THE X-RAY PACKAGE FOR SPECTROSCOPIC MEASUREMENTS OF SOLAR PLASMA COMPOSITION

J. Sylwester[1] and Z. Kordylewski[1]

[1]*Space Research Centre, Polish Academy of Sciences, 51-622 Wroclaw, Kopernika 11, Poland*

ABSTRACT

We present the instrument package dedicated for spectroscopic studies of coronal flaring plasma composition. The package consists of two Bragg spectrometers RESIK and DIOGENESS. These instruments are to be launched aboard the Coronas-F solar observatory later this year. The composition of coronal flaring plasma heated to several million Kelvins (MK) is known to vary between individual structures up to the factor of around 4. The analysis of spectra to be measured will allow to determine absolute abundances of several important elements including low and high FIP ones. It will be possible to investigate potential fast (time scales below one minute) changes of plasma composition in flares and hotter active regions. This will lead to better understanding of the processes causing elemental differentiation within the coronal plasma. The RESIK spectrometer is being developed by the Consortium including NRL (USA), MSSL (UK), RAL (UK), IZMIRAN (Russia) and Space Research Centre (SRC) of Polish Academy of Sciences. DIOGENESS has been developed in Poland and in Astronomical Institute of Czech Republic.

INTRODUCTION

The Bragg, soft X-ray crystal spectrometers are among the most suitable instruments for detailed study of the spectra of hot coronal plasma. Several spectrometers have been launched in 70-ties and 80-ties in Russia, UK, USA and Japan,. According to Bragg law $\lambda = 2d\sin(\Theta)$, where λ is the wavelength, $2d$ is the crystal spacing, Θ is angle of incidence. By means of scanning (changing the angle of incidence of X-rays onto the crystal) it was possible to measure spectral features in the range between 1 Å and 25 Å (for review see Doschek, 1975; Feldman, 1981). Disadvantage of scanning spectrometers is that particular spectral features are not recorded at the same time. For a fast changing plasma conditions such as in solar flares this introduce additional uncertainty when analyzing spectral line ratios. In order to avoid these problems bent crystal spectrometers have been developed at MSSL (Culhane et al. 1981, 1991) and successfully flown on SMM and Yohkoh. By using position sensitive proportional detectors, it was possible to instantly measure the entire spectra within selected wavelength ranges.

For more than twenty years now, Poland is also interested in the construction of soft X-ray spectrometers. Our first scanning spectrometer had flown on the Vertical-8 and -9 geophysical rockets (Siarkowski and Sylweseter, 1985). We also initiated soft X-ray spectroscopic determinations of flare plasma composition (Sylwester, Lemen and Mewe, 1984).

In the present paper we describe the construction and rationale for two spectrometers to be flown this November 2000 aboard Russian Coronas-F solar observatory.

Teams involved

Several groups of researchers are involved in developing RESIK and DIOGENESS. Following institutes/scientists are involved in the instrument development:

RESIK – Institute of Terrestrial Magnetism and Radiowave Propagation, IZMIRAN, Russia (Victor Oraevsky, Anatoly Stepanov); Mullard Space Science Laboratory, UK (Len Culhane, Bob Bentley, Phill

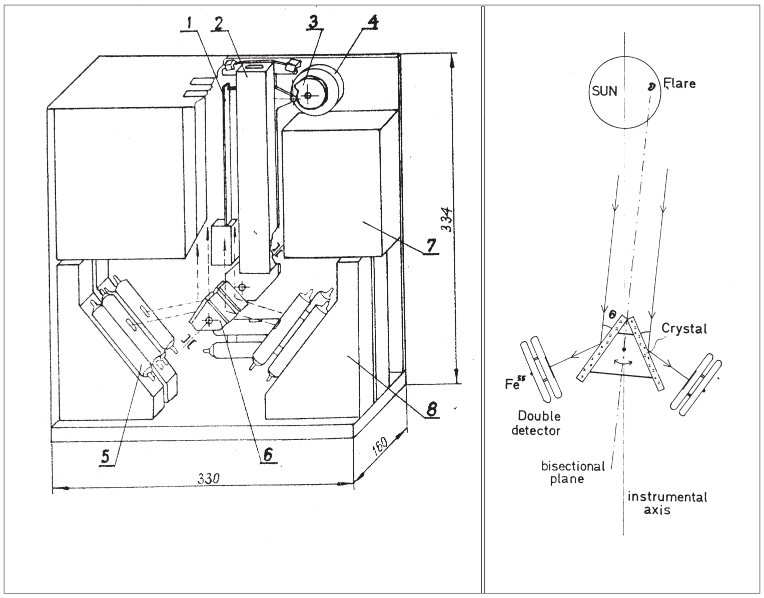

Fig. 1. *Schematic drawing of BS spectrometer and the scheme of so-called dopplerometer section. The key numbers have the following meaning: 1 - strain gauge doubly compensated angle readout sensor, 2 - scanning collimator (10 arc sec FWHM) mounted on the moving arm, 3 - rotating Archimedean cam moving the arm, 4 - stepper motor and reduction gear, 5 - double proportional counters, 6 - four crystals with two of them organized as Dopplerometer, 7 - microprocessor controller, 8 - pre-amplifiers and HV power supply. As concerns the Dopplerometer, the situation is shown (left panel) when the bisector plane of the pair of identical crystals points towards the source (flare). Therefore, the Bragg condition for the chosen Ca* XIX w *line is fulfilled at the same time for both crystals. Provided the lines are Doppler-shifted, the maxima of lines will not coincide in time and precise estimates of plasma radial velocities can be made.*

Guttridge, Matt Whyndham); Naval Research Laboratory, USA (George Doschek, Charlie Brown, Uri Feldman, John Mariska and John Seely); Rutherford-Appleton Laboratory, UK (Ken Phillips, Jim Lang); Space Research Centre, Polish Academy of Sciences (Janusz Sylwester-**PI**, Zbigniew Kordylewski, Marek Siarkowski).

DIOGENESS – Institute of Terrestrial Magnetism and Radiowave Propagation, IZMIRAN, Russia (Victor Oraevsky, Anatoly Stepanov); Astronomical Institute, Czech Academy of Sciences (Franta Farnik); Space Research Centre, Polish Academy of Sciences (Janusz Sylwester, Zbigniew Kordylewski)

Details concerning the division of tasks in the instruments' development can be found on the web pages http://www.cbk.pan.wroc.pl/.

DIOGENESS Description

DIOGENESS is a scanning flat crystal spectrometer (Figure 1) and photometer. The instrument consists of three functional blocks: the spectrometer (BS), the photometer (BF) and the onboard computer (PRAM). The scanning range covers 140 arcmin. Details concerning the crystal selection and wavelength ranges are given in Table 1. The spectrometer is composed of four crystals. A special construction of double Archimedean cam driving the scanning motion of the crystals allows for two phases of scanning. The first phase lasting approximately 120 s constitutes the slow scan with the angular velocity of the scanning arm of 1 arcmin/s. As the arm moves further-on the reciprocal fast scan is executed with the angular velocity six times faster. In this way by turning the cam round the clock at the same speed, slow and fast scans are executed intermittently. During intense flares the scanning is envisaged to be performed four times faster. In this way we lessen the effects of time variability within the recorded spectra. Two of the crystals used in DIOGENESS are identical quartz $(10\bar{1}1)$ with $2d = 6.6859$ Å mounted in the so-called Dooplerometer configuration ((Figure 2). Such arrangement of the crystals allows for precise measurement of possible Doppler shifts of X-ray lines. For plasma at rest, the maxima of lines scanned in opposite directions would be measured at the same instant. If any radial motions are present, the lines will be off-set in time. The off-set can be directly translated to the velocity. Known projected motion of the spacecraft relative to the Sun will be used in order to precisely calibrate this dependence. The observed widths of spectral lines to be measured (Figure 2) reflect mostly the intrinsic line widths (thermal and non-thermal broadening) since the instrumental rocking curves widths are smaller. The source brightness profile along dispersion axis can be deconvolved from the line profiles based on the collimator records (2 keV - 4 keV and 4 keV - 8 keV). Besides the spectral range shown in Figure 2, BS spectrometer will measure diagnostically important line complexes including the helium-like "triplets" of S XV (being observed also by Yohkoh) and Si XIII. This latter triplet (not observed in solar spectra from the SMM era) contains the "coolest" lines (T > 5 MK) in the set of RESIK and DIOGENESS spectra. In this latter range, diagnostically important lines of H- and He-like ions of silicon are also present as well as 1s-3p, and 1s-4p lines of Helium-like aluminum and 1s-4p, 1s-5p lines of H-like magnesium (cf. review by Dubau and Volonte, 1980).

PRAM computer is able to be reprogrammed from the ground if necessary. It is placed in the pressurized section of Coronas-F. The other two units are placed on the instrument payload pointed towards the centre of the solar disc to within 10 arcmin. The satellite is expected to roll around this solar-pointed axis at the rate of few arcsec/s, and therefore the scanning plane may slowly rotate relative to solar coordinate system.

The photometer consists of a system of two simple proportional detectors with apertures of 0.3 cm^2 and 0.01 cm^2. The detectors are on-line self-calibrating using the Fe^{55} radioactive source. This prevents from detector ageing (gain variations).

Table 1: DIOGENESS Characteristics

Channel	1	2	3	4
Crystal	Quartz	ADP	Beryl	Quartz
Plane	$10\bar{1}1$	101	$10\bar{1}0$	$10\bar{1}1$
$2d_1$	6.6855	10.5657	15.9585	6.6875
λ_{obs}	3.1779	5.0348	6.6492	3.1779
λ_{theor}	3.1781	5.0374	6.6488	3.1781
Line	Ca XIX w	S XV w	Si XIII w	CaXIX w
λ_{min}	3.1436	4.9807	6.1126	2.9601
λ_{max}	3.3915	5.3721	6.7335	3.2123
R_C [μrd]	91	91	15	90
FWHM [arcsec]	24.1	68.1	94.1	25.6

R_C – The total reflection coefficient;
The Beryl crystal has been cut from left-over SMM FCS monocrystal (thanks to RAL).

Using two apertures allows to measure the solar X-ray fluencies in the range of 2 keV - 4 keV and 4 keV - 8 keV for times of low (large aperture) and high (small aperture) activity with the sensitivity superior to GOES X-ray detectors. The measurements from the photometer are transferred to telemetry system each 2 s for quiet periods and each 0.125 s during flares. The photometer data will be used in order to interpolate the line fluxes recorded from the spectrometer. Photometer fluxes are to be constantly monitored in order to detect the radiation belt passages. The satellite 500 km orbit is quasi Sun-synchronous with the inclination of 92^o. This means that the satellite encounters the polar fringes of van Allen radiation belts four times per 95 min orbit. Additionally on few consecutive orbits passages through the South Atlantic Anomaly takes place. During radiation belt passages the high voltage will be turned off from the detectors. This means that the overall duty cycle of active solar measurements will be around 70% notwithstanding that the satellite day may last up to several days.

Scientific Rationale The following parameters/problems can be derived/addressed based on the analysis of DIOGENESS spectra:

1. spectra "formation" temperature for each range covered (obtained from fitting of the synthetic spectra)
2. turbulent line widths
3. differential emission measure distribution for hot coronal structures ($5 < T < 25$ MK)

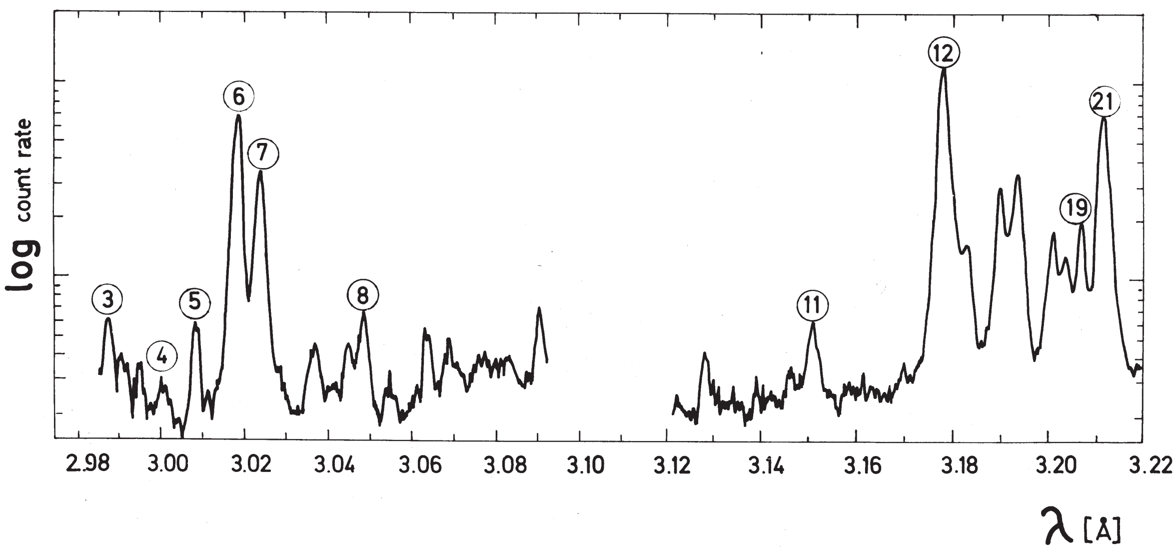

Fig. 2. *A sample of the flare spectrum to be observed within the Dopplerometer section of BS. The numbers above the stronger spectral features correspond to the following transitions: 3* - Ar XVIII $1s\,^2S_{1/2}$ - $4p\,^2P_{1/2,3/2}$*; 4* - Fe XXV $1s\,^1S$ - $1s4p\,^1P$ *(2nd order); 5* - K XVIII $1s\,^1S_0$ - $1s3p\,^1P_1$*; 6* - Ca XX $1s\,^2S_{1/2}$ - $2p\,^2P_{3/2}$ *(Ly_{α_1}); 7* - Ca XX $1s\,^2S_{1/2}$ - $2p\,^2P_{1/2}$ *(Ly_{α_2}); 8* - Ca XIX $1s2p\,^1P_1$ - $2p^2\,^1D_2$ *(J-satellite); 11* - Ar XVIII $1s\,^2S_{1/2}$ - $3p\,^2P_{1/2,3/2}$*; 12* - Ca XIX $1s^2\,^1S_0$ - $1s2p\,^1P_1$ *(w); 19* - Ca XVIII $1s^22p\,^2P_{1/2}$ - $1s2p^2\,^2D_{3/2}$ *(k -satellite); 21* - Ca XIX $1s^2\,^1S_0$ - $1s2s\,^3S_1$ *(z). The Figure has been compiled based on spectral measurements made from NRL P-78 satellite in 1979.*

4. plasma composition for elements with low (4.34 eV for K) and high (15.79 eV for Ar) FIP
5. "absolute" flaring plasma Doppler motions of the hotter component (Ca XIX w, T > 10 MK) using dopplerometer concept (shifts of few km/s can be reliably measured)
6. ionization state of the plasma (i.e. the analysis of "equivalent" ionization temperature) as derived from respective hydrogen (Ly_α) to helium-like resonance lines ratios of Si and Ca ions.
7. study of B ratio between the Ly_{α_1} and Ly_{α_2} components of spin doublets for K, Si and Ca hydrogen-like ions

Additionally, DIOGENESS covers two of the four wavelength ranges being now measured by Yohkoh BCS. Cross comparison of the spectra between these instruments will allow to better understand the linearity of the BCS wavelength scale and help to calibrate other instrumental problems related to bent crystal devices, (both RESIK and BCS). In order to calculate the synthetic spectra the best available atomic data (Utrecht SPEX code: http://saturn.sron.nl/general/projects/spex/) will be used.

RESIK Description

This is bent crystal spectrometer designed to cover the spectral range below 6Å with the aim to measure line and continuum fluxes for hundreds of lines belonging to ions with atomic numbers $30 > z > 14$. The crystals used as dispersive elements are thin wafers of silicon and quartz monocrystals of large area (Table 2). The wavelength channels of RESIK spread over ten different spectral bands covering almost entirely 1.1 Å - 6.1 Å range. The crystals are bent to a convex cylindrical profiles since this geometry allows to reduce the overall size of the crystal-detector assembly. As a consequence of the wavelength coverage selected the widths of most of the lines to be measured are defined (in the first order of reflection) by the detector bin widths which means that the observed line widths will be larger than respective real widths. The crystals selected for the spectrometers were chosen because they are not subject to fluorescence. Previous spectrometers have had problems with background flux caused by photons emitted from diffracting crystals when they were illuminated with energetic photons (E >11.2 keV in case of germanium crystals). The elimination of this fluorescence contamination is of particular importance during the flare impulsive phase. The absence of fluorescence contamination is essential when abundance measurements involving the ratio of the line to continuum fluxes are to be made.

Table 2: RESIK Characteristics

Section	A	A	B	B
Crystal No.	1	2	3	4
Material	Si	Quartz	Si	Quartz
Plane	111	$10\bar{1}0$	111	$10\bar{1}0$
Dimensions [mm]	128 x 40 x 1	128 x 40 x 1	116 x 40 x 1	128 x 40 x 0.5
Mass (crystal) [g]	14	14	14	7
Mass (support) [g]	241	240	266	213
Desired bent radius [mm]	1110	1450	1000	525
2d [Å]	6.27122	8.510558	6.27122	8.510558
Wavelength range				
1st order [Å]	3.369 – 3.879	4.307 – 4.890	3.821 – 4.326	4.960 – 6.086
2nd order [Å]	forbidden	2.154 – 2.445	forbidden	2.480 – 3.043
3rd order [Å]	1.123 – 1.293	1.436 – 1.630	1.274 – 1.442	1.653 – 2.029
Crystal plate – detector angle [^{o}]	55.22	55.22	49.80	49.80
Central grazing angle[a] [^{o}]	34.8	32.7	40.5	40.5
Average reflecting properties[b]				
Central ray				
1st order λ[Å]	3.579	4.599	4.073	5.523
R_c [μrad]	51	20	50	17
FWHM [$\mu rad/arcsec$]	84/17	62/13	113/23	94/19
Peak reflectivity [%]	51	24	36	13
2nd order λ[Å]	forbidden	2.299	forbidden	2.762
R_c [μrad]	–	11	–	11
FWHM [$\mu rad/arcsec$]	–	15/3.1	–	22/4.5
Peak reflectivity [%]	–	64	–	40
3rd order λ[Å]	1.193	1.533	1.358	1.841
R_c [μrad]	4.5	1.5	4.6	1.4
FWHM [$\mu rad/arcsec$]	5.2/1.1	2.4/0.5	7.0/1.4	3.6/0.7
Peak reflectivity [%]	84	56	68	34

[a] – the grazing angle at the midpoint of the crystal;
[b] – from Cowan & Brenens Code (Brennan S. and Cowan P.L.: 1992, *Rev. Sci. Instr.*, **63**, 850).

In each of the two RESIK spectrometer units a double position-sensitive proportional counter is used in order to record the crystal–diffracted photons. The detectors used are upgraded spares from Solar-A (Yohkoh) BCS (Culhane et al, 1991). There are no moving parts (except for the stepper motors used with the Fe^{55} calibration sources) and no collimator is used, so the X-ray radiation of the entire solar corona will contribute to the spectra. More details concerning the construction of RESIK can be found on its web pages. In Figure 3 we present the overall coverage of 10 wavelength bands to be measured by RESIK (bottom bars) and DIOGENESS (upper bars). **Scientific Rationale** Investigation of synthetic spectra to be recorded by RESIK in various conditions of solar activity allows us to consider the following scientific objectives:

1. Determination of relative and absolute coronal abundance (and/or the upper limits) for elements with atomic numbers z = 13 – 30. Expected time resolution is few seconds.
2. Studies of coronal composition variability in time and between different coronal structures, investigations of possible solar cycle effects.
3. Studies of ionization state of high temperature solar plasma.
4. Verification of atomic theory for ionization balance.
5. Search for possible local non-Maxwellian velocity distribution of collisional exciters.
6. Investigation of the spectrum close to ionization limits of individual ions and the relative intensities of higher members of H- and He-like resonance line series.

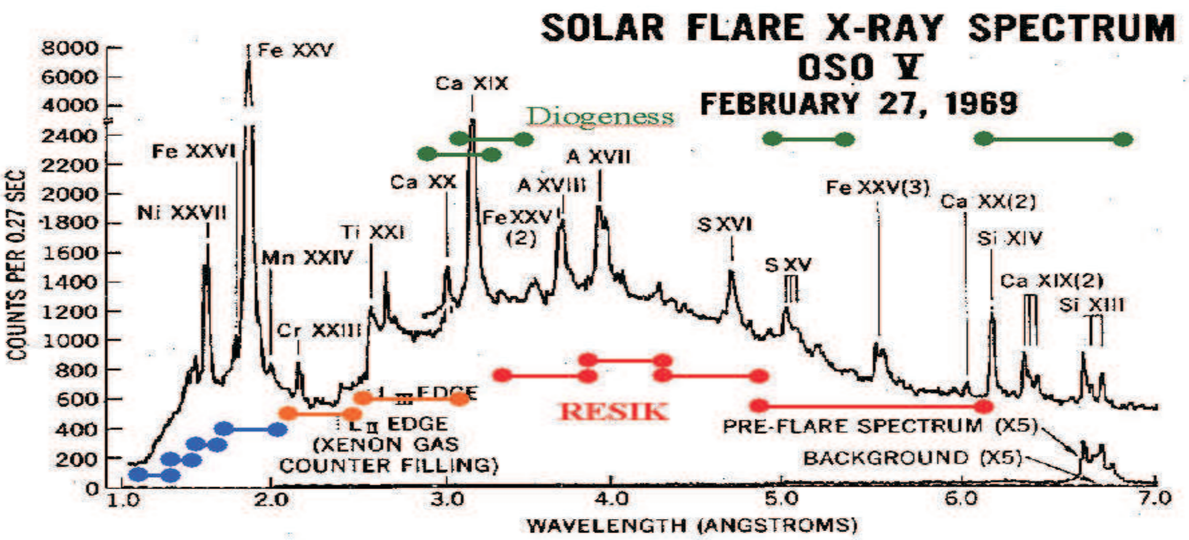

Fig. 3. *The wavelength coverage of individual bands of DIOGENESS (upper dot–limited bars) and RESIK (lower bars) at the first second and third orders of reflection. The background spectrum is one of the few available covering the entire range.*

Conclusions

The described X-ray solar plasma composition package is in the final stage of pre-flight tests. RESIK detector linearity and sensitivity tests are now successfully underway at RAL. The package represents unique combination of the Bragg spectrometers which will allow to determine the absolute coronal plasma composition and its time variations with the accuracy of few per cent for the most abundant coronal elements.

ACKNOWLEDGMENTS

This work has been supported by Polish Committee for Scientific Research Grant *Organization of Magnetic Fields in the Corona* 2.P03D.024.17.

REFERENCES

Culhane, J.L. Gabriel, A.H. Acton L.W. and 15 co-authors, X-ray Spectra of Solar Flares Obtained with a High-resolution Bent Crystal Spectrometer, *Astrophys. J.*, **244**, pp. L141-L145, 1981.

Culhane, J.L. Hiei, E. Doschek, G.A. and 24 co-authors, The Bragg Crystal Spectrometer for Solar-A, *Solar Phys.*, **136**, 89-104, 1991.

Doschek, G.A., in Solar Gamma-, X-, and EUV Radiation ed. S.R. Kane, Reidel, pp. 165-181, 1975.

Dubau, J. and Volonte, S., Dielectronic Recombination and its Applications in Astronomy, *Rep. Prog. Phys.*, **43**, 199-251, 1980.

Feldman, U., The Use of Spectral Emission Lines in the Diagnostics of Hot Solar Plasmas, *Physica Scripta*, **24**, 681-711, 1981.

Siarkowski, M. and Sylwester, J.,The Analysis of Mg XI Ion X-ray Spectra Obtained from Vertical 9 Rocket Experiment, *Artificial Satellites, Space Physics*, **20**, 63-70, 1985.

Sylwester, J., Lemen, J.R. and Mewe, R.,Variation in Observed Coronal Calcium Abundance of X-ray Flare Plasmas, *Nature*, **310**, 665-666, 1984.