DETERMINATION OF WAVELENGTHS AND LINE SHIFTS BASED ON X-RAY SPECTRA FROM DIOGENESS

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ABSTRACT

Diogeness is the uncollimated scanning flat crystal spectrometer 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. In two spectral channels, the same emission lines (around Ca XIX w resonance line, λ = 3.177 Å) are scanned in opposite directions. The X-rays are reflected from precisely adjusted identical Quartz monocrystals mounted on the common shaft in so-called *Dopplerometer* configuration. This novel spectrometer design allows for highly accurate determinations of wavelengths and precise determination of line Doppler shifts. We explain the concept of the X-ray Dopplerometer and present results of analysis of the Doppler line shifts for the spectra collected during 25 August 2001 X5.3 flare. We compare derived line of sight plasma velocities with those measured by *Yohkoh* BCS.

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

1. INTRODUCTION

Based on design experience gained from early experiments, we developed and flight tested novel type of spectrometers and imagers (Sylwester, 2001). One of them is so-called X-ray Dopplerometer. A scheme of the Dopplerometer section (left panel) and the corresponding expected spectral recordings (right panel) are shown in Figure 1. The section consists of the two crystals fixed mechanically on the common shaft at the exact (to within few arcsec) angle 2Θ where Θ is the corrected Bragg angle corresponding to the rest wavelength of a strong emission line. According to Bragg condition:

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

(Θ = Bragg angle, k diffraction order, d = crystal lattice spacing).

By rotating the crystal section, the X-ray spectra are recorded using a pair of appropriate proportional counters. The scanning takes place in the opposite directions for each of the crystals in the couple. Such arrangement of the crystals allows for precise (difference) measurements of the possible Doppler shifts of the measured lines. For the source plasma being at rest, the line maxima are to be recorded at the same wavelength (i.e. same instant during the scan). Any radial motions of hot flaring plasma will cause the maxima of the lines to be recorded slightly shifted in time. This time shift is proportional to the value

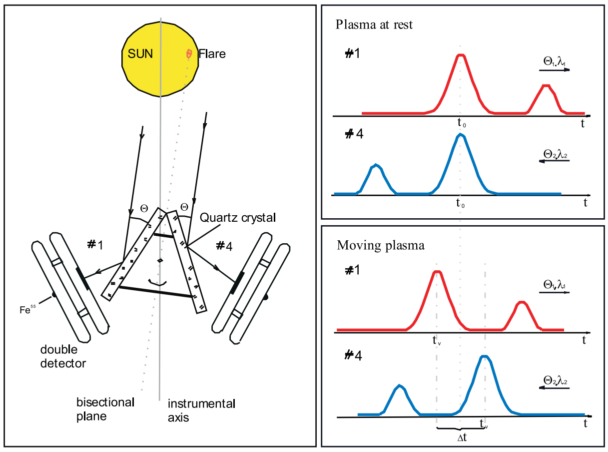

Figure 1. The scheme of Dopplerometer configuration adopted in the experiment (left). Bi-sector plane of the crystal pair #1 and #4 (dotted line) points momentarily towards the source (flare). Crystals are fixed mechanically at the exact angle of 2Θ. By rotating fixed crystal section back and forward, the Bragg-reflected spectra in the vicinity of strong lines are measured by a pair of double proportional counters. In the ideal case of perfect co-alignment and for the source plasma being at rest, the line centres are recorded in channels #1 and #4 at the very same time during the scans performed in the opposite wavelength sense (upper right panels). Any radial motions of the hot flaring plasma will displace (in time) the relative position of lines (lower panel). The displacement is proportional to the line Doppler shift and is independent of the position of the source (flare) on the disc and/or the relative pointing, provided they are stable.

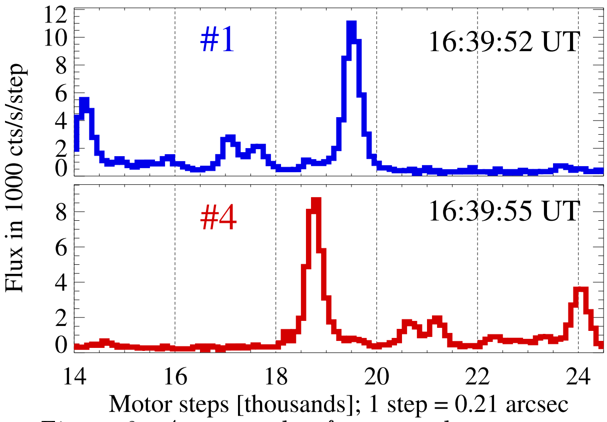

Figure 2. An example of measured spectra recorded nearly simultaneously in channels #1 and #4 during the maximum phase of the X5.3 flare. Indicated are the times, when the centre of the strongest resonance line is measured.

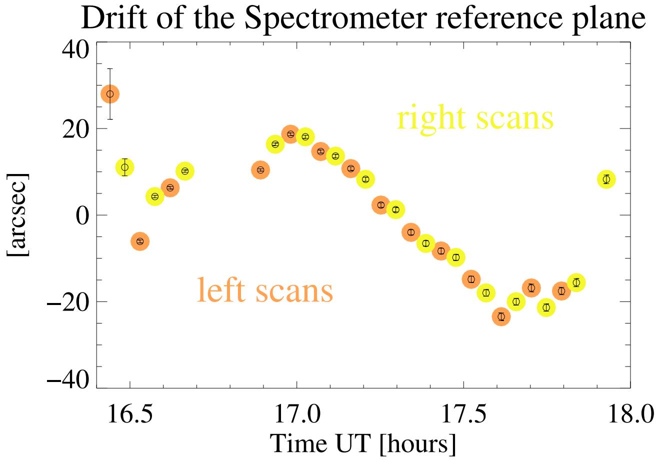

Figure 3. Relative drift of the Diogeness reference plane (satellite pointing/flare transversal motions), as projected on the dispersion plane of the spectrograph. This residual motion has been detected with accuracy of few arcsec by the Dopplerometer. The drift shown does not influence the accuracy of wavelength scale determination.

of radial component of source plasma velocity. The time difference effect is independent of the position of the source (flare) on the disc and/or the relative pointing of the spectrometer, provided the pointing does not change fast. The accuracy of the velocity determination is expected to be very good, down to few km/s as a result of adopted concept of difference measurement. The scanning (uniformly changing the angle of incidence of X-rays) enables to measure spectral features in the chosen X-ray range using crystals with appropriate spacing. Two of the crystals used in Diogeness are identical Quartz $(10\bar{1}1)$ with $2d = 6.6859$ Å which enable us to measure the spectra in the vicinity of Ca XIX w line. Bragg condition for the chosen line is fulfilled approximately at the same time for both crystals in the section. Provided the lines are Doppler-shifted, the maxima of lines will not coincide in time and precise determination of plasma radial velocities can be made.

Diogeness has been placed aboard the *CORONAS-F* satellite launched 31 July 2001 from Plesetsk (Russia). During first month it collected more than 2000 spectra for a number of flares, including a strong X5.3 flare on 25 August 2001. For details concerning the Diogeness spectrometer construction see the paper by Siarkowski et al., (2002). In the present contribution, we concentrate on determination of the line Doppler shifts for this X5.3 flare.

On 25 Aug. 2001, during two satellite orbits 15 left and right scans have been recorded by the Dopplerometer for a very intense long duration flare. Most of the spectra recorded correspond to the maximum and decay phase of this flare when its intensity was above the M1 X-ray level. In Figure 2 an example of measured spectra recorded nearly simultaneously in Channels #1 and #4 (forming the Dopplerometer) during the maximum phase of X5.3 flare on 25 Aug. 2001 is presented. On the horizontal axis the motor step Nos. are plotted. The motor scanned (forward and backward) the X-ray spectra within a narrow angular range of ~140 arcmin including the Ca XIX triplet lines. The data gather interval (DGI) of 0.25 s has been used (corresponding to 21 arcsec change of crystal rotation). The most prominent spectral features seen on both spectra are the resonance w lines corresponding to the $1\,s^2\,{}^1S_0$ - $1\,s2p\,{}^1P_1$ transition in the He-like Ca XIX ion. The scanning in both channels is executed in the opposite wavelength sense as seen by proportional detectors #1 and #4. Thus the intercombination (x, y) and forbidden z lines comprising the Ca XIX triplet are seen on the opposite sides of the presented motor step range, being recorded approximately 20 s apart in time for z lines. It is of primary importance to have the precise determination of wavelength scale in order to determine the small Doppler shifts. Determination of "absolute" experimental wavelength scale (i.e. assignment of wavelengths to time through appropriate calibration of the motor steps) has been achieved in the several steps. In the first step, the background and the continuum emission have been removed from all the spectra in the sequence, and the spectra have been normalized (respective to w line maximum) in order to correct for a slightly different spectrometer sensitivities in both Dopplerometer sections. In order to find the relative time offset Δt between the instants corresponding to line centres as recorded by the two crystals in a given scan, the line centre motor step positions have been determined. In this respect the fitting (χ^2 minimization) of the Gaussian profiles has been used. Appropriate uncertainties of the fits have been determined based on the count statistics. The time t_c (located central between recording of the w resonance lines in both crystals sections) defines the orientation of the bi-sector plane of Dopplerometer (we assume the scanning being uniform, the source and the satellite pointing being stable within this short ~3 s time interval). In order to check for the pointing stability of the *CORONAS-F* spacecraft, we analysed the crystal addresses (motor steps) corresponding to these mid-times. In case there is no S/C pointing changes (or flare transversal motions), these addresses should keep constant. We observe

Table 1. $10\bar{1}1$ Quartz crystal properties as determined from laboratory measurements

Crystal	2d[a] [Å]	R_c[b] [μrd]	FWHM[c] [arcsec]
#1	6.6857 ± 0.0004	77 ± 30	25 ± 2.5
#4	6.6859 ± 0.0005	73 ± 30	24 ± 2.5

[a] - from laboratory measurements ($T = 22\ ^oC$) done using collimator with single crystal monochromator tuned to characteristic K-line of Cr.

[b] - extrapolated for the Bragg angle corresponding to the Ca XIX *w* resonance line from measurements done using double crystal monochromator tuned to K-line of Ca. The extrapolation uncertainties are included in the measurement error.

[c] - from laboratory measurements done using double crystal monochromator (1,-1), tuned to characteristic K-line of Ca.

however small changes of these crystal addresses during the period of ~2 hours when the X5.3 flare has been observed. In Figure 3, we plot this detected slow drift of the spacecraft pointing (or transverse source motion) with time. For clarity, we express the drift/motion in arcsec. Slightly different shades of the points plotted corresponds to forward/backward scans respectively. The observed amplitude of the drift is well within the limits of ~10 arcmin pointing accuracy of the z-axis of *CORONAS-F* and the maximum angular velocity of the drift (~ 0.0005 arcsec/s) is less than respective velocity allowed in the S/C technical specification. However, it comes from the prompt inspection of the *Yohkoh* SXT Be119 images, that the flaring plasma changed its location slightly, so the interpretation of the drift observed is under study. The amplitude of the effect indicates that the assumption of negligible role of S/C slews (plasma transversal motions) for differential Doppler velocity determinations is justified. In the next step leading to assignment of wavelength scale, we based on laboratory calibrations of the crystals used in the spectrometer. In Table 1 we present results of laboratory measurements of the crystal properties important for the present study. In the next step, we checked for possible effects of thermal dilatation, by looking into readouts of the temperature sensors placed on the crystal support. No substantial (within less than 2^oC) changes of the temperature have been found during two hours of measurements, but we found temperatures of each of crystals slightly different (by $\sim 3^oC$). Appropriate corrections have been taken into account in the further analysis. The fact, that the temperature of the crystals do not change substantially is in agreement with the S/C orbital information indicating that *CORONAS-F* was on a constantly Sun-lit portion of its semi-sun-synchronous orbit during the measurements. In respect with, one can safely assume that the orbital plane was approximately perpendicular to the direction towards the Sun, so the projected radial motions of the satellite along this line are negligible.

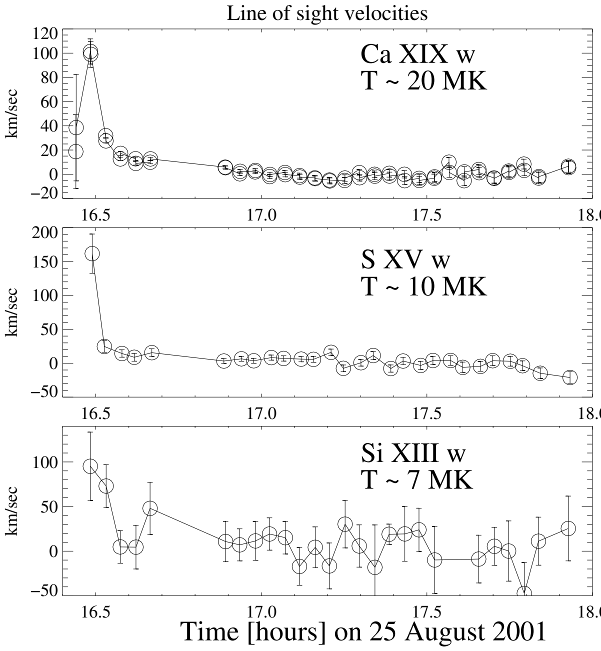

Figure 4. Velocities determined from X-ray line shifts observed by Diogeness. In the upper panel determinations for Ca "w" line from both sections of Dopplerometer are superimposed. In the lower two rows, plots of the velocities found from S XV *and Si* XIII *are displayed. A high blue-shift observed early in flare are of similar value in all three lines measured. The uncertainties shown represent combined relative error of wavelength scale determination. For Ca "w" line the uncertainties around the flare maximum are few km/s only.*

2. DETERMINATIONS OF X-RAY LINE DOPPLER SHIFTS

With the satellite drift motions effect negligible, and the temperature effects taken into account, any relative shifts of the line positions in respect to the bisector plane can be interpreted as a consequence of the Doppler effect. By assuming that during the late phase of flare decay, the flaring plasma stay at rest as concerns its average bulk velocity, it is possible to accurately determine the bulk plasma velocities for times of *w* line scans. In Figure 4 (upper panel) we plot the results obtained using Ca XIX *w* line. Note very small values of uncertainties assigned to the presented velocity determinations. They represent combined statistical uncertainty of the differential measurement of centre of line separation. They are of the order of few km/s only during flare maximum phase. The estimated line-of-sight plasma velocities reach maximum (~120 km/s) during the rise phase. Based on results of laboratory calibrations of the crystal alignment for all four crystals comprising Diogeness spectrometer, it was also possible to determine the Doppler shifts and respective plasma velocities as seen in the other resonance lines observed, namely S XV and Si XIII. These lines are effectively formed in a plasma significantly cooler than this contributing to Ca XIX emission (as indicated in

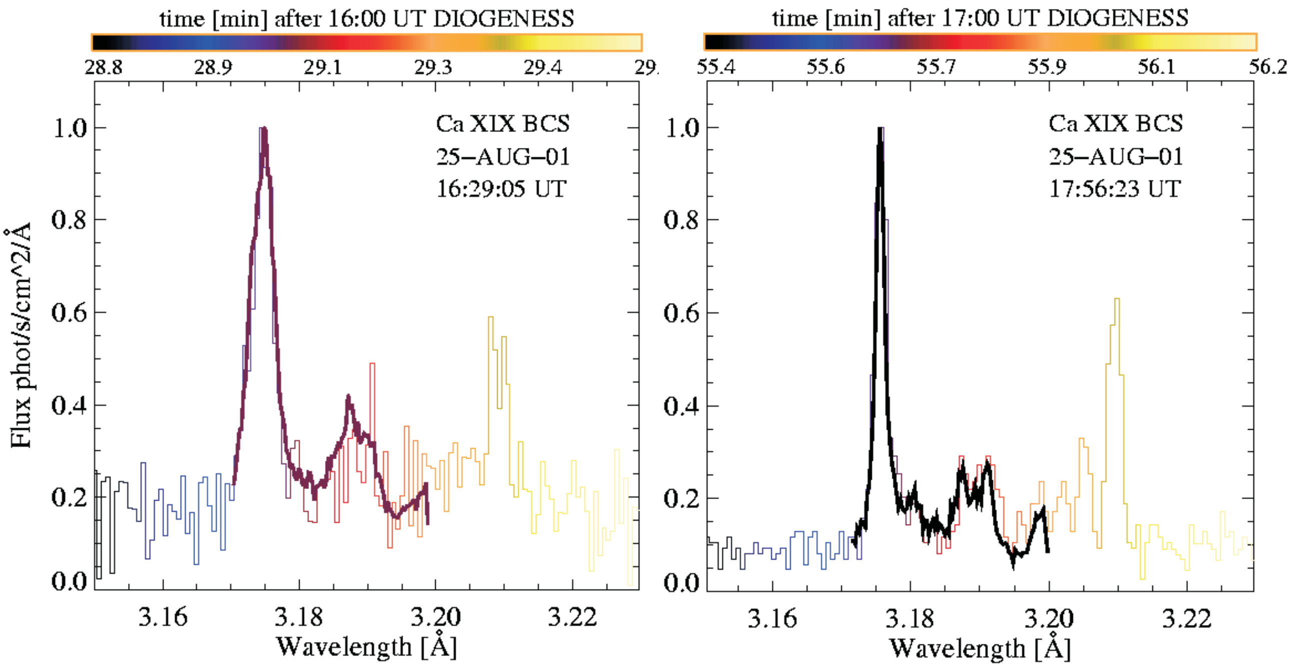

Figure 5. The comparison of normalized Ca XIX *spectra observed during the rise (left) and decay (right) phase of the flare by Diogeness and Yohkoh BCS. A substantial difference in the widths of w line is seen between the rise and decay phases. The* BCS *spectra overplotted (black line) have been observed during collection of Diogeness spectral scan (rise phase) or 20 s afterwards (decay phase).*

the Figure). It is interesting, that the character of variations in derived velocities is similar in all different lines observed, suggesting uniform projected bulk motions (towards the observer) of the flaring plasma, independent of its formation temperature.

3. COMPARISON WITH *YOHKOH* BCS OBSERVATIONS

Diogeness was not a unique Bragg spectrometer observing the 25 August 2001 X-flare. By a fortunate coincidence the Bragg, bent Crystal Spectrometer (BCS, Culhane et al., 1991) aboard *Yohkoh* recorded X-ray spectra in the wavelength ranges matching two of these observed by our instrument. BCS records spectra instantly in the entire spectral band covered with its crystal being bent and the detector position sensitive. It is also much more sensitive than Diogeness, which actually is a disadvantage when observing strong flares, since it becomes saturated for events above M2 X-ray class. This leaves small room for cross-comparison of the two spectrometers for the period during the X-flare when its intensity was above Diogeness sensitivity threshold and below BCS saturation limit. Few spectra in common have been identified, and direct comparison of the spectral records is shown in Figure 5 for the initial rise and late decay phase.

4. CONCLUSIONS

The soft X-ray Dopplerometer concept has been successfully flight tested within the Diogeness spectrometer flown aboard *CORONAS-F* solar observatory. It has been proven that the use of this new concept of Bragg spectrometer construction allows for very precise determinations of X-ray line shifts due to line-of-sight velocity component. Further analysis of the recorded spectra collected by this spectrometer will allow for determination of the other physical characteristics (temperature, emission measure, elemental abundances) of the investigated X-class flare. The result presented indicate that the Dopplerometer crystal configuration would be very useful concept to be incorporated in the future Bragg spectroscopy missions.

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REFERENCES

Culhane J.L., Hiei E., Doschek G.A. et al., 1991, Solar Phys., 136, 89

Sylwester J., 2001, ESA-SP 493, 377

Siarkowski M., Sylwester J., Plocieniak S., Kordylewski Z., 2002, ESA-SP, 506, *this issue*