ANALYSIS OF DYNAMICS OF LOOPS IN AN ACTIVE REGION ASSOCIATED WITH A SMALL C-CLASS FLARE

Peter Gömöry*[(1)], Ján Rybák[(1)], Aleš Kučera[(1)], and Hubertus Wöhl[(2)]

[(1)]*Astronomical Institute of the Slovak Academy of Sciences, 05960 Tatranská Lomnica, Slovakia, email: gomory@astro.sk; choc@astro.sk; akucera@astro.sk*
[(2)]*Kiepenheuer-Institut für Sonnenphysik, 79104 Freiburg, Germany, email: hw@kis.uni-freiburg.de*

ABSTRACT

A study of the dynamics of magnetic loops before and during an X-ray C1.4 class flare in NOAA AR 10646 is presented using data taken by the *SOHO*/CDS spectrometer in He I 584.33 Å (chromosphere), O V 629.73 Å (transition region) and Si XII 520.67 Å (corona) lines. Several precursors and the main impulsive phase of the flare were detected in all spectral lines. Analysis of two selected chromospheric precursors with clear relation to the main impulsive phase and the main impulsive phase of the flare itself has shown time delays between the chromospheric/transition region and coronal occurrence of events, upflows during precursor events and peaks of downflow and upflow velocities during the main impulsive phase. These results indicate that the chromospheric evaporation could be the driving mechanism of the observed flare. Further investigation of remaining precursors and analysis of the co-observations obtained by the *TRACE* and the *DOT* telescope are necessary for confirmation of this conclusion.

Key words: Sun: activity – Sun: flares – Sun: UV radiation.

1. INTRODUCTION

The reconnection of magnetic field lines is the most accepted mechanism which can release magnetic energy during flares. This energy is subsequently transformed to kinetic energy of non-thermal particles and to heat. The resulting accelerated beams of particles and/or thermal conduction fronts then propagate downward and heat the chromospheric plasma to coronal temperatures. As the chromospheric material heats, it expands upward into the corona. This process is known as *chromospheric evaporation*. Observational evidence for chromospheric evaporation is therefore based mainly on detection of strong upflows ($\sim$300 km s^{-1}) in coronal emission lines (formed at temperatures higher than 10^7 K) during the main impulsive phase of the flare (Antonucci & Dennis, 1983; Doschek et al., 1996; Silva et al., 1997; Bornmann, 1999, and references therein).

Fisher et al. (1985a,b,c) studied the response of upper chromosphere and the transition region to chromospheric evaporation. Their hydrodynamic simulations revealed an energy threshold separating two different regimes of the discussed mechanism. *Explosive evaporation* occurs when the flare energy deposited to the chromosphere is higher than the threshold energy. The chromospheric material is consequently heated much faster than it can radiatively cool and its temperature jumps to coronal temperatures in a very short time. The resulting overpressure of the evaporated material then drives plasma simultaneously upward towards the corona and downward into the chromosphere. Fisher et al. (1985b) predicted that spectral lines which are formed at temperatures $\sim 10^5$ K should therefore exhibit downflow velocities of around 40 km s^{-1} (note that soft X-ray emission spectral lines exhibit significant upflows during the explosive evaporation). Energy fluxes less than the threshold value lead to *gentle evaporation*. In this case the transition region spectral lines should exhibit upflow velocities of $\sim$ 20 km s^{-1} (Fisher et al., 1985b).

Fárník et al. (1996) revealed that at least 15% (at most 41%) of their flare sample show precursors, i.e. brightenings appearing close to the main impulsive phase site which are closely related with the flares. Brosius & Phillips (2004) pointed out that the precursors are probably results of the gentle evaporation while the main impulsive phase appears to be due to explosive evaporation.

In this article we concentrate on analysis of measurements of a small X-ray C1.4 class flare in NOAA Active Region 10646. In particular, we discuss the properties of the two selected precursor events and the main impulsive phase of the flare.

2. DATA AND DATA REDUCTION

The data presented here are part of the observing sequence taken with the Coronal Diagnostic Spectrometer (CDS, Harrison et al., 1995) onboard the Solar and Heliospheric Observatory (*SOHO*, Domingo et al., 1995) in Joint Observing Programme 171[1] on July 15, 2004 from 08:52:09 UT to 10:12:38 UT. The 4 arcsec wide slit (oriented in the north – south direction) was used to measure the temporal evolution of the spectral profiles of the He I 584.33 Å ($\log T = 4.3$), O V 629.73 Å ($\log T = 5.3$) and Si XII 520.67 Å ($\log T = 6.3$) during flaring activity within the NOAA AR 10646 (Fig. 1). The CDS pointing was fixed at *Xcen* = 914.6 arcsec, *Ycen* = 144.8 arcsec and the solar rotation was not compensated. The exposure time was 10 s and a set of 320 spectral images was obtained every 15.1 s.

* Sterrekundig Instituut, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

[1] JOP 171 proposal: www.astro.sk/~gomory/jop171/proposal.ps

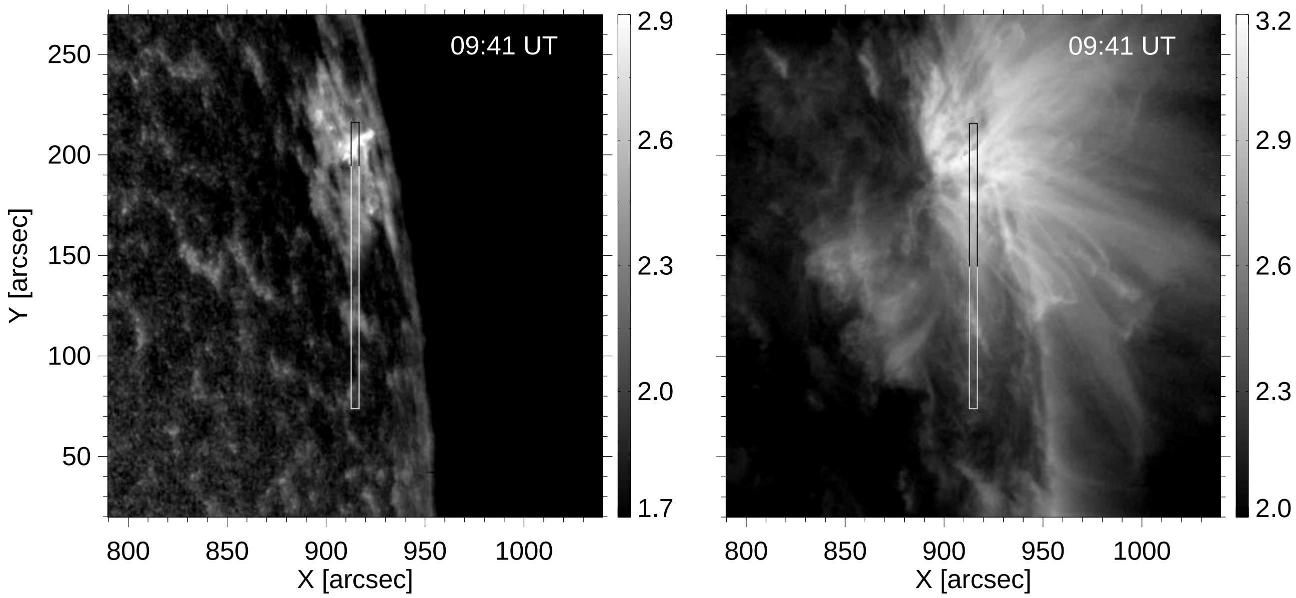

Figure 1. TRACE 1600 Å (left) and 171 Å (right) filtergrams showing location of the CDS slit within NOAA AR 10646. The images were taken during the main impulsive phase of the flare under study. Spectral data described and discussed here were detected between 191.1 arcsec and 214.9 arcsec along the slit. Solar north is up, and west is to the right. The intensity values in counts s^{-1} are displayed in logarithmic scale.

Using standard CDS software,[2] raw measurements were corrected for cosmic rays and all instrumental effects. The data were then converted to physical units. As the CDS line profiles deviate significantly from Gaussians since the loss of *SOHO* control in 1998, we used the "broadened Gaussian" profile with a linear background for the profile fitting.[3] This was accomplished using the SolarSoftware routine CFIT[4] which is based on the Levenberg-Marquardt method of minimalization of the least squares (Press et al, 1986). The fitted data product consist of the intensities and the Doppler shifts per spatial pixel per exposure. The wavelength scales were calibrated relative to the average Doppler shifts of the "quiet Sun". These values were derived from laboratory wavelengths of the selected spectral lines which were corrected for average redshift/blueshift of the transition region/coronal spectral lines (Peter & Judge, 1999). The effect of solar rotation was also subtracted from the Doppler shifts.

3. RESULTS

Temporal evolution of the He I, O V and Si XII intensities (left) and the Doppler shifts (right) detected between 191.1 – 214.9 arcsec along the CDS slit are shown in Fig. 2. We describe only this partial dataset in detail here as it covers the whole X-ray C1.4 class flare. The events under study are marked by rectangles in Fig. 2.

The precursor events (numbers 1 and 2 in Fig. 2) appear simultaneously in the intensities of the He I and O V lines (hereafter frequently called "cooler lines"), at times between 08:57:41 – 09:09:30 UT and 09:21:34 – 09:32:23 UT. Only the second analyzed precursor event has clear coronal counterpart in the Si XII intensity. It starts and ends approximately 2 min later then it does in cooler lines. The main impulsive phase of the flare (number 3 in Fig. 2) occurs at the same time in the intensities of cooler lines. They exhibit rapid intensity rise starting at 09:37:40 UT, the intensity peaks at 09:42:12 UT and the fast postflare decline ending around 09:47:59 UT during this phase. The He I intensity moreover shows a period of gradual decline (not detected in the O V intensity) before it reaches the preflare quiescent level (09:58:02 UT). In the case of the Si XII spectral line the rapid intensity rise and the intensity peak appears $\sim$45 s later as compared to cooler lines and only the gradual postflare decline ending at 09:53:01 UT is visible. The peak of soft X-ray emissions, detected by the *GOES* instrument, occurs at 09:43 UT but note that the temporal resolution of the *GOES* data is only 1 min.

The He I and O V Doppler shifts exhibit upflow velocities of peak values 20.8 km s^{-1} and 28.1 km s^{-1}, respectively, during the first precursor event. The significant upflows of maximum values 56.1 km s^{-1}, 55.7 km s^{-1} and 17.0 km s^{-1} are also visible during the second precursor in the Doppler shifts of the He I, O V and Si XII lines, respectively. The relevant peak of downflow velocities followed by a peak of upflows occur in the Doppler shifts of all used spectral lines during the main impulsive phase of the flare. The maximum downflow velocities measured in the He I, O V and Si XII lines are 37.2 km s^{-1}, 53.3 km s^{-1} and 19.6 km s^{-1}, respectively, and the maximum upflow velocities are 23.6 km s^{-1}, 31.2 km s^{-1} and

[2] Details: http://solar.bnsc.rl.ac.uk/software/uguide/uguide.shmtl
[3] Details: http://solar.bnsc.rl.ac.uk/swnotes/cds_swnote_53.ps
[4] Details: http://solar.bnsc.rl.ac.uk/swnotes/cds_swnote_47.ps

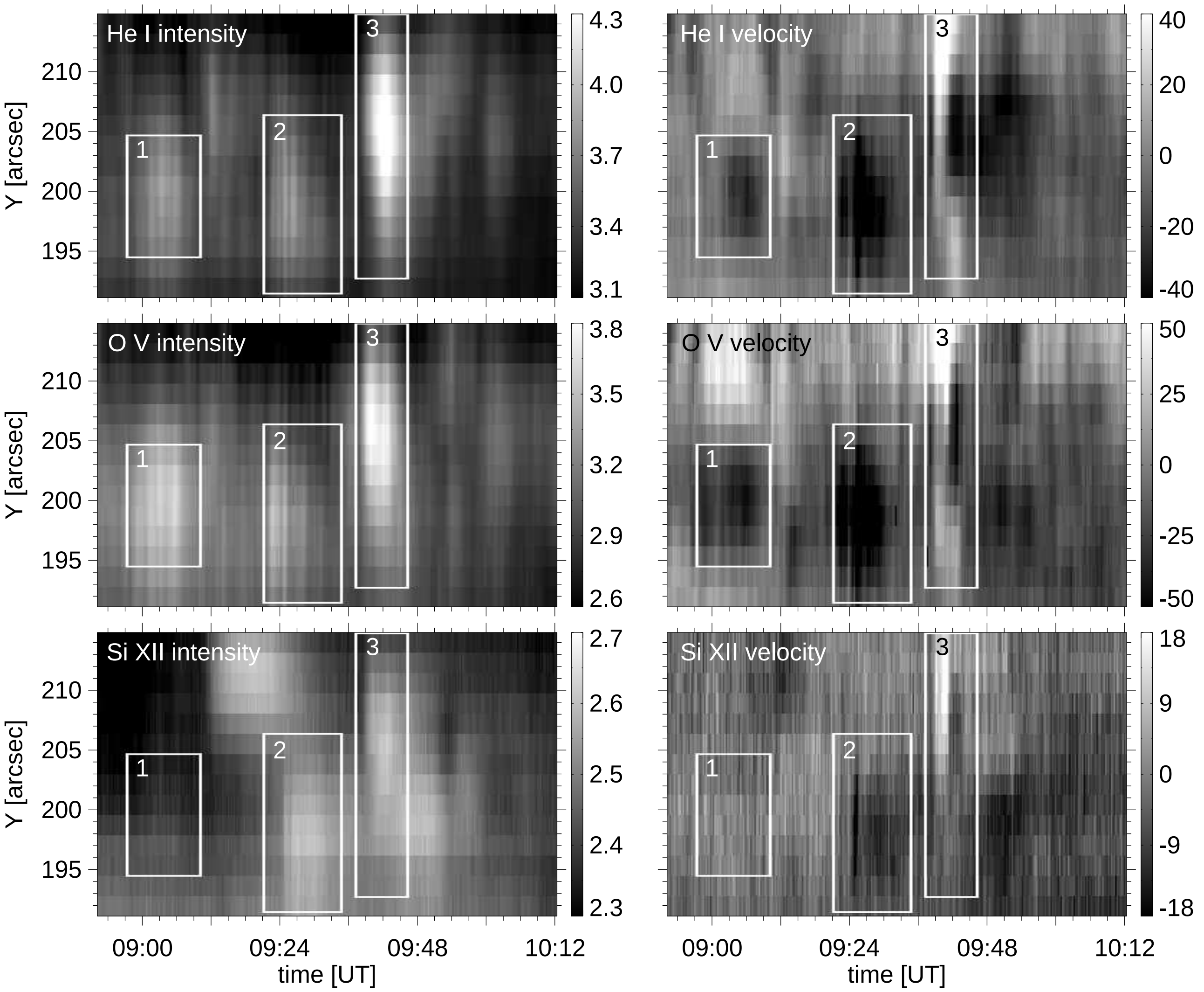

Figure 2. Time-space maps of the He I*, O* V *and Si* XII *intensities (left) and the Doppler shifts (right). The analyzed precursor events (1, 2) and main impulsive phase (3) of the flare are circumscribed by rectangles. The intensity values in* $erg\,cm^{-2}s^{-1}sr^{-1}\mathring{A}^{-1}$ *are displayed in logarithmic scale. The Doppler shifts are in* $km\,s^{-1}$*. Positive Doppler shifts correspond to downflows.*

$6.3\,km\,s^{-1}$, respectively. But similarly to behaviour of the Si XII intensity during the main impulsive phase the Doppler shifts of this line reach the maximum values ~ 45 s later as compared to cooler lines. The He I Doppler shifts show significant upflows of $\sim 20\,km\,s^{-1}$ also during the gradual intensity decline phase.

4. DISCUSSION

It was found that the main impulsive phases of the flares are frequently (but not always) preceded by precursor events which are observed in the optical, UV or X-ray part of the electromagnetic spectrum (Fárník et al, 1996). Bumba and Křivský (1959) studied precursors in Hα line and found that their typical lifetimes are in the range of 5 – 10 min and that they appear 10 – 50 min before the main impulsive phase of the flare. The duration of the two particular precursor events discussed here were 11.8 min and 10.8 min and they appeared 40 min and 16 min earlier than the main impulsive phase.

The determined time delays between the chromospheric/transition region and coronal onsets of the second precursor and the main impulsive phase and the fact that the first precursor was detected only in the cooler lines indicate that these events represent a chromospheric response to flare energy released in the corona, otherwise they would have been seen in the Si XII line first. These time delays moreover lead to the assumption that the beams of non-thermal particles were responsible for transferring the flare energy from its coronal release site to the lower parts of the solar atmosphere during discussed events. If the thermal conduction front dominated, we can again expect that the events would have been seen in the Si XII line first as the conduction front moved from the corona to lower heights. In contrast, the beams of particles are stopped much more effectively in denser chromosphere than in the tenuous corona and therefore they can deposit the energy to lower parts of the solar atmosphere without affecting the corona.

The rapid intensity rise detected in all spectral lines during the precursor events is very similar, but less intense than that observed during the main impulsive phase. Therefore, we can assume that the precursors and impulsive phase were probably caused by the same physical mechanism which however appeared on different scales. Moreover, we revealed significant upflows and the peak of downflows during the precursor events and main impulsive phase, respectively. This coincides nicely with the predictions of Fisher et al. (1985b) regarding the behaviour of the Doppler shifts during gentle and explosive evaporation. Brosius & Philips (2004) analyzed an X-ray M2 class flare observed in NOAA AR 9433 on April 24, 2001 and reported the EUV lines exhibit upflows of $\sim 40\,\mathrm{km\,s^{-1}}$ during precursor events and downflow velocities of $\sim 40\,\mathrm{km\,s^{-1}}$ during the main impulsive phase of the flare. They interpreted these results as evidence that the gentle evaporation occurred during the precursor events and the explosive evaporation during the main impulsive phase too. On the other hand, we moreover found relevant upflow velocities followed the peak of downflows during the main impulsive phase. This probably predicts that the explosive evaporation consequently changed to the gentle evaporation which could be caused by a decrease of the energy of particle beams. The slow intensity decline and the persisting upflows detected after the main impulsive phase only in the He I line support this suggestion as they can indicate the presence of the chromospheric evaporation which was too weak to affect higher parts of the solar atmosphere, i.e. ending part of the gentle evaporation.

5. CONCLUSION

Our results presented here are consistent with the theoretical and observational predictions that the gentle and explosive evaporations occur during the precursor events and main impulsive phase of the flare, respectively. We also revealed that the flare energy was probably transported form the corona to the chromosphere by the beams of non-thermal particles. But additional investigation of the possible connection among flare and the remaining events, e.g. "coronal precursor" detected in the Si XII line which had no chromospheric counterpart (Fig. 2; *time* = 09:12 – 09:24 UT, $Y = 204.7$–214.9 arcsec) and strong downflows occurred in the O V Doppler shift without any significant intensity enhancement (Fig. 2; *time* = 08:58 – 09:06 UT, $Y = 206.4$–214.9 arcsec), as well as the analysis of co-observations taken by *TRACE* instrument and *DOT* telescope are necessary for corroboration of these preliminary results.

ACKNOWLEDGMENTS

CDS is part of *SOHO*, the Solar and Heliospheric Observatory, which is a mission of international cooperation between ESA and NASA. P.G., J.R. and A.K. are grateful to the Slovak grant agency VEGA for support of this work (grant No. 2/3015/23). This research is part of the European Solar Magnetism Network (EC/RTN contract HPRN-CT-2002-00313) and part of the Marie Curie Fellowship stay at the NOVA training site (contract HPMT-CT-2001-00245).

REFERENCES

Antonucci A. and Dennis B.R., *Sol. Phys.*, Vol. 86, 67, 1983.

Bornmann P.L., in: Strong, K.T., Saba, J.L.R., Haisch, B.M., & Schmelz, J.T. (eds.) *The Many Faces of the Sun: A Summary of the Results from NASA's Solar Maximum Mission*, New York: Springer, 301, 1999.

Brosius J.W. and Phillips K.J.H., *ApJ*, Vol. 613, 580, 2004.

Bumba V. and Křivský L., *Bull. Astron. Inst. Czech.*, Vol. 10, 221, 1959.

Domingo V., Fleck B. and Ploand A.I., *Sol. Phys.*, Vol. 162, 1, 1995.

Doschek G.A., Mariska J.T. and Sakao T., *ApJ*, Vol. 459, 823, 1996.

Fárník F., Hudson H. and Watanabe T., *Sol. Phys.*, Vol. 165, 169, 1996.

Fisher G.H., Canfield R.C. and McClymont A.N., *ApJ*, Vol. 289, 414, 1985a.

Fisher G.H., Canfield R.C. and McClymont A.N., *ApJ*, Vol. 289, 425. 1985b.

Fisher G.H., Canfield R.C. and McClymont A.N., *ApJ*, Vol. 289, 434, 1985c.

Harrison R.A., Sawyer E.C., Carter, M.K., et al., *Sol. Phys.*, Vol. 162, 233, 1995.

Peter H. and Judge P.G., *ApJ*, Vol. 522, 1148, 1999.

Press W.H., Flanery B.P, Teukolsky S.A. and Vetterling W.T., *Numerical Recipes*, Cambridge University Press, Cambridge, 1986.

Silva A.V.R., Wang H., Gary D.E., Nitta N. and Zirin H., *ApJ*, Vol. 481, 978, 1997.