Wrocław in Space: X-ray diagnostics of solar corona

M. Siarkowski*, A. Kępa*, B. Sylwester* and J. Sylwester*

*Space Research Center, Polish Academy of Sciences, Kopernika 11, 51-622 Wrocław, Poland

Abstract. X-ray observations of the solar corona have been undertaken in Solar Physics Division (Space Research Centre of the Polish Academy of Sciences, Wrocław) for more than 35 years. Short history of these observations is presented. We focus mainly on the results from the latest experiments. These are hard X-ray photometer onboard the *INTERBALL-Tail* Probe and two Bragg crystal spectrometers recording solar X-ray spectra from *CORONAS-F* satellite. Such observations provide useful information on solar coronal plasma heated up to temperatures of several 10^6 - 10^7 K.

Keywords: Solar physics; Solar corona; Solar flares; Solar X-ray
PACS: 96.60.Pb, 96.60.Rd, 95.85.Nv

INTRODUCTION

Solar Physics Lab in Wrocław was stated in 1970 with small staff of engineers and solar physicists and yet in 1970 first Polish space experiment took place. It was X-ray spectroheliograph with pin-hole camera onboard Russian geophysical rocket Vertical-1. This date also opened international co-operation (at the beginning mainly with Russian Academy of Sciences) which made this and next experiments possible. During following 15 years many rocket experiments were performed. These were mainly photometers, spectrometer, telescopes and collimators all in the X-ray band. In Figure 1 the first Polish X-ray image of the Sun (Sylwester, 2001) together with the first Polish X-ray spectra of the hot solar corona (Siarkowski and Sylwester, 1985) are presented. In early 90's with technology development a new era of remote satellites began. Below, we shortly review the results from latest X-ray satellite experiments. These are X-ray photometer onboard the *INTERBALL-Tail* Probe and two Bragg crystal spectrometers recording solar X-ray spectra from *Coronas-F* satellite.

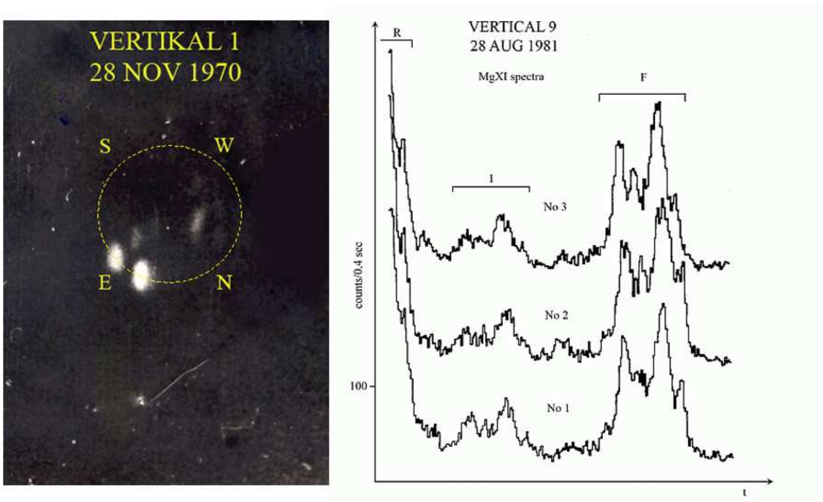

FIGURE 1. *Left*: The first Polish image of the X-ray solar corona obtained in 1970 using pin-hole camera and Be 50μ filter. Dotted circle represents solar limb and two bright areas show emission from the hot coronal active regions. *Right*: The first Polish spectra of the hot X-ray solar corona obtained in 1981. These are three successive spectra around Mg XI He-like 'triplet' between 9.16 Å and 9.35 Å (R - resonance, I - intercombination, F - forbidden). Time on the horizontal axis is related to the wavelength by Bragg equation. The superposition of the line components arising from several active regions present on the solar disk during measurements is seen.

INTERBALL-TAIL MISSION

RF15-I Soft and Hard X-ray Photometer (Sylwester et al., 2000) was placed onboard the *INTERBALL-Tail* satellite lunched on 3 August 1995 and operated continuously up to the middle of October 2000. The photometer was common Polish and Czech Academies of Scienes project and performed observations of the whole disk solar X-ray fluxes in the 3–240 keV energy range using two detectors. The proportional detector nominally measured the soft X-ray solar fluxes in three energy channels: 2–3 keV, 3–5 keV and 5–8 keV with the 2 seconds time resolution. The scintillation detector, NaI(Tl), measured hard X-ray fluxes in five channels: 10–15–30–60–120–240 keV. In the first hard channel (h1: 10–15 keV) the data were collected synchronously with the softer channels each 2 seconds. In the higher energy channels (h2–h5) the data were collected every 0.125 s.

Only during the first three years of observations, RF15-I has registered about 1800 flares (Siarkowski et al., 1999). Using these data we have identified a class of very soft, low intensity and long duration flares (Siarkowski et al., 2002a). They have decay times of the order of hours, low *GOES* class (A or B) and usually no detectable emission above 10 keV. Using soft X-ray images from *YOHKOH* satellite we have found, that as in bigger flares, there is a large diversity in the morphology of small events.

Because of relative high sensitivity in comparison with other X-ray photometers RF15-I was especially useful to investigate small intensity events. This photometer registered many flares strong in soft X-ray but having not significant emission extending above 15 or 30 keV and several small soft X-ray intensity events with noticeable emission above 30 keV (Siarkowski et al., 1999; Gburek and Siarkowski, 2002).

CORONAS-F MISSION

The *CORONAS-F* mission has been launched on July 31, 2001. Two Polish Bragg spectrometers (constructed in the international cooperation) have been placed on the satellite platform. The most interesting results from these spectrometers are presented below.

DIOGENESS

Diogeness was the uncollimated scanning flat crystal spectrometer (and photometer) observing flare X-ray spectra in four narrow wavelength bands in the vicinity of Ca XIX, S XV and Si XIII He-like 'triplets' around 3.18 Å, 5.04 Å and 6.65 Å respectively (Sylwester et al. 2005a). In two spectral channels, the same emission lines around Ca XIX 3.178 Å resonance were scanned in opposite directions, which allowed for Doppler shift measurements. During early phase of the *CORONAS-F* mission many big flares have been observed by Diogeness. In particular, tens of high resolution spectra have been obtained during initial, maximum and decay phase of X5.3 flare, on 25 August 2001 (Siarkowski et al. 2002b). An excellent quality of spectra measured allowed for prompt identification of a number of spectral features rarely seen before e.g. spectral features corresponding to transitions in Ar XVIII (Lyβ) and Si XIV ions. Analysis of appropriate line Doppler shifts allowed for line of sight velocities determination (Płocieniak et al., 2002).

RESIK

RESIK was the bent crystal spectrometer aboard the *CORONAS-F* satellite designed to observe solar active region and flare plasmas spectra (Sylwester et al. 2005a). Silicon and quartz bent crystals allowed for registration of the spectra in four wavelength bands from 3.1 Å to 6.1 Å. This spectral region includes emission lines of Si, S, Cl, Ar, and K from H- and He-like ions. In third diffraction orders also He-like Fe (1.85 Å) and Ni (1.55 Å) lines were observed during the most intense and hot flares. The principal aims of RESIK were the measurements of relative and absolute element abundances in the emitting plasma and the temperature distribution of plasma (DEM-differential emission measure) over the temperature interval 3 MK and 50 MK.

Cl line identification and abundances. In Figure 2 a part of averaged over 80 time intervals RESIK spectrum covering the range of expected resonance Cl lines is shown. Dotted vertical lines indicate for the locations of theoretical H- and He- like transitions. The vertical dashed lines bound the region of the Cl resonance line at λ = 4.444 Å taken for the flux determination. The thin line at the bottom of the spectrum represents the continuum level as calculated based on the temperature and emission measure estimated based on the total fluxes measured in channels 1 and 4. Using these fluxes we have calculated the temperature and emission measure (in the isothermal approximation)

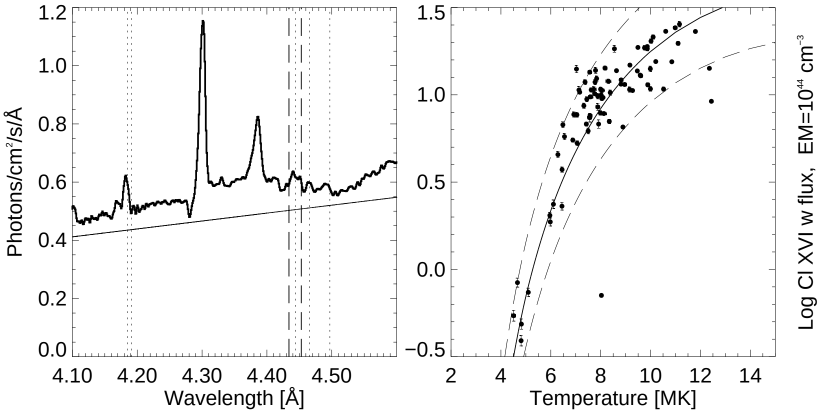

FIGURE 2. *Left*: The part of RESIK average spectrum in the vicinity of H- and He- like Cl lines. *Right*: Chlorine abundance determination from Cl resonance line fluxes (see text for details).

and the Cl resonance line fluxes for 80 cases. The results are plotted in the right panel of Figure 2. Theoretical dependencies of Cl line flux on temperature are presented in the Figure as well. The shapes and positions of these dashed lines are calculated for assumed unit emission measure (10^{44} cm^{-3}) and three different chlorine abundances: $3.98\ 10^{-7}$, $\mathbf{7.76\ 10^{-7}}$ and $1.58\ 10^{-6}$. The middle one fits the observed points the best and represents the **new** $\mathbf{A_{Cl}}$ determination (Sylwester et al., 2004).

Potassium (K) abundances. Using RESIK spectra the absolute abundance of potassium has been determined for the first time from X-ray solar flare line and continuum spectra (Phillips et al., 2003). Obtained K/H abundance ratio is $(3.7 \pm 1.0)\ 10^{-7}$. The absolute and relative abundances of Ar and S have been also determined. These measurements confirmed a pattern in which low-FIP elements (as K) are enriched in the corona by a factor 3 and high-FIP elements (including S) have equal coronal and photospheric abundances.

A quick-look inspection of RESIK spectra of 1163 events observed early in 2003 indicates the presence of substantial flare-to-flare variations in the line-to-continuum ratio of several lines, in particular He-like potassium (K XVIII) lines (Sylwester et al., 2005b). The observed variations are larger than expected from temperature variations. This indicates for the possibility that there are event-to-event variations in the abundance of potassium.

High n transition lines' identification. RESIK observed strong emission lines due to transitions $1s^2$ -$1snp$ 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 (Kępa et al., 2005). Example of identifications of these features, not previously observed in astrophysical spectra, is presented in Figure 3 for channels 1 and 2 of RESIK.

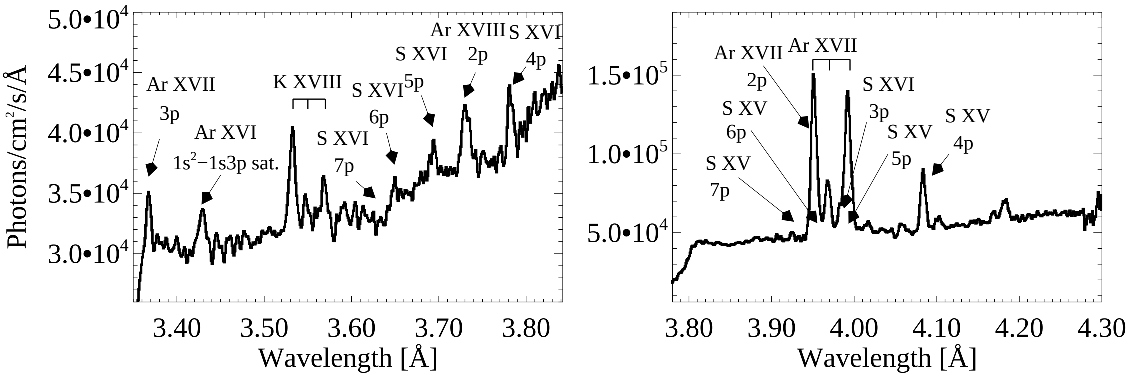

FIGURE 3. Average spectra in the first two RESIK channels with high n transition lines indicated.

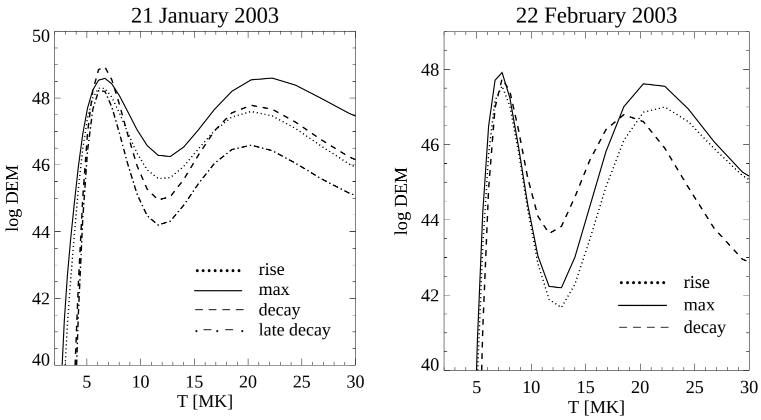

FIGURE 4. Time evolution of the DEM calculated for two solar flares. *Left*: for 21 January 2003: M1.9, long lasting (240 min in soft X-ray radiation), limb flare. *Right*: for 22 February 2003: C5.8, short lasting (12 min), located at the center of solar disk.

DEM. We have calculated differential emission measure (DEM) based on Withbroe-Sylwester multiplicative algorithm (Sylwester et al., 1980; Kępa et al., 2004) and the set of fluxes in several lines observed by RESIK. In Figure 4 the DEM distributions are presented for the rise, maximum and decay phase of two solar flares (Sylwester et al., 2005c). One can notice that the shapes od DEM represent two component distributions. One component contains the relatively cold plasma with temperatures between 6 MK and 9 MK and the other component contains the hotter plasma (T>12 MK). The cold component is rather stable during the flare evolution while the hot plasma distributions depend on the flare phase.

CONCLUSIONS

During 35 years, experimental investigations of X-ray solar radiation have been undertaken by small group (10 people at present) working at Solar Physics Division (SPD) within the frame of Space Research Centre of Polish Academy of Sciences. Several instruments have been designed at SPD based on new concepts and launched aboard Russian sounding rockets and satellites. With our experience in instruments construction, experiment remote control and data analysis, we hope to continue our work extending cooperation with other countries and organizations.

ACKNOWLEDGMENTS

This paper was supported by Polish Ministry of Scientific Research and Information Technology grant No. 1 P03D 017 29 entitled: 'Investigations of physical conditions and composition of coronal plasma from X-ray spectra obtained by RESIK, Diogeness and the other instruments'.

REFERENCES

1. S. Gburek, and M. Siarkowski, 2002, *Adv. Space Res.*, **30/3**, 601–604.
2. A. Kępa, J. Sylwester, B. Sylwester, and M. Siarkowski, 2004, IAU Symposium, No. **223**, pp. 461–462.
3. A. Kępa, B. Sylwester, J. Sylwester, K.J.H. Phillips, and V.D. Kuznetsov, 2005, *Adv. Space Res.*, *in press*.
4. S. Płocieniak, J. Sylwester, Z. Kordylewski, and B. Sylwester, 2002, ESA SP Series (SP-506), pp. 963–966.
5. K.J.H. Phillips, J. Sylwester, B. Sylwester, and E. Landi, 2003, *Astrophysical Journal*, **589**, pp. L113–L116.
6. M. Siarkowski, J. Sylwester, 1985, *Artificial Satellites*, **20**, pp. 63–75.
7. M. Siarkowski, J. Sylwester, S. Gburek, and Z. Kordylewski, 1999, ESA SP Series (SP-448), pp. 877–882.
8. M. Siarkowski, S. Gburek, and P. Rudawy, 2002a, *Adv. Space Res.*, **30/3**, 589–594.
9. M. Siarkowski, J. Sylwester, S. Płocieniak, and Z. Kordylewski, 2002b, ESA SP Series (SP-506), pp. 753–756.
10. J. Sylwester, J. Schrijver, and R. Mewe, 1980, *Solar Physics*, **67**, pp. 285–309.
11. J. Sylwester, F. Farnik, O. Likin, et al., 2000, *Solar Phys.* **197**, 337–360.
12. J. Sylwester, 2001, ESA SP Series (SP-493), pp. 377–382.
13. B. Sylwester, J. Sylwester, M. Siarkowski, K.J.H. Phillips, and E. Landi, 2004, IAU Symposium, No. **223**, pp 671–672.
14. J. Sylwester, I. Gaicki, Z. Kordylewski et al., 2005a, *Solar Phys.* **226**, 45–72.
15. J. Sylwester, B. Sylwester, K.J.H. Phillips, J.L. Culhane, C. Brown, J. Lang, A.I. Stepanov, 2005b, *Adv. Space Res.*, *in press*.
16. B. Sylwester, J. Sylwester, A. Kępa, Z. Kordylewski, K.J.H. Phillips, and V.D. Kuznetsov, 2005c, *Astronomichesky Vestnik*, Pleiades Publishing, Inc., *to be published*.