SOFT X-RAY HEATING OF THE SOLAR CHROMOSPHERE: GRADUAL PHASE OF A SOLAR FLARE

A. Berlicki¹, P. Heinzel² and J. Jakimiec¹

¹Astronomical Institute of the Wrocław University
ul. Kopernika 11, 51–622 Wrocław, Poland
tel: +48–71–3729374
e-mail: berlicki@astro.uni.wroc.pl

²Astronomical Institute, Academy of Sciences of the Czech Republic
25165 Ondrejov, Czech Republic
tel: +420–204–620233
e-mail: pheinz@zksl.asu.cas.cz

ABSTRACT

In this paper we present the analysis of energetics of solar flaring chromosphere heated by soft X–ray radiation coming from overlying hot flare loops. During the solar flare, a large amount of its energy is emitted from hot coronal part in soft X–ray spectral range. This radiation can penetrate into the chromosphere and transmit the energy. This additional heating modifies vertical structure of the chromosphere and it can cause the enhanced emission from some parts of the flare. Therefore, such a mechanism can be responsible for emission of chromospheric flaring structures commonly observed in Hα and other spectral lines during the gradual phases when non-thermal processes are unimportant. To analyze the effect of X-ray heating we used the observations of the solar flare of 25 September 1997. This flare was observed with the Wroclaw Multichannel Subtractive Double Pass spectrograph (MSDP) coupled with the Large Coronagraph. We also use X-ray observations of the flare taken with the SXT telescope. Within the approximation of the quasi steady-state we have calculated the deposit of X–ray energy in the chromosphere. By means of the non–LTE radiative transfer calculations we show that enhanced emission of some H-alpha structures observed during the gradual phase of this solar flare can be partially explained in terms of the soft X–ray heating of the chromosphere by hot 'post-flare' loops seen on the SXT images. We also analyzed the energy budget of X-ray heated flaring chromosphere and found that radiative losses from the chromosphere can be balanced by soft X–ray heating only in some layers of the solar chromosphere.

1. INTRODUCTION

Soft X–ray heating of the low chromosphere by radiation coming from hot coronal structures was first proposed by Jefferies (1957) and Svestka (1957). The importance of this mechanism was also demonstrated by Somov (1975) and Hénoux and Nakagawa (1977) for solar flares during strong soft X–ray emission (SXR) originated in flaring coronal loops. They have made detailed calculations of the rate of energy deposition by X–rays in chromospheric layers. They concluded that X–ray radiation must be taken into account in interpreting the modification of the solar chromosphere during a flare and that the SXR heating predominates in low temperature part of the chromosphere. Machado (1978) analyzed observational evidence of SXR heating in upper and lower chromosphere and found that photons of the X–ray band 0.8–1.2 nm release their energy probably just in the Hα–forming region. The SXR heating is now routinely included into the flare modelling (Fang and Hénoux 1983; Hawley and Fisher 1992). In all published papers there is wide agreement, that soft X–ray radiation plays an important role in the heating of the solar chromosphere. Nevertheless, there was no detailed analysis of the SXR heating based on observations of some parts of flaring structures performed in X–ray as well as in some chromospheric lines (for example, in Hα line). In our paper we study gradual phase of one solar flare. Analysis of the Hα spectral images taken with MSDP and soft X–ray images recorded with Yohkoh SXT telescope allow us to determine the rate of the soft X–ray energy deposition in the chromosphere within some parts of flare ribbons. In order to calculate energy budget in analyzed structures we calculate simple chromospheric models for all the structures and then determine net radiative losses.

2. OBSERVATIONS OF THE FLARE

The C7.2 class solar flare was observed in the active region NOAA 8088 on 25 September 1997. At 12:00 UT this active region was located roughly 29 degrees to the south from the equator, passing across the central meridian. Hα observations of the active region were
performed using the Multi Channel Subtractive Double Pass Spectrograph (MSDP) coupled with the Large

![Image](image1.png)

Figure 1. Image of the flare taken in the centre of Hα line with MSDP spectrograph at 12:42 UT overplotted by the SOHO/MDI magnetogram taken at 08:00 UT (a). The thick white contours correspond to positive polarity magnetic field while the thin contours to negative polarity magnetic field. Labelled structures are described in the main text. Below (b) the SXT image of the loops recorded at 12:38 UT with A1.1 filter and overplotted contours of the sunspots observed at 12:45 UT. Labelled structures are described in the main text.

Coronagraph and the Horizontal Telescope of the Wrocław University (Rompolt et al., 1994). During the flare between 11:50:31 and 12:42:48 UT, we obtained 14 full scans (Hα images) covering decay phase of the flare. The data were processed in standard way (Mein, 1991). The times of the MSDP observations cited below correspond to the beginning of the appropriate scan. The spatial resolution of the obtained images was limited by seeing, on the average it was about 1 arcsec, but occasionally it was worse.

At 11:50 UT the first strong increase of Hα emission was observed in an MSDP image. The Hα flare emission was concentrated mainly in seven brightenings (see Figure 1a). Four of them were located in eastern part of the active region close to the cluster of the following spots, FS. Other three flare brightenings were situated in the north–east direction from the leading spot, LS. The leading spot and the flare kernels KA, KB, KC and KD were located inside the area of negative–polarity magnetic field (NPMF) while the group of following spots and kernels KE, KF and KG in the positive polarity magnetic field (PPMF) (see Figure 1a). During the flare the kernel KA partially covered the leading spot umbra. Detailed description of the Hα evolution of the active region NOAA 8088 before the flare and development of the flare was presented by Falewicz and Rudawy (1999).

From the X-ray flux curve recorded by GOES 9 satellite it follows that the flare started at 11:43 UT, reached maximum at 11:49 UT and decayed until 14:00 UT. Images of the flare taken with the SXT telescope with B119 filter show two big, parallel loops, L1 and L2, rooted between the leading spot and the eastern group of following spots (see Figure 1b). Another X-ray loop L3 was probably located below L1 and L2 loops. Its eastern footpoint was anchored as well as inside the PPMF area in the group of following spots, the western end of L3 loop was rooted about 25 000 km to the west side from the leading spot inside the NPMF area. Comparison of the Hα filtergrams with SXT images showed that footpoints of hot loops were situated close to the observed flare kernels. The loops L1 and L2 spanned the KA, KB and KE Hα flare kernels, while the loop L3 spanned the kernels KC and KG (see also Figure 1a).

3. SOFT X-RAY ENERGY DEPOSIT IN FLARING CHROMOSPHERE

For analysis of SXR heating we chose three small areas, A, B and C located in the chromosphere close to the observed SXR loops footpoints (see Figure 2 and 3).

![Image](image2.png)

Figure 2. Hα Image of the active region with marked areas A, B and C used in analysis of soft X–ray heating and overplotted SXT contours of the X–ray loops observed at 12:06:26 UT.

Using such location of we can apply plane–parallel approximation in the modeling of the solar chromosphere. Analysis of MSDP spectral images
allowed us to obtain the mean Hα line profiles in those areas (see Figure 4, upper row).

Figure 3. SXT image of flare loops and boxes A, B and C representing the areas chosen for analysis of soft X-ray heating.

We performed our analysis during decay phase of the flare for two moments of time at 12:05:52 UT and 12:18:15 UT. Calculating a grid of synthetic Hα line profiles we found the best fit between observed and calculated profiles. In this way we obtained non-LTE models of the solar chromosphere for each area A, B and C. The distributions of the temperature for these models are presented in Figure 4 (lower row). In our calculations we used the non-LTE code for solar chromosphere developed by Heinzl (1995).

On the basis of SXR observations made through two filters we calculated the mean emission measure EM and temperature T within areas A, B and C. These parameters were used in the calculation of the soft X-ray energy deposited in the vicinity of analyzed areas. Detailed description of used methods was presented by Henoux and Nakagawa (1997) and by Heinzl and Berlicki (2002). In Figure 5 we present the SXR energy deposition for the calculated models of the solar chromosphere within areas A, B and C. We also show net radiative cooling rates (NRCR) for these models.

Figure 4. Mean Hα line profiles (upper row) observed in areas A, B and C at two times: solid line—12:05:52 UT, dashed line—12:18:15 UT. We also plotted Hα line profile (QS) emitted from the quiet sun chromosphere. The curves plotted below (lower row) represent temperature distribution corresponding to the chromospheric models calculated for analyzed areas at two times. For comparison we also plotted temperature distribution for VAL3C model of the quiet chromosphere.
Figure 5. Soft X-ray energy deposited in the solar chromosphere within areas A, B and C at $t_1$ and $t_2$ – solid lines, and net radiative cooling rates calculated for the chromospheric models corresponding to analyzed areas – dashed curves. We also plot for comparison net radiative cooling rates for VAL3C model of quiet chromosphere – marked with "VAL".

4. CONCLUSIONS

In Figure 5 the following functions are shown for several models of the flaring chromosphere ([Z] is the height above the photosphere):
1. The soft X-ray energy deposition (the lower solid curves), 2. The net radiative cooling rates (NRCR—the dashed curves), 3. The net radiative cooling rates for the model of quiet–chromosphere VAL3C are also shown for comparison (the solid curve "VAL").

We can see that in general the X-ray energy deposition is much lower than NRCR. Only for the layers $Z \approx 750$ km in some models (see model [B, t_1]) the X-ray energy deposition can provide a significant contribution to the NRCR. Kasarova and Heinzel (2002) showed that in flaring chromosphere central part of H\alpha line emission arise mainly in its upper layers ($Z \geq 1100$ km). Therefore, SXR heating cannot explain bright H\alpha emission as was observed in the investigated areas A, B and C. Nevertheless, in other flares there is a possibility that SXR heating can provide enough energy to explain enhanced H\alpha emission Berlicki (2002).

REFERENCES