

Sizes of flaring kernels in various parts of the $H\alpha$ line profile

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Abstract. In this paper we present new results of spectrophotometrical investigations of the flaring kernels' sizes and their intensities measured simultaneously in various parts of the $H\alpha$ line profile. Our investigations were based on the very high temporal resolution spectral-imaging observations of the solar flares collected with Large Coronagraph (LC), Multi-channel Subtractive Double Pass Spectrograph and Solar Eclipse Coronal Imaging System (MSDP-SECIS) at Biłków Observatory (University of Wrocław, Poland).

We have found that the areas of the investigated individual flaring kernels vary in time and in wavelengths, as well as the intensities and areas of the $H\alpha$ flaring kernels decreased systematically when observed in consecutive wavelengths toward the wings of the $H\alpha$ line. Our result could be explained as an effect of the cone-shaped lower parts of the magnetic loops channeling high energy particle beams exciting chromospheric plasma.

Keywords. Solar physics, astrophysics, and astronomy (Energetic particles; Magnetic fields; Photosphere and chromosphere)

1 Introduction

Solar flares have been investigated for more than a century, nevertheless some very important questions still remain unanswered. One of them is a problem of very fast heating of a relatively dense and cold chromospheric plasma by charged particles streaming down along flaring loops from primary energy sources located somewhere close to the tops of the loops and – to some extent – by conduction and by electromagnetic radiation. The accelerated particles travel with nearly relativistic speeds and collide with the chromosphere in fractions of seconds after their release.

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Satellite-born observations made in the hard X-ray domain of the spectrum clearly reveal that primary regions of the magnetic energy conversion are located high in the corona. There are also secondary hard X-ray sources, located near the feet of the flaring loops (so-called “foot-point HXR sources”). The co-temporal observations made in visible wavelengths (like in hydrogen $H\alpha$ line, 656.3 nm) usually reveal numerous bright compact and/or extended emission sources localized in the closest vicinity of the foot-point HXR sources. The high time resolution observations of the visible flaring kernels show that their intensities undoubtedly vary in time.

It is commonly accepted that due to the fast change in the magnetic β parameter between the lower corona and photosphere, the chromospheric parts of the magnetic loops (for example, channeling high energy particle beams exciting chromospheric plasma in the course of the flares), should be roughly cone-shaped (e.g. Gabriel, 1976; Foukal, 1990; Stix, 1989; Aschwanden, 2006). Unfortunately, the very strong and variable in time deformations of the apparent shape of the tiny solar structures caused by highly variable atmospheric seeing, as well as a necessity of the simultaneous 2-D observations in numerous wavelengths, made the observational proof of this assumption very challenging. Taking advantage of the unique parameters and abilities of the MSDP spectrograph we made an attempt to record directly the sizes of the $H\alpha$ flaring kernels simultaneously in numerous wavelengths of the line profile. While various parts of the $H\alpha$ line are formed on different depths in the chromosphere (Vernazza et al., 1973, 1981), even taking into account all obvious factors connected with heterogeneous vertical structure of the plasma, its strong turbulence, etc., the emission recorded in a particular part of the line profile could be used for at least a crude determination of the precipitation depth of the non-thermal electrons, as well as for the evaluation of the size of the emitting region.

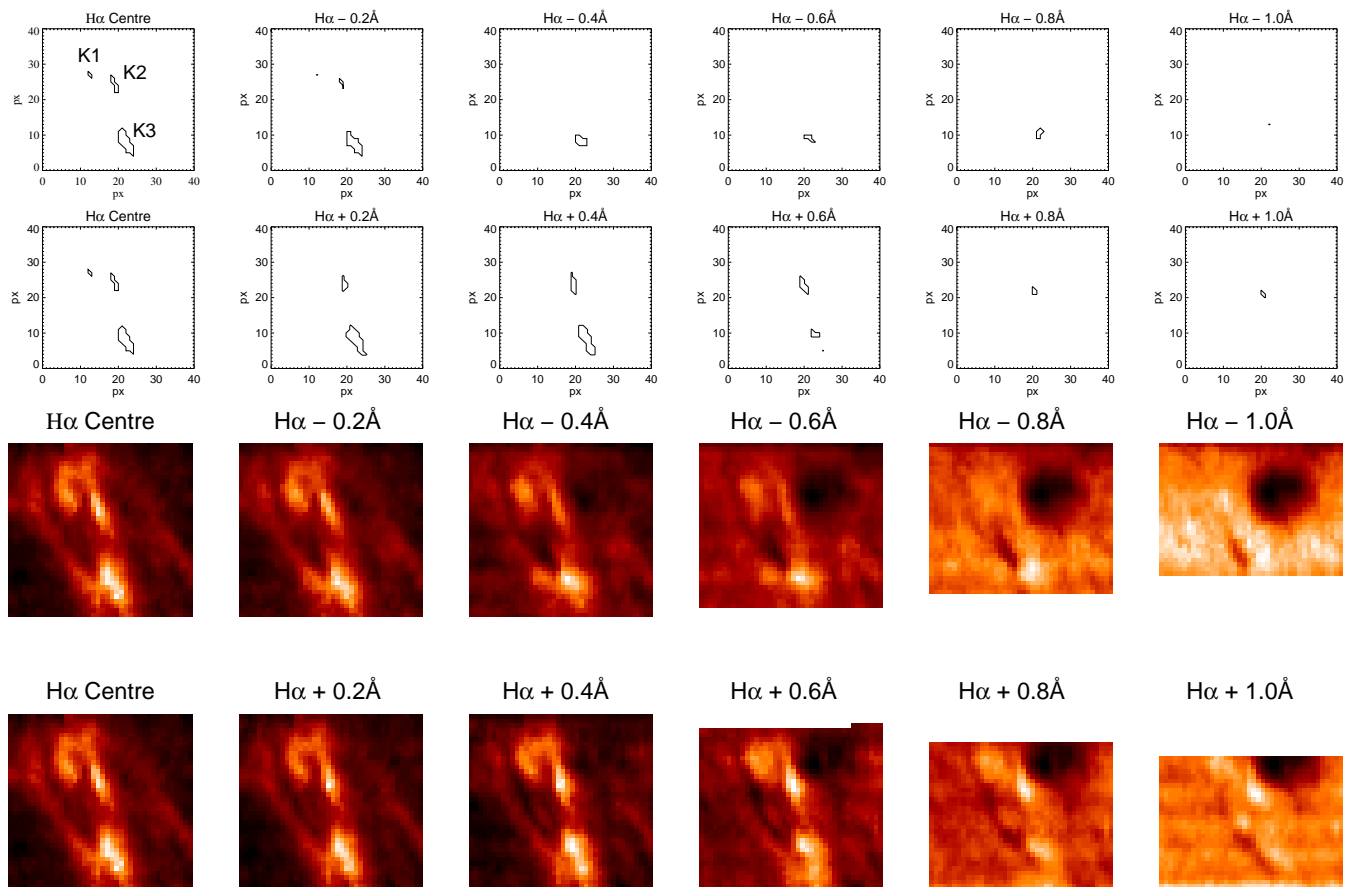


Fig. 1. C1.2 class solar flare observed in NOAA 10410 active region at 16:03:45 UT on 16 July 2003. Upper panel: sizes and shapes of the flaring kernels K1, K2 and K3 delimited with isophote on the level of 75% of the net maximum brightness of the kernel. Lower panels: 2-D quasi-monochromatic images of the observed flaring kernels, obtained simultaneously in various wavelengths. See main text for details.

The observational data and data reduction are described in Sect. 2 while the results are presented in Sect. 3 and discussion of the results in Sect. 4.

2 Observations and data reduction

The $H\alpha$ spectra-imaging observations of the flaring kernels were collected with the Large Coronagraph (LC) equipped with MSDP and Solar Eclipse Coronal Imaging System (SECIS) at the Białków Observatory of the University of Wrocław. The LC has a 53-cm diameter main objective, its effective focal length is equal to 1450 cm. Spatial resolution of the instrument, usually limited by visual conditions, is about 1 s of the arc. During windy days the LC, which is very susceptible to gusts was replaced by our Horizontal Telescope with a compact Jensch-type coelostat, with the main objective of the aperture of 15 cm and the focal length of 5 m. The MSDP spectrograph has a rectangular (2-D) entrance window, which covers an equivalent area of $325 \times 41 \text{ arcsec}^2$ on the Sun (Mein, 1991; Rompolt et al., 1994) and creates

$H\alpha$ spectra for all pixels inside the field of view simultaneously.

The MSDP spectrograph has a nine-channel prism-box, giving (for each pixel of the field of view) nine intensities in the $H\alpha$ line-profile bandwidth range, separated by 0.4 \AA . Next, the continuous $H\alpha$ profiles are interpolated typically in the range of $\pm 1.2 \text{ \AA}$ from the line center. Due to the basic optical properties of the MSDP-type spectrographs, the actual range of the band-width of the restored profiles depends on the location of the pixels in the frame of the field of view and thus decreases slightly toward the edges of the images (this effect is well visible in Figs. 1, 3 and 5). On the basis of the restored $H\alpha$ line profiles the quasi-monochromatic images were reconstructed in freely-chosen wavelengths in the line-profile bandwidth range (e.g. separated in wavelengths by 0.2 \AA from each other as in the present work). The spectra-images created by the spectrograph were recorded with the fast CCD camera of SECIS ($512 \times 512 \text{ px}^2$, $1 \text{ px} = 1 \text{ arcsec}^2$, up to 70 images per second) (Phillips et al., 2000; Rudawy et al., 2004). Thus the MSDP spectrograph with SECIS is

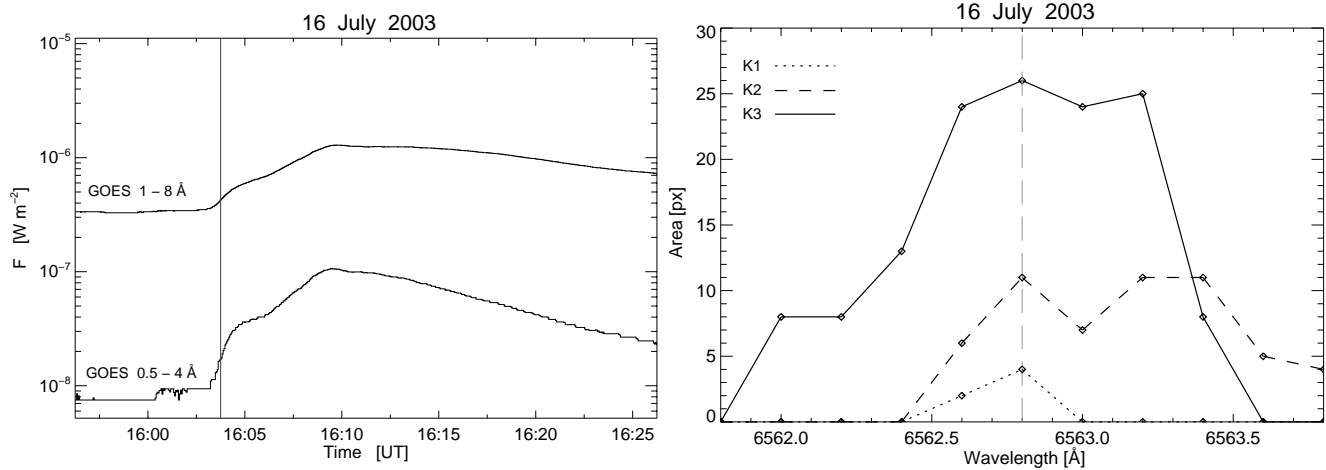


Fig. 2. Areas of the K1, K2 and K3 flaring kernels of the C1.2 class solar flare at 16:03:45 UT on 16 July 2003. Left panel: X-ray GOES fluxes in 0.05–0.4 nm and 0.1–0.8 nm bands recorded during the flare. The vertical line marks 16:03:45 UT. Right panel: areas of the K1, K2 and K3 flaring kernels (in pixels) measured simultaneously in various wavelengths in a frame of the $H\alpha$ line profile (up to $\pm 1.0 \text{ \AA}$ from the $H\alpha$ line center). The vertical dashed line points the $H\alpha$ line center.

very suitable for studies of the fast variations of the spectral line profiles emitted by individual $H\alpha$ flaring kernels or investigations of the solar structures observed simultaneously in various wavelengths and can be a very valuable source of the observational data for modeling of the sub-second flaring processes (Heinzel, 2003).

In a course of three observational seasons 2003–2005 we recorded data for almost forty solar flares. For each event we recorded 10 or 20 thousand spectra-images with time resolution freely selected between 0.04 s (25 images per second) and 0.075 s (slightly more than 13 images per second) – depending on the intensity of the light beam. More detailed information concerning the MSDP-SECIS system and data reduction are available in papers by Radziszewski et al. (2006) and (2007).

As a result of the numerical reduction of the collected spectra-images of each particular flare we obtained a series of 10 or 20 thousand of “data-cubes”, consisting of thirteen two-dimensional, quasi-monochromatic images (band-width equal to 0.06 \AA), separated in wavelengths by 0.2 \AA . Due to the actual localizations of the investigated flaring kernels in the frames of the fields of views, we decided to present the restored profiles consistently for all flares up to $\pm 1.0 \text{ \AA}$ from the $H\alpha$ line center only.

The collected data allow us to investigate local temporal variations of the $H\alpha$ emission and Doppler-shifts of the emitting material. The temporal variations of the obtained $H\alpha$ data (profiles, intensities, areas of the emitting kernels, etc.) were compared with temporal variations of the X-ray fluxes recorded with Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and also with X-ray photometers on board the GOES satellites. Our observations, based on high

cadence spectra-imaging spectrograph MSDP and RHESSI satellite data, have confirmed the high temporal correlation between HXR and $H\alpha$ emissions for several solar flares (see Radziszewski et al., 2006, 2007, and references therein).

From among almost forty events observed with LC-MSDP-SECIS or HT-MSDP-SECIS systems we have chosen for this work three small and medium GOES class events, observed from the beginning of the soft X-ray flux increase and having well separated, individual flaring kernels. The quality of the selected data was among the best from all collected (stable pointing of the telescope as well as good seeing and weather conditions). The selected data include: C1.2 class solar flare observed in NOAA 10410 active region at 16:10 UT on 16 July 2003 (Figs. 1 and 2); B2.5 class solar flare in NOAA 10603 active region observed at 07:26 UT on 3 May 2004 (Figs. 3 and 4) and C8.3 class solar flare in NOAA 10786 active region observed at 08:03 UT on 12 July 2005 (Figs. 5 and 6).

3 Results of the observations

After standard photometrical and geometrical processing of the raw observational data we established locations, sizes, areas and the brightness of the numerous flaring kernels observed simultaneously in various wavelengths (in a frame of the $H\alpha$ line profile up to $\pm 1.0 \text{ \AA}$ from the $H\alpha$ line center). It is crucial and obligatory to stress that all photometrical and geometrical parameters of the kernels were evaluated strictly at the same moment for all wavelengths (i.e. between each other, under exactly the same influence of the observed, which could also be considered as wavelength independent of a whole profile of a single spectral line). In Figs. 1, 3 and 5

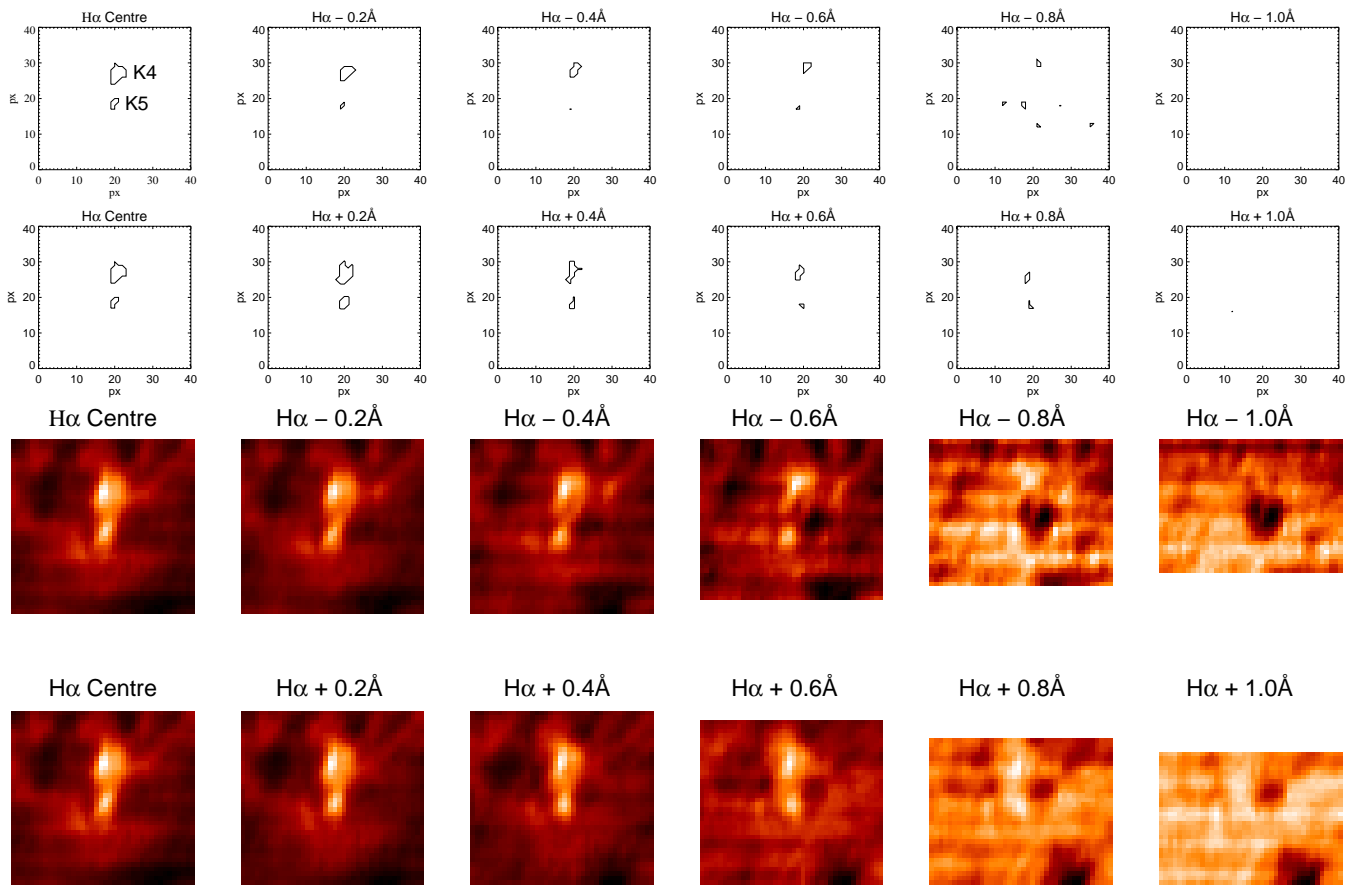


Fig. 3. B2.5 class solar flare (kernels K4 and K5) in NOAA 10603 active region observed at 07:24:33 UT on 3 May 2004. The upper and lower panels are the same as on Fig. 1.

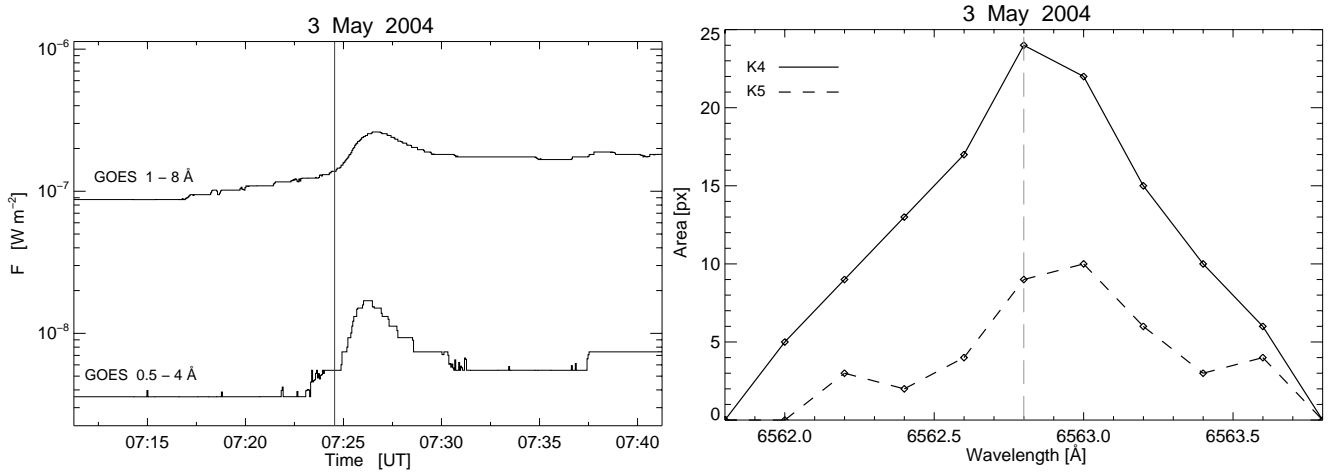


Fig. 4. Areas of the K4 and K5 flaring kernels of the B2.5 class solar flare at 07:24:33 UT on 3 May 2004. The left and right panels are the same as on Fig. 2.

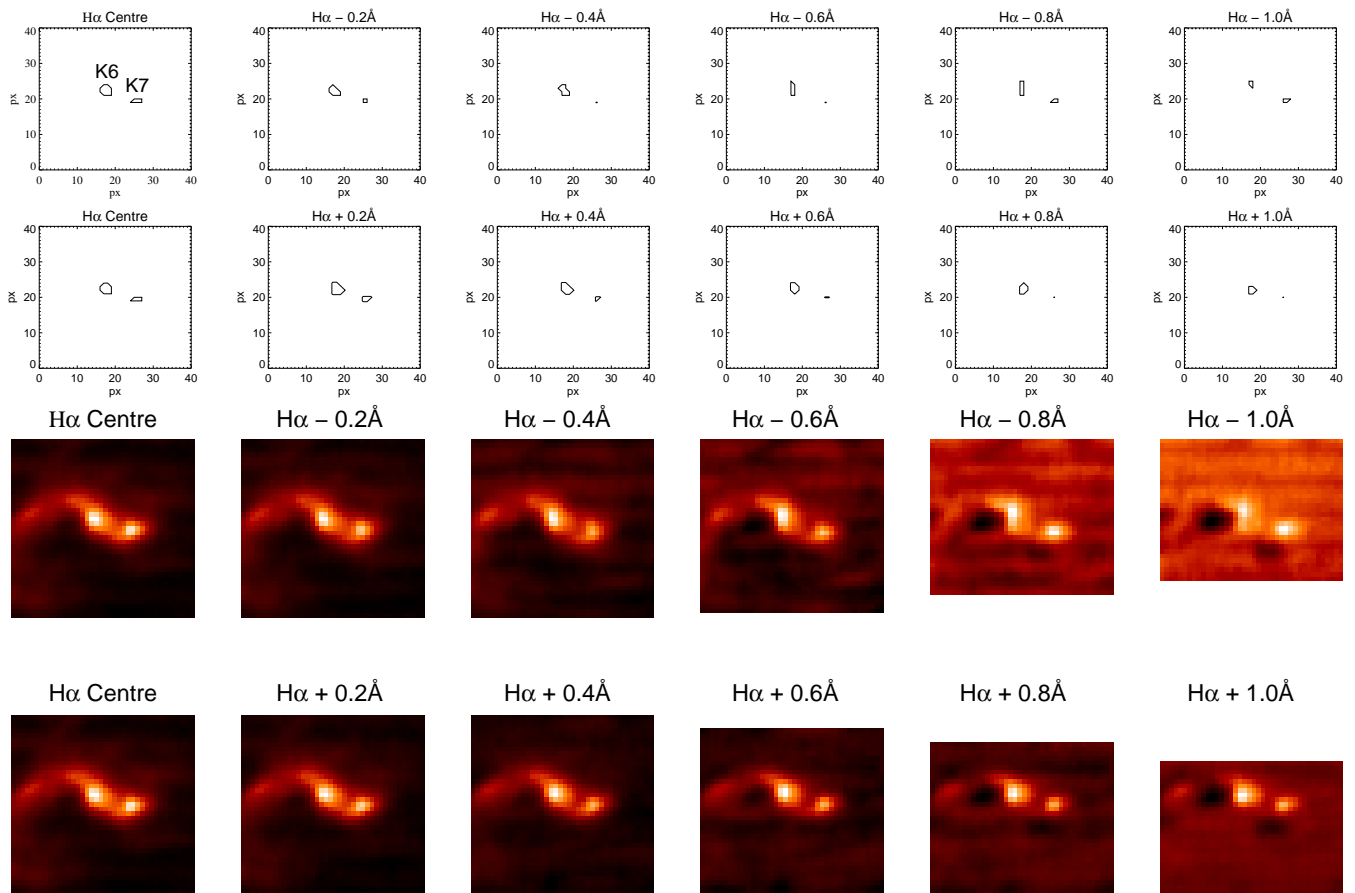


Fig. 5. C8.3 class solar flare (kernels K6 and K7) in NOAA 10786 active region observed at 08:01:22 UT on 12 July 2005. The upper and lower panels are the same as on Fig. 1.

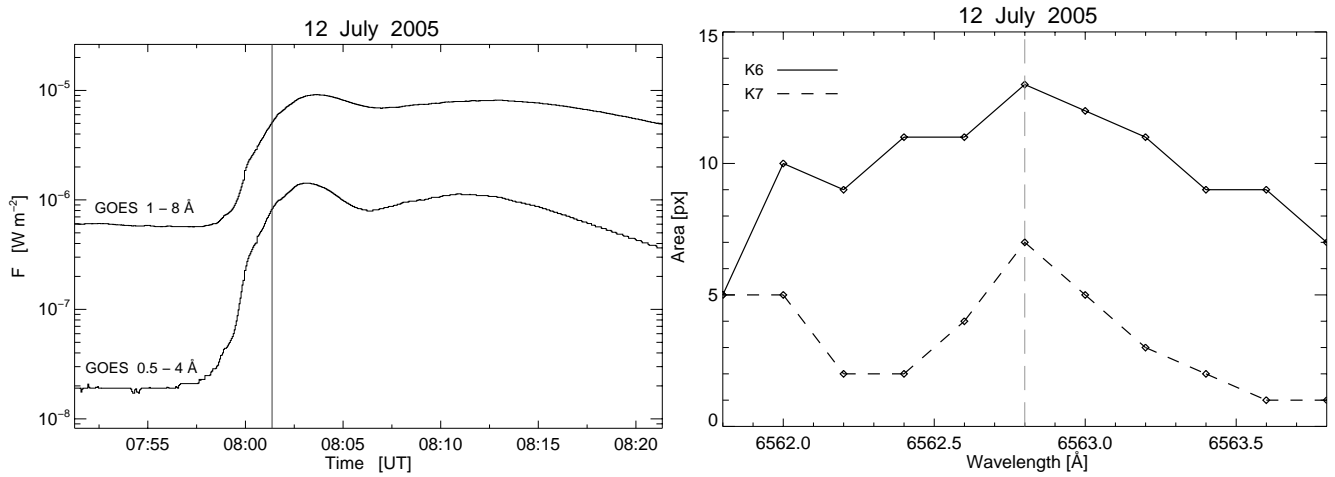


Fig. 6. Areas of the K6 and K7 flaring kernels of the C8.3 class solar flare at 08:01:22 UT on 12 July 2005. The left and right panels are the same as on Fig. 2.

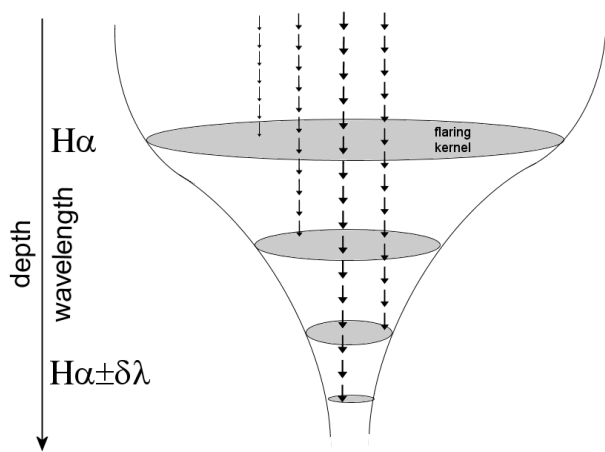


Fig. 7. Plasma located on various depths in the lower part of the magnetic loops is excited and heated by non-thermal electrons of various energies. Due to the cone-shaped lower part of the loop, the actual size of the flaring kernel will depend on the wavelength in a frame of the $H\alpha$ line profile.

there are 2-D quasi-monochromatic images presented of the selected flaring kernels, obtained simultaneously in various wavelengths and (as a contour maps) sizes and shapes of the flaring regions, delimited with an arbitrary selected isophote on the level of 75% of the net maximum brightness of the kernel (the intensity of the brightest pixel of the evaluated kernel minus the mean emission of the adjacent quiet chromosphere). We checked various methods of determination of the kernels' sizes in various wavelengths. According to us, the applied method is the most stable and reliable, especially for long series of data, taken under circumstances of variable atmospheric transmittance and observing. We also checked brightness distributions of the investigated kernels and we did not reveal any local strong increases of brightness, which could cause false estimations of the kernel sizes.

After evaluation of whole series of data (usually covering a period of 8–10 min of the flare) we have found that:

- the most significant changes in emission were detected during the early phases of the flare, when high-energy particles beams hit the chromosphere;
- the sizes of the flaring kernels (area or equivalent radius defined as a radius of the circle having the same area as irregular surface) of the investigated flares are the greatest when measured on images taken in the $H\alpha$ line center or in wavelengths close to the line center;
- the effect of the decrease of the kernels' areas in $H\alpha$ line wings was also detected for a series of consecutive images taken during the increase phases of the flares;
- the sizes of the flaring kernels decreased significantly and systematically when measured on images taken (at

exactly the same moment) in increased distances from the line center toward the line wings (see Figs. 2, 4 and 6), i.e. to some extent, toward the deeper layers of the chromosphere (see Fig. 7). Most of the kernels show roughly a symmetrical decrease in the visible areas in increased distances from the line center (kernels K1, K3–K7); one kernel only (K2) shows a very asymmetrical decrease in the visible areas (it shrank and disappeared much faster when observed in the blue wing of the $H\alpha$ line than in the red one). One can also notice a slight increase in the area of the K7 kernel observed in the far blue wing of the $H\alpha$ line.

The effect of the decrease in the flaring kernels sizes was investigated by us only for faint and mid-class solar flares, while in such flares the individual flaring kernels could be easily identified and measured.

4 Discussion

Taking advantage of the unique parameters and abilities of the MSDP spectrograph we recorded on each spectra-image directly the sizes of the $H\alpha$ flaring kernels in numerous wavelengths of the $H\alpha$ line profile simultaneously, with very short exposure time (0.04–0.075 s) and under exactly the same influence of the atmospheric observation. We have found that the sizes of the flaring kernels are greatest when measured on images taken in the $H\alpha$ line center and decreased significantly when measured on images taken in increased distances from the line center toward both line wings (see Figs. 2, 4 and 6, right panels).

Due to the very heterogenous vertical structure and obvious strong turbulence of the plasma located in the feet of the flaring loop, fast bulk motions of the plasma caused by chromospheric evaporation processes it is not a straight, time independent and linear dependent between wavelengths and depth. Nevertheless, our observational results, obtained for numerous flaring kernels of the faint and mid-class solar flares could be caused by a cone-shape of the lower parts of the magnetic loops channeling particle beams exciting chromospheric plasma (see diagram on Fig. 7).

In this work we presented in detail the results obtained for seven flaring kernels observed in three solar flares only. A brief inspection of the observations taken during the other ten flares of various GOES classes (B and C), recorded during less favorable observing conditions and having lower overall quality, revealed qualitatively the same effect. However, the effect was not detected by us in the strong X3.8 flare observed on 17 January 2005, having bright and extended flaring structures. Such strong flares (especially X class events) seem to be not sufficient for our investigations, due to the lack of well separated, individual kernels.

As a next step in our work we plan to investigate spatial displacements of the emission arriving co-temporary from the same kernel but in various wavelengths and temporal

changes of kernel positions (their centroids) observed in selected wavelengths (e.g. blue wing) of the H α line, as was already reported by Ji et al. (2004).

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