Observations of Doppler Shifts of X-Ray Lines in Solar Flare Spectra Based on DIOGENESS Spectrometer Data

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The idea of measurement of X-ray lines Doppler shifts in spectra of the Sun, applied in DIOGENESS spectrometer, was previously developed and verified in rocket experiment with RDR X-ray Dopplerometer (Vertical-11 Rocket, 1981) [3]. Upon the obtained results two X-ray DIOGENESS spectrometers have been manufactured; the first one was operated aboard the CORONAS-I satellite (launch in 1994) [6], while the second was operated aboard the CORONAS-F. The general view of the instrument is shown in Fig. 1.

The spectrometer with flat oscillating crystals is used for Doppler shifts measurement in DIOGENESS. According to Bragg law, the X-radiation, inciding crystal surface at θ angle, is reflected from the crystal at the same angle at a single wavelength. The crystal, due to the interference, quench all radiation except the radiation with λ wavelength, defined by Bragg condition

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

where d is the crystal lattice spacing and k is the order of reflection. By changing θ incidence angle, e.g., through crystal rocking back and forth, it is possible to receive X-ray source radiation spectrum within wavelength range, corresponding to scanning extreme angles.

The concept of spectrometer which can operate as the Dopplerometer system is based on mounting of two identical crystals fixed at the precise angular position against each other at the α angle and attached to rocking table. The crystals scan the spectrum in opposite directions, i.e., in the direction of increasing and

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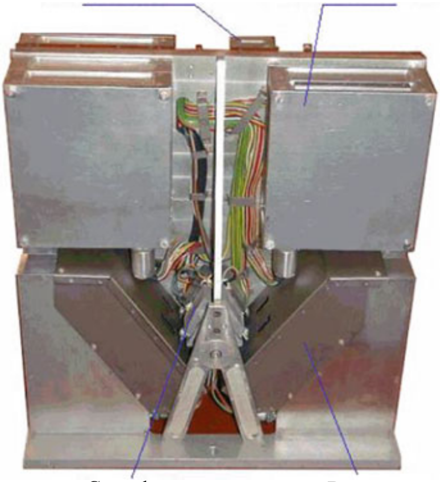

Fig. 1 DIOGENESS X-ray spectrometer, designed for operation in the Dopplerometer system. From [7]

decreasing wavelengths. When the incidence angle reaches the value $\theta = \alpha/2$, the same wavelength is measured in both spectra. Figure 2 shows a basic scheme of Dopplerometer measurements.

The angle α between the crystals should be selected in a manner to ensure the simultaneous registration of selected intense spectral line from radiation source staying at rest relative to Dopplerometer. In case of the presence of a source moving along the line toward the instrument, the Doppler effect occurs, which causes the change in wavelengths. The spectral line in such a case will not be observed in both spectra simultaneously. The angle of table rotation between the detected lines in both spectra will represent a measure of Doppler shift and speed of the source along the line of sight.

There are four crystals in DIOGENESS spectrometer unit (two quartzes, beryl and ADP); their parameters have been adjusted with the purpose to receive the full spectrum in the vicinity of helium-like triplet lines Ca XIX (3.18 Å), S XV (5.04 Å) and Si XIII (6.65 Å) for table rocking by angle $140'$. Two quartz crystals, cut from the same single crystal block, were utilized in a system of the Dopplerometer adjusted accurately for resonance line of helium-like ion Ca XIX ($\lambda = 3.18$ Å). The spectrometer parameters are specified in Table 1.

The spectra from all crystals were registered by double proportional counters with beryllium entrance windows of the 145 μm thickness, filled with argon under the pressure of $\sim$0.5 atm. Physical connection of two gas detector chambers (working and control ones) ensured the identity of gas parameters in the whole double counter. The window of detector control chamber was covered with ^{55}Fe radioactive isotope emitting reference radiation at the energy of 5.9 keV. This ensured the constant energy gain of detector electronic system.

There was the multi-slit collimator attached to the rocking table. The narrow (FWHM $= 10''$) transmission window of collimator scanned the disc of the Sun

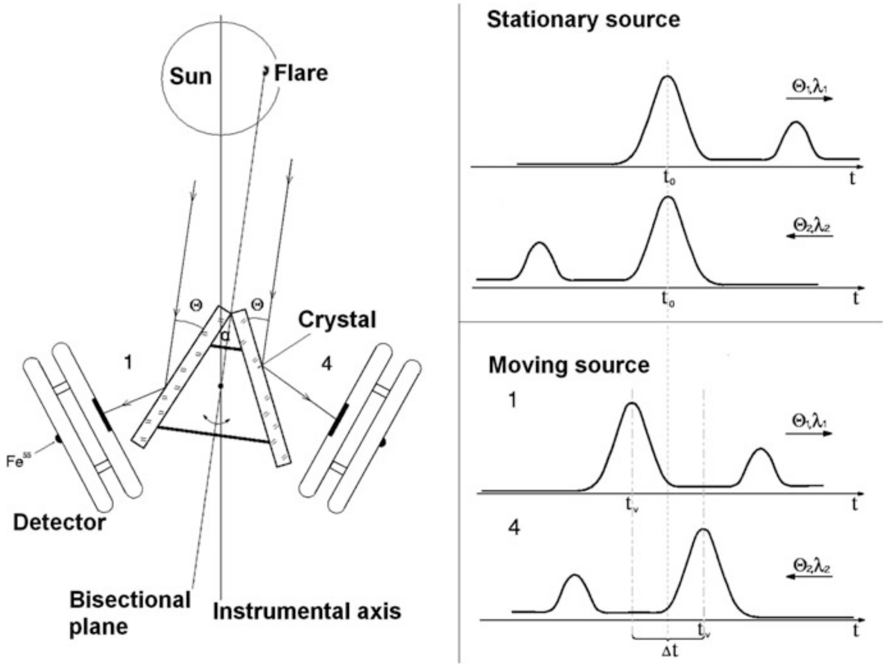

Fig. 2 The scheme of X-ray Dopplerometer is shown in the *left part*. The simultaneous scanning of Sun spectra in opposite dispersion directions is obtained by rocking the table with two identical crystals. From [6]. The *right part* shows the schematic spectral records as obtained from the source at rest and moving (at the *bottom*). From [4]. For moving source the time interval between the registration of line centers in both spectra represents the measure of source speed along the line of sight

Table 1 DIOGENESS spectrometer parameters

Channel	1	2	3	4
Crystal	Quartz	ADP	Beryl	Quartz
Plane	1011	101	1010	1011
$2d$ spacing (Å)	6.6855	10.5657	15.9585	6.6875
λ (Å)	3.1781	5.0374	6.6488	3.1781
Principal lines in range	Ca XIX	S XV	Si XIII	Ca XIX
$\lambda_{minimum}$ (Å)	3.1436	4.9807	6.1126	2.9601
$\lambda_{maximum}$ (Å)	3.3915	5.3721	6.7335	3.2123
Reflectivity (μrad)	91	91	15	90
Full Width at Half Maximum (FWHM) (arcsec)	24.1	68.1	94.1	25.6

along the direction of spectrometer dispersion. Transmitted radiation was registered in two wavelengths ranges (2–4 keV and 4–8 keV), by the proportional counter. It was expected that the scans would give the localization of radiation source on the Sun, but, unfortunately, the operation of this detector terminated early during a flight.

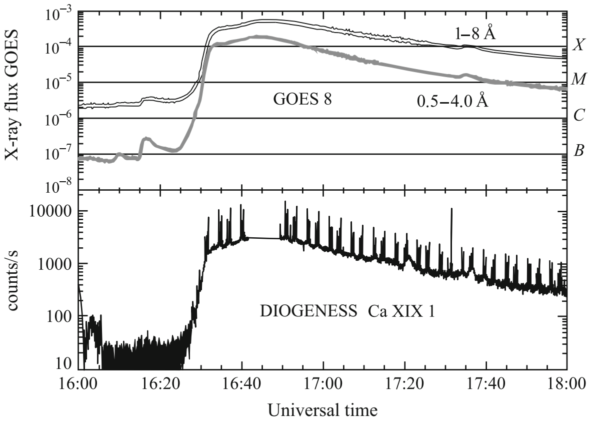

Fig. 3 Observation of X-ray class X5.3 flare (importance 3B H_α) of August 25, 2001. The X-ray radiation measured by GOES satellite detectors (two *upper curves*) and in DIOGENESS spectrometer first channel (*lower curve*) are presented. The peaks related to scanning of Ca XIX helium-like ion line spectra are seen atop the continuum level, corresponding to time changes of this level in the spectral band $\lambda = 3.1$–3.2 Å. From [2]

The rocking motion of table-collimator system with $1\,\text{arcmin}\,\text{s}^{-1}$ angular velocity was actuated by the step motor which rotated back and forth the Archimedian spiral-shaped disc, against which the arm with collimator was pressed by a spring. The full scan in one direction required 40,000 motor steps.

Till mid September 2001, when the device stopped its operation, probably because of the mechanical damage of spectrometer drive, hundreds of spectra of solar flares above M1 class (according to GOES classification) have been obtained. The observations of the highest quality are that obtained on August 25, 2001 (4×30 spectra), when a strong flare of 3B optical flare importance occurred on the Sun. According to X-ray radiation the intensity of this event has reached X5.3 class. Figure 3 (bottom) illustrates the time evolution of X-ray radiation of this flare. For comparison the X-ray measurements in two standard ranges measured by GOES satellite detectors are also provided. The continuum level evolution is similar as seen with DIOGENESS spectrometer: on the regular shape of the continuum the groups of strong X-ray emission lines, recorded in turn in two opposite directions along the dispersion plane, are notable in a form of narrow spikes.

As DIOGENESS device had very narrow instrumental width (better than in previous spectrometers), the observed spectral lines widths correspond to the "true" physical widths, caused by *thermal* and *nonthermal* spectral plasma widening. In the designed spectrometer the detailed laboratory calibration of mechanical drive has been performed, and the crystal rocking profiles have been measured with high accuracy. During the flight the control of the temperature of the crystal mount was constantly performed. Upon these data and with the consideration of effects caused by inaccuracy of pointing and stabilization of instrument axis relative to the Sun disc center, the obtained spectra could be accurately referred to wavelengths scale. This allowed to increase the reliability of identification of the observed spectral lines. Figures 4–6 show (separately for the "right" and "left" direction of rocking the crystals) the averaged spectra of solar flare of August 25, 2001. The detail coincidence of spectra received by scanning in opposite directions confirm the

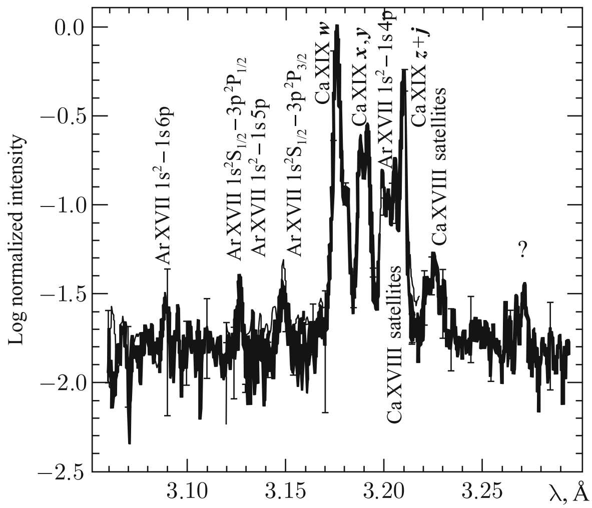

Fig. 4 Averaged flare spectrum of August 25, 2001, obtained by DIOGENESS spectrometer in channels 1 and 4. There are two exactly coinciding spectra (*thick* and *thin curves*), averaged separately for the scans performed in opposite spectral directions. The *lines* identification are given. For the purpose of weak lines highlighting, the normalized spectra are shown in a logarithmic scale. From [5]

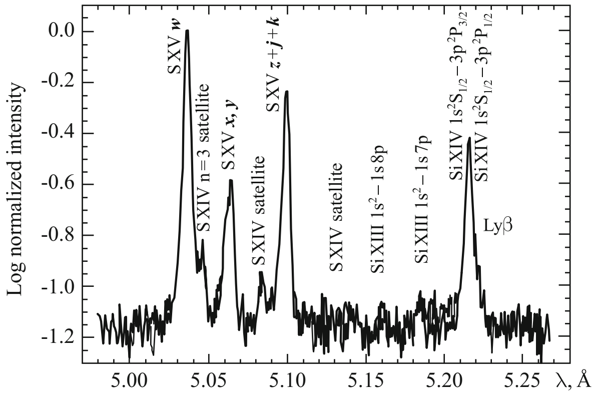

Fig. 5 Averaged flare spectrum of August 25, 2001 flare, obtained by DIOGENESS spectrometer in the 4.98–5.26 Å range (shown, there are two well coinciding spectra averaged separately for the scans taken in two opposite directions). The spectrum covers the lines corresponding to indicated transitions. From [5]

reality of all spectral features. Many of them which have, according to atomic physics calculations, known intensities and wavelengths values have been identified for the first time. Identification of numerous spectral lines is in progress. The spectra, obtained by DIOGENESS spectrometer for the study of analyzed flare and other events, will be used for the analysis of temperature changes and emission measure analysis, with the purpose of formation of a complete image of time changes of principal thermodynamic characteristics of flaring plasma.

The good quality of spectra of August 25, 2001 flare also allowed to identify the Doppler shifts of spectral lines. Figure 7 shows two concurrent spectral scans embracing Ca XIX line triplet, which have been obtained by quartz crystals mounted in Dopplerometer configuration. It may be seen that resonance lines were not registered simultaneously. It was partially caused by small constant inaccuracy of adjustment of the angle α between atomic planes of Dopplerometer crystals pair, which has been noticed in course of device laboratory tests. Such inaccuracy

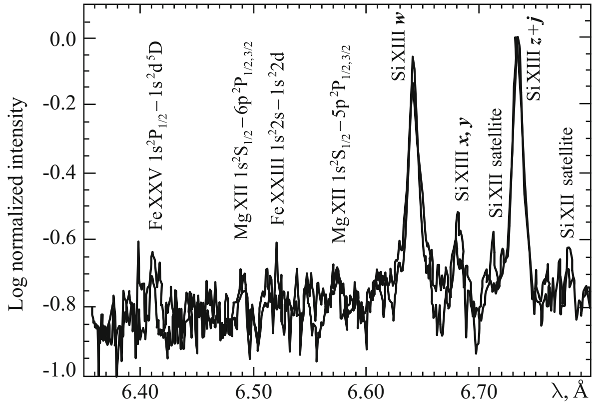

Fig. 6 Two averaged X-ray flare spectra (two almost coinciding *curves*) of August 25, 2001 flare, obtained by DIOGENESS spectrometer in course of scanning in opposite spectral directions. The identification of principal lines in 6.35–6.80 Å range has been performed. From [5]

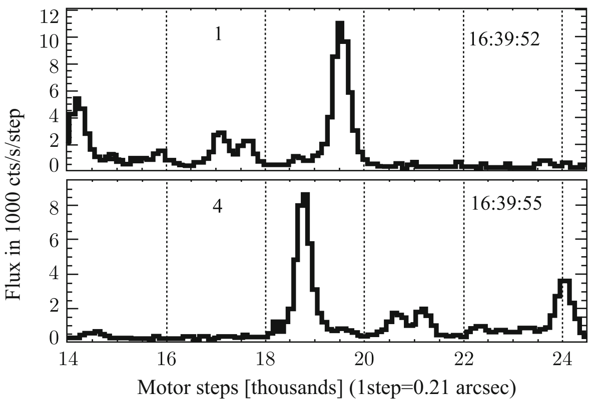

Fig. 7 The example of two scans, covering spectral ranges of Ca XIX ion line triplets. The spectra have been obtained by the Dopplerometer system during the flare of August 25, 2001. The rotation angles are shown on the horizontal axis represented by the steps of the drive motor of the rotating table with crystals. It may be seen that the strongest resonance lines are not measured simultaneously. After elimination of the constant instrumental shift, the remaining difference of the positions of centers of the registered lines evidences the presence of a Doppler shift. From [1]

amounted to 20 arcsec, and it could be easily accommodated during the line shift determinations. After the correction for this instrumental shift the remaining displacement of lines may be interpreted only by Doppler effect, caused by the motion of flaring source along the line of sight. The results of such interpretation are shown in Fig. 8, which illustrates the change of radial component of flare hot plasma speed with time, i.e., in its development phase. The highest speed (100–150 km/s in the direction from the Sun) was observed in initial phase of the flare. The reliability of the obtained results is confirmed by the fact that similar velocity values have been

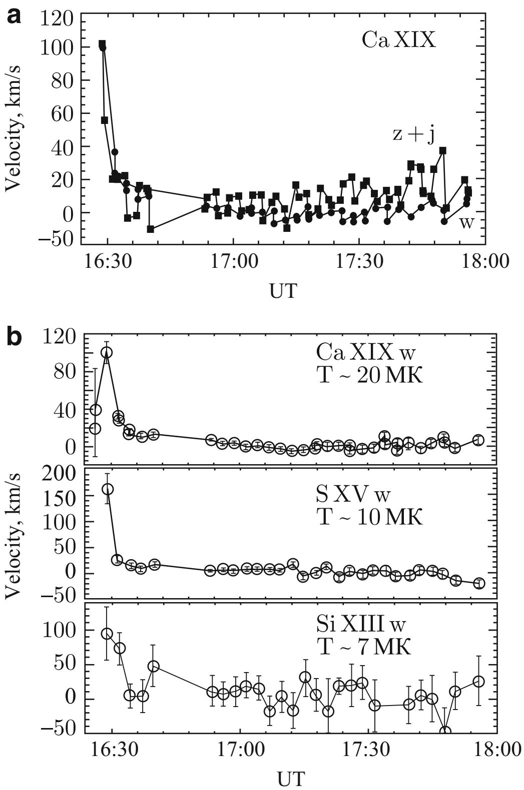

Fig. 8 (**a**) The time dependence of plasma Doppler velocity for the flare of August 25, 2001. The "w" letter marks the values of velocity obtained from the measurement of relative shifts of Ca XIX resonance line ($\lambda = 3.178$ Å). The "z + j" letters mark the velocities for a line representing the blend of j satellite line and so-called forbidden line z of Ca XIX ion. From [5]. (**b**) Comparison of the time dependence of Doppler velocities obtained for resonance lines of Ca XIX, S XV, and Si XIII ions. The characteristic temperatures for the formation of these lines are specified. From [1]

independently obtained by measurements of both resonance (the strongest one) and forbidden lines of Ca XIX ion.

Ca XIX ion resonance line is effectively formed in a hot plasma with the temperature above 7 MK only. The maximum of efficiency occurs at ~20 MK. In the given flare the plasma had such a temperature in the very initial phase of the event, during the rise phase. The sulfur and silicon lines are formed in a lower temperature plasmas. DIOGENESS spectrometer was not designed for operation in Dopplerometer arrangement for a spectral range including the lines of these elements. However, the knowledge about device geometry has allowed to analyze, for S XV and Si XIII ion lines, their shift relative to the position of imaginary bisector of angle between the crystals. The results obtained in such a manner are also shown in Fig. 8, qualitatively they coincide with the data obtained for calcium ion lines.

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