have also been made of the Lyman-α lines

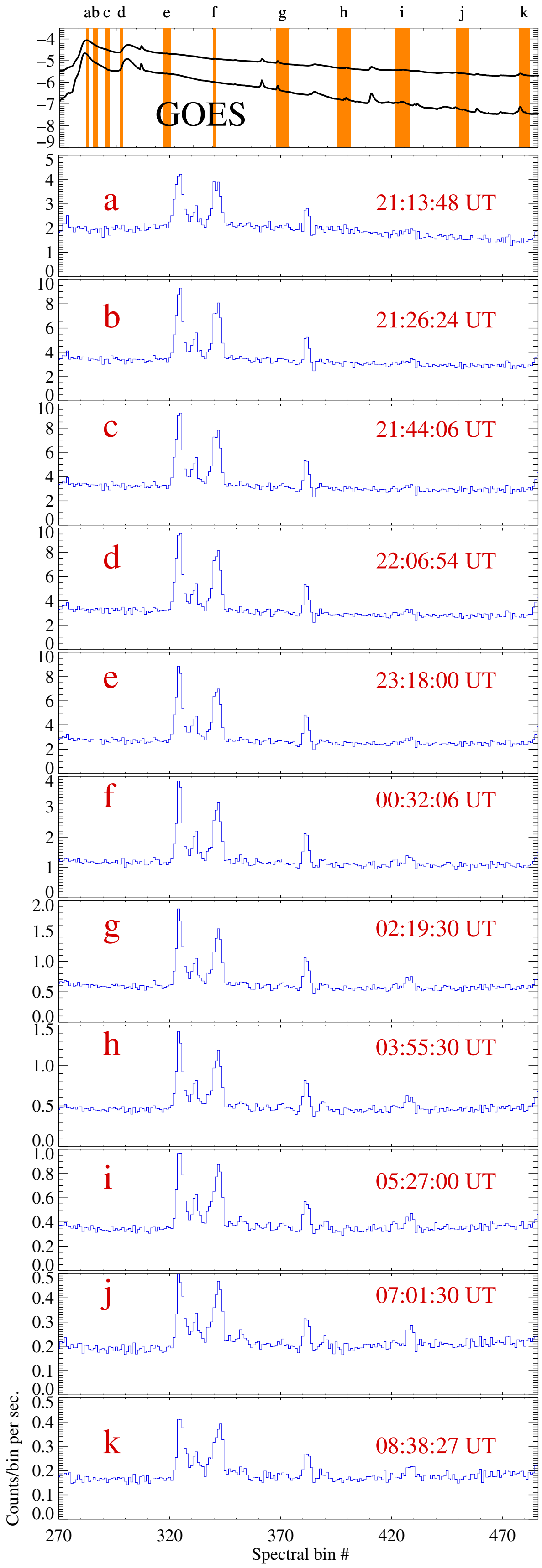

Figure 1. Spectra in the Ar XVII RESIK channel #2 obtained for the 26/27 July 2002 M8.7/M4.6 flares. Spectral bin No. are used on the horizontal axis.

of H-like S (S XVI) and Ar (Ar XVIII) and higher-n members of the $1s^2 - 1snp$ ($n = 3, 4$) sequence in He-like Si and S. In this paper reporting preliminary data analysis, we discuss a selection of some of the extensive observations made by RESIK during flares in the past year and their interpretaion.

2. THE RESIK INSTRUMENT

The RESIK instrument consists of two spectrometers (A and B) each having a single proportional counter which detects spectra Bragg-diffracted by two crystals. The crystals are slightly bent concave so that the Bragg diffraction condition

$$k\lambda = 2d\sin\theta$$

(θ = Bragg angle, k diffraction order, d = crystal lattice spacing) is slightly different for each part of the crystal. The design is along the lines of the Bragg Crystal Spectrometer (BCS) on the *Yohkoh* spacecraft which until loss of operations in December 2001 had operated successfully since launch in August 1991. Table 1 gives brief details of the instrument. There is no collimator (as with the *Yohkoh* BCS but unlike the Bragg Crystal Spectrometer on *SMM*) in order to maximize instrument sensitivity. The crystal material is either Si (111 plane) or quartz ($10\bar{1}0$ plane). The nominal wavelengths listed in Table 1 are for a source along the instrument's optical axis and first diffraction order These ranges are slightly different for flares located elsewhere. For each of the four channels, second-order or third-order diffraction or both are possible, allowing other wavelength ranges to be accessible to RESIK. This can be achieved by changing the pulse height discriminator levels for the position-sensitive proportional counter detectors which are used in RESIK. These detectors have a 'wedge-and-wedge' design identical to those on the *Yohkoh* BCS; reconstruction of the spectra in each range, which are formed simultaneously in data-gathering intervals which are typically 10 s, is made electronically in the instrument before the data are downloaded. A time resolution of 10 s ensures that spectra from the most rapidly developing flares can be observed if the photon count statistics permit. Solar X-rays are liable to fluoresce the crystal material thus forming a background to the observed spectra; in the case of RESIK, the discriminators are set such that the fluoresced photons are rejected and so a continuous background usually observed in all four RESIK channel spectra should be true X-ray continuum and not instrumentally formed.

RESIK is one of several instruments aboard the *CORONAS-F* spacecraft which was constructed by the Izmiran Institute in Russia; the spacecraft was launched from Plesetsk, Ukraine, on July 31, 2001. The spacecraft orbit is circular with height 500 km, and in a polar orbit which is sun-synchronous so that for 20 days at a time the spacecraft is in continuous sunlight. Data from the spacecraft are downloaded from tracking stations in Troitsk (Russia) and Neusterlitz (Germany). The spacecraft is pointed to within 10 arcmin of Sun centre, with a roll stability of 3 arcsec/s. RESIK is co-aligned with the spacecraft Sun-pointing axis. As it has no collimator, flares occurring anywhere on the sun will give rise to line emission on the detectors. The dispersion axis of the RESIK crystals varies according to the roll angle for any occasion. Possible confusion results in the observed spectra if there are two or more flares or bright active regions on the Sun, though in practice this has been found to occur hardly at all in the past year of operations. Roll angle information is provided to the Space Research Center in Wrocław (where most of the analysis has taken place) by the Izmiran spacecraft operations staff with the RESIK data downloads.

The spacecraft is unable to take solar data when there are high particle background rates such as when passing through the South Atlantic Anomaly. In addition, since the spacecraft orbit is polar, there are short time intervals in each orbit when the spacecraft encounters particle radiation in the auroral oval regions near each pole.

For exceptionally large flares, the RESIK detectors became saturated for short periods near flare maxima, but for the most part spectra were successfully observed for all phases of flares with *GOES* class greater than about C1.

3. HELIUM-LIKE ARGON LINE SPECTRA

Line emission due to He-like Ar (Ar XVII) appears in RESIK channel 2 as a 'triplet' of line features, with resonance line at 3.949 Å, intercombination lines (x, y, blended in RESIK spectra) at 3.967 Å, and forbidden line (z) at 3.994 Å (around bins No. 330 - 340). Numerous dielectronic satellites due to Li-like Ar occur in the vicinity of these lines. Most are weak and not distinguishable in RESIK spectra, though a relatively intense one (k) is visible on the short-wavelength side of the z line. A satellite of comparable intensity (j) is blended with the z line. Data from RESIK show that the Ar XVII lines are observable down to flares as small as *GOES* class C1. A *GOES* near X-class flare on 2002 July 26 with maximum near 2100 UT with a second maximum shortly after, followed by a very slow decay, has a particularly fine set of observations of the Ar XVII lines for several hours, until at least 0900 UT on July 27. Nearby S XV $1s^2 - 1s3p$, $1s4p$ lines are also present over this time as well as an unidentified line at ~ 4.19 Å (bin No. 430). Fig. 1 shows a selection of RESIK channel 2 spectra at various times starting near the flare peak. *GOES* light curves are also shown, with times of spectra indicated. As the flare decays the blend of the Ar XVII z line and satellite j steadily becomes more intense with respect to the Ar XVII w line, and the satellite k clearly becomes more intense at later times. Since the intensity ratio of the satellite lines to the w line varies as T_e^{-1} this behaviour indicates a cooling plasma which is shown by the decreasing *GOES* intensities. There is also a change with time in the continuum slope, which probably also indicates a change in the plasma emitting temperature. Finally the unidentified line at ~ 4.19 Å appears to show an increase of relative intensity with time, giving possible clues as to the emitting line.

Eventually we hope to instal software that will routinely calculate electron temperatures from observed RESIK spectra in much the same way as they are derived from the He-like S, Ca, and Fe line spectra observed by the BCS on *Yohkoh* using IDL SolarSoftWare procedures. Observations of the Ar XVII lines by a spectrometer on *SMM* have been analyzed by (Phillips et al., 1993); data from this work will be used in this software. Hence in time a good temperature indicator for the flare plasma will be available which should be of use when comparing with other spacecraft operating at present observing flares such as *RHESSI* and *TRACE*.

4. POTASSIUM LINE SPECTRA

Channel 1 of RESIK in first order covers the He-like K (K XVIII) ion triplet which has wavelengths 3.531 (w), 3.545, 3.549 (x, y), and 3.570 (z). There do not appear to be any solar flare observations of these lines from previous instruments, though Feldman et al., (1974) have observed these lines from laboratory laser-produced plasmas. The RESIK observations which have been made of these lines are therefore unique. Potassium is an odd-Z element which has low solar abundance and so the X-ray emission from its He-like stage in solar flares is expected to be very weak, but is of great interest in the continuing debate on whether coronal element abundances depart from photospheric element abundances by factors that depend on element first ionization potential. Potassium's FIP of 4.34 eV is the lowest of any element lighter than Fe (the highest-Z element from which X-ray flare spectra are commonly observed). Observations of its line intensity during flares thus have much significance. They are of particular interest when compared with Ar XVII line emission which is observed by RESIK as Ar has a relatively large (15.76 eV) FIP. As K is intermediate between Ar and Ca in Z, the temperature of the peak emissivity of the K XVIII w line is expected to be about 3×10^7K though with significant emission at temperatures down to about 10^7K (Mewe et al., 1985). Such temperatures are attained at the maxima of flares having *GOES* class C5 at least, many of which have already been observed by RESIK.

Fig. 2 shows a spectrum from channels #1 to #4 integrated over 3 minutes from an X1.5 flare observed on 2002 April 21 (*GOES* flare maximum at 01:51 UT). The K XVIII w, $x + y$, and z lines in RESIK channel 1 are all distinguishable in this spectrum. Their intensities relative to one another are comparable in intensity to those from Ca XIX spectra observed by the *Yohkoh* BCS for flares of similar intensity. Though not visible in this spectrum, the Lyman-α line (an unresolved doublet) due to H-like Ar XVIII occurs near by (3.734 Å). As these lines have emissivities which are not too different, it is hoped that flare spectra will eventually be used to examine the time variation during flares of the element abundance ratio K/Ar which should be very useful in the FIP problem investigations.

5. OTHER LINE EMISSION

Several other line features are observed for many flares by RESIK and are being analyzed at present.

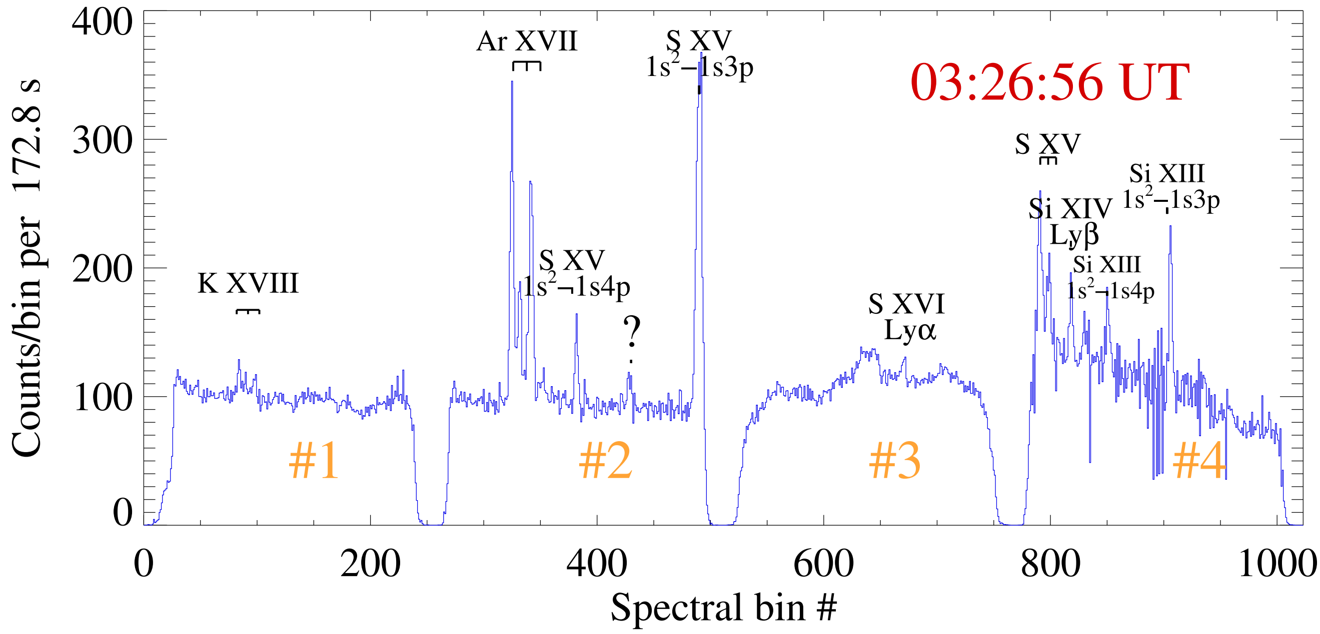

Figure 2. Spectra in the four RESIK channels obtained near the peak of the X1.5 - class flare on April 21, 2002. The four bin ranges #1, #2, #3 and #4 correspond to 3.37 - 3.88 Å, 3.82 - 4.33 Å, 4.31 - 4.89 Å and 4.96 - 6.09 Å wavelenght bands respectively.

Among them are the He-like S XV, lines at ~ 5.05 Å. These are observed near the lower end of RESIK's channel 4 wavelength range as in Fig. 2 though for sources significantly off-axis the emission is clear of the range limit. As some of the earlier RESIK observations were made when the *Yohkoh* BCS was still operating, in 2001, there are likely to be simultaneous observations of these lines and so there is a possibility of a cross-calibration. In this same RESIK channel there are lines due to $1s^2 - 1s3p$, $1s^2 - 1s4p$ transitions of He-like Si XIII, marked in Fig. 2. It should be possible to find temperature information about their relative intensities for flares which have sufficiently high temperatures. RESIK channel 3 includes the Ly-α line of H-like S XVI (4.730 Å). It is normally weak (as in Fig. 2) but observable for flares above *GOES* class M1. Line emission due to S XV transitions $1s^2 - 1s3p$ (4.299 Å), $1s^2 - 1s4p$ (4.088 Å), and $1s^2 - 1s5p$ (3.998 Å), is evident in Fig. 2 on the long-wavelength side of the Ar XVII triplet at 3.94 Å. Again, this offers the possibility of temperature determination as these transitions have different excitation energies. As indicated earlier, the background emission in Fig. 2 should be true solar continuum without any instrumental contribution; line-to-continuum emission ratios should therefore be measurable during flares and so give information on the possibility of time-varying coronal element abundances.

Several line features have been observed during flares with RESIK in a mode that detects second-order and third-order diffraction spectra. A number of such scans were taken between 2002 May 24 and June 6.

6. SUMMARY

Observations of many solar flares since July 31, 2001 by the RESIK instrument on *CORONAS-F* show that the instrument is performing very well and up to pre-launch expectations. Routine observations of lines such as Ar XVII and K XVIII during flares will enable temperature and emission measure information to be derived and so comparison with data from the *RHESSI*, *TRACE* and *SOHO* missions will in time give much insight into processes occurring in high-energy flares. The lines of K XVIII and several other lines have previously been very little observed and should give some new element abundance determinations and the possibility of time variations.

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REFERENCES

Culhane J. L., Rapley C. G., Bentley R. D., et al., 1981, ApJ 244, L141

Culhane J. L., Bentley R. D., Hiei E., et al., 1991, Sol. Phys. 136, 89

Doschek G.A., Kreplin R.W., Feldman U., 1979, ApJ 233, L157

Feldman U., Doschek G.A., Nagel D.J., et al., 1974, ApJ 192, 213

Gabriel A.H., 1972, MNRAS 160, 99

Mewe R., Gronenschild E.H.B.M., van den Oord G.H.J., 1985, A&A Supp. 62, 197

Neupert W. M., Gates W., Swartz M., Young R., 1967, ApJ, 149 L79

Phillips K.J.H., Harra L.K., Keenan F.P., et al., 1993, ApJ, 419 426

Tanaka K., Nitta N., Akita K., Watanabe T., 1983, Sol. Phys. 86, 91