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## SPECTRAL STUDY LOWER SOLAR ATMOSPHERE OF THE ACTIVE REGION SITE WITH THE ELLERMAN BOMB AND ACCOMPANYING H $\alpha$ -EJECTIONS

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**ABSTRACT.** The results of studying in details the features formation and development of the Ellerman bomb (EB) and accompanying H $\alpha$ -ejections arose on the NOAA 11024 active region site, are presented. This site was in the region of emerging new magnetic flux. Spectral data with high spatial and temporal resolution were obtained with the French–Italian solar telescope THEMIS on July 4, 2009. Spectra with the H $\alpha$  line and with the spectral region  $\lambda\lambda \approx 630$  nm were used. Stokes I profiles were obtained with an interval corresponding to 160 km on the Sun surface.

The H $\alpha$  line profiles obtained for different periods of EB development were asymmetric with an excess of emission in the short-wavelength wing. The temporal variations of intensity in the H $\alpha$  line wings at distances  $\pm 0.1$  and  $\pm 0.16$  nm from its center indicated that two periods can be distinguished in EB evolution: the preheating phase and the flaring phase, during which the gradual and pulse energy release occurred.

H $\alpha$ -ejections (surges) are small-scale eruptions of cold matter in the solar atmosphere. In all spectra they were visible in the absorption. The surge profiles were projected onto the blue or red H $\alpha$  line wing. Its Doppler shifts were used to calculate the line-of-sight velocities ( $V_{\text{los}}$ ) of chromospheric matter in surges. The velocity distribution in the surges indicated their multi-flow structure. One of the surges showed signs of plasma vortex motions. Most surges occurred with a high velocity –  $V_{\text{los}}$  up reached -110 km/s, and down to 90 km/s.

We obtained temporal  $V_{\text{los}}$  variations in a wide interval (140 – 490 km) of photospheric heights for the area of EB development and its immediate surroundings. At all photospheric levels predominantly upward motions were found. In the central part of the EB in the upper layer of the photosphere the  $V_{\text{los}}$  varied between  $-0.5 \div 0.2$  km/s, in the lower layer –  $-1.1 \div -0.1$  km/s. An increase the core intensity of all photospheric lines was correlated in time with an increase of the emission intensity in the H $\alpha$  line wings.

The new observational data for the Ellerman bomb and accompanying H $\alpha$ -ejections, which have been obtained and analyzed, can be used to verify existing and create new theoretical models.

**Keywords:** Sun, chromosphere, photosphere, Ellerman bomb, surges, line-of-sight velocities.

**АНОТАЦІЯ.** Представлено результати детального вивчення особливостей формування та розвитку бомби Еллермана та супутніх їй H $\alpha$ -викидів, що виникли на ділянці активної області NOAA 11024. Ця ділянка знаходилася в області появи нового магнітного потоку. Спектральні дані з високою просторовою і часовою роздільною здатністю було отримано на французько-італійському сонячному телескопі THEMIS 4 липня 2009 року. Ми використали спектри з H $\alpha$ -лінією (центральна частина) та з спектральною областю  $\lambda\lambda \approx 630$  нм. Профілі Стокса I було отримано з інтервалом, що відповідає 160 км на поверхні Сонця.

Профілі лінії H $\alpha$ , отримані для різних періодів розвитку БЕ, були асиметричними з надлишком емісії в короткохвильовому крилі. Зміни інтенсивності в крилах лінії H $\alpha$  на відстанях  $\pm 0,1$  і  $\pm 0,16$  нм від її центру вказували на те, що в еволюції БЕ можна виділити два періоди: фазу попереднього нагріву і спалахову фазу, під час яких відбувалося поступове та імпульсне виділення енергії.

H $\alpha$ -викиди (сьоржі) це невеликі виверження холодної речовини в сонячній атмосфері. На всіх спектрах їх видно в поглинанні. Профілі сьоржей проектувалися на синє або червоне крило лінії H $\alpha$ . Їх доплерівські зсуви було використано для розрахунку променевої швидкості ( $V_{\text{пром}}$ ) хромосферної речовини в сьоржах. Розподіл швидкостей у сьоржах свідчить про їх багатопотокову структуру. Один зі сьоржів мав ознаки руху плазмового вихру. Більшість сьоржів з'являлися з великою швидкістю –  $V_{\text{los}}$  вгору досягала -110 км/с, а донизу – до 90 км/с.

Ми отримали часові варіації  $V_{\text{пром}}$  у широкому інтервалі (140 – 490 км) фотосферних висот для області розвитку БЕ та її околиці. На всіх рівнях фотосфери виявлено, переважно, висхідні рухи. У центральній частині БЕ у верхньому шарі фотосфери  $V_{\text{los}}$  коливалася в межах  $-0,5 \div 0,2$  км/с, у нижньому шарі –  $-1,1 \div -0,1$  км/с. Збільшення інтенсивності в ядрах всіх фотосферних ліній корелювало в часі зі збільшенням інтенсивності емісії в крилах лінії H $\alpha$ .

Нові дані спостережень для бомби Еллермана та супутніх їй H $\alpha$ -викидів, які було отримано і проаналізовано, може бути використано для перевірки

існуючих і створення нових теоретичних моделей.

**Ключові слова:** Сонце, хромосфера, фотосфера, бомба Еллермана, сьоржі, променеві швидкості.

## 1. Introduction

Among the many manifestations of solar activity, such fine scale, short and impulsive events as Ellerman bombs and chromospheric ejections play an important role. They arise in the lower solar atmosphere as a result of magnetic reconnection processes during the interaction between the new emerging magnetic flux and the already existing magnetic field. Such small-scale magnetic reconnections can affect the energy balance of the solar chromosphere – they effectively help inject dense plasma into the upper atmosphere. EBs are often accompanied by small, short-term chromospheric surges (Fang et al., 2006). Since their dynamics is the movement of plasma along the force lines of the magnetic field, surges are useful for studying the structure of the magnetic field and its changes. Many articles emphasize the importance of detailed studies into the formation and development of individual chromospheric structures such as EBs and H $\alpha$ -ejections based on observational data with high spatial and temporal resolution. Also, special attention should be paid to how these dynamic phenomena interact with each other (Nelson et al., 2013).

## 2. Observational material

Spectropolarimetric observations of the active region NOAA 11024 were carried out with the telescope THEMIS on Tenerife (Canary Islands) on 4 July 2009. Spectral data with high spatial (below 1 arcsec) and temporal (about 3 seconds) resolution were obtained. During observations from 9<sup>h</sup>52<sup>m</sup>35<sup>s</sup> to 10<sup>h</sup>11<sup>m</sup>26<sup>s</sup>, 400 spectra were obtained. We used two spectral regions, containing the chromospheric line H $\alpha$  (central part) and the photospheric lines FeI  $\lambda$  630.15, 630.25, 630.35 nm, and the TiI  $\lambda$  630.38 nm. Figure 1 presents H $\alpha$  spectrum. The field of THEMIS vision is divided into three parts. The spectrum number and the time it was received are given. The position of the EB (two long

emission bands in the H $\alpha$  line wings), pore and surges (dark details) that existed on the site at that time are indicated. The site which we are investigating is marked L1, its length was 10 Mm. It was located in the region of the emerging a new magnetic flux in the form of a serpentine magnetic field (Valori et al., 2012). The AR site without active formations and located outside the region of the emerging magnetic flux is marked L2. The availability of this site spectrum gave us an opportunity to study the changes that took place in the solar atmosphere at the L1 site under the influence of the developing EB and chromospheric surges.

## 3. Ellerman bomb

### 3.1. Chromosphere

The spectra were used to obtain Stokes I profiles of H $\alpha$  line with an interval corresponding to the distance of 160 km on the Sun's surface. Figure 2 shows the H $\alpha$  line profiles for the EB central part with the maximum emission intensity increase in the blue wing up to 73% (profile 1) and in the red wing up to 35% (profile 2), which occurred at a distance of approximately  $\pm 0.16$  nm from the line core. For comparison, profile 3 for section L2 is shown. The work (Pasechnik, 2021) detailed the features of the EB development during our observations. Figure 3 shows temporal variations of the emission intensity (EB light curves) in the short-wave (blue curve) and long-wave (red curve) H $\alpha$  line wings at distances of  $\pm 0.16$  nm from its center for the EB central part. The numbers indicate the moments of intensity peaks. Two periods can be distinguished from the obtained EB light curves. The first period, during which the intensity changed little, lasted approximately 8 min (9:57:05 – 10:05:21 UT). It consisted of three intensity peaks with a time interval of 1 min 45 sec. The second period of approximately 6 min (10:05:21 – 10:11:26 UT), during which EB brightness was increasing, consisted of five intensity peaks (interval  $\sim 1$  min). The light curves of the studied EB obtained in this work show that we observed two phases of its evolution: the preheating phase and the flaring phase, during which the gradual and pulse energy releases occurred.

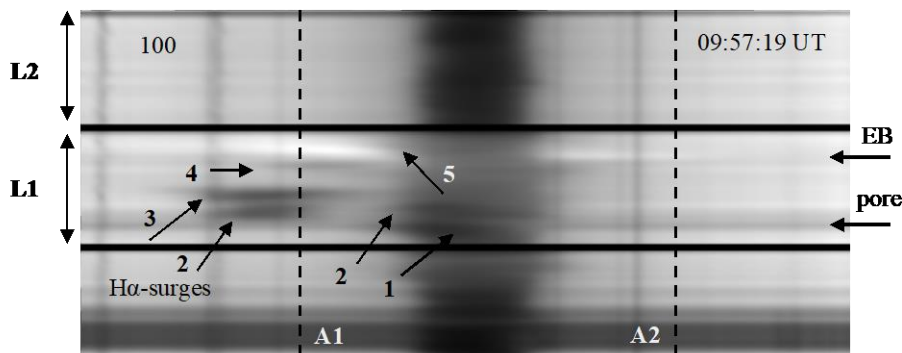


Figure 1: H $\alpha$ -spectrum of the AR site. EB – Ellerman bomb. L1, L2 – see text. The numbers in the fig. correspond to the surge numbers. Vertical lines A are the photometric sections across spectra at the distances of  $\pm 0.16$  nm from the line center.

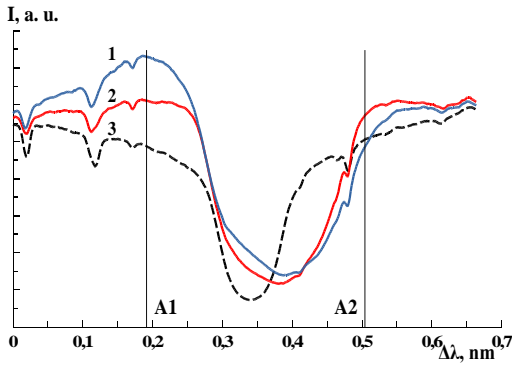


Figure 2: Profiles of the H $\alpha$  line for EB region (1 and 2) and profile (3) for the AR site L2. *I* is given in arbitrary units.

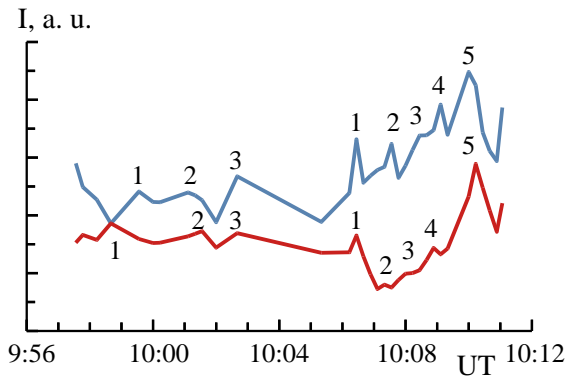


Figure 3: Temporal variations of the emission intensity (EB light curves) in the H $\alpha$  line wings at the distances of  $\pm 0.16$  nm from the line core, in the short-wave (blue line) and long-wave (red line) wings.

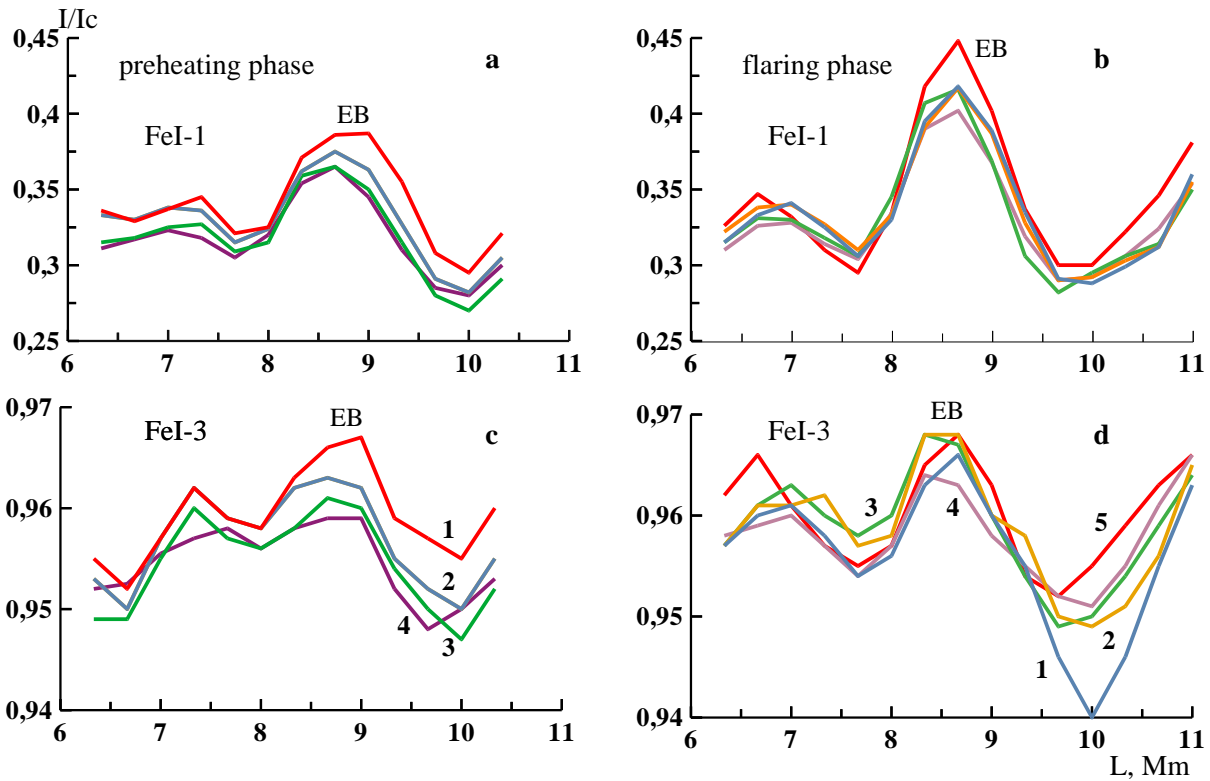


Figure 4: Variations of the photospheric line central intensities along the spectrograph slit at different observation moments: a, c – 9:57:05, 9:59:41, 10:01:06, 10:02:31 UT, curves 1-4, respectively; b, d – 10:06:31, 10:07:42, 10:08:25, 10:09:22, 10:10:32 UT, curves 1-5, respectively.

### 3.2. Photosphere

The spectral region of  $\lambda \approx 630$  nm was used to study the changes of physical conditions at different photospheric levels in the process of EB evolution. This region includes lines that are formed in a wide range of heights: two strong Fraunhofer lines FeI  $\lambda$  630.15, 630.25 nm and two weak lines: FeI  $\lambda$  630.35, TiI  $\lambda$  630.38 nm, they are in the text

designated – FeI-1, FeI-2, FeI-3 and TiI, respectively. The central intensities of the two first and two last lines should be formed in the upper and lower photospheric layers.

Figure 4 shows variations of the photospheric lines central intensities  $I/I_c$  along the spectrograph slit at different observation moments. The area where the EB was located is very different in the upper and lower photosphere of increased intensity. The greatest increase  $I/I_c$  (red curves)

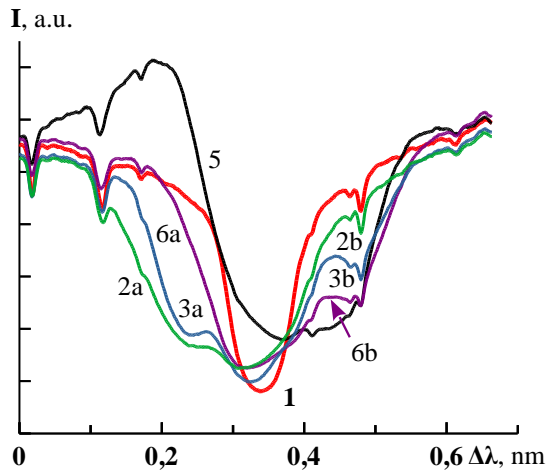


Figure 5: The H $\alpha$  line profiles (2 -6) for AR site L1 for the observation moment of 10:07:42 UT and profile (1) for the AR site L2. The numbers correspond to the surge numbers.

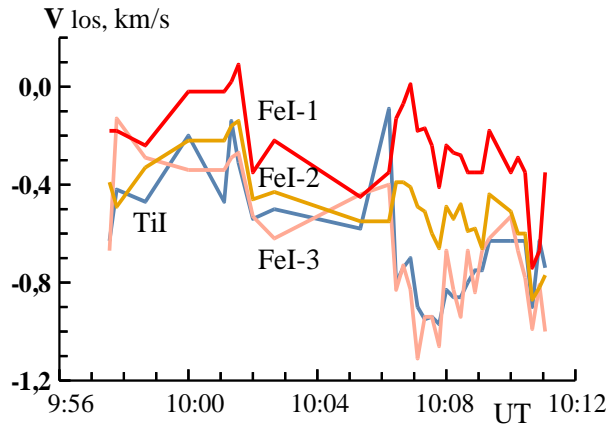


Figure 6: Temporal variations of the line-of-sight velocities matter in the EB central part in the upper (FeI-1 and FeI-2 lines) and in the lower (TiI and FeI-3 lines) photospheric layers. Negative velocity values correspond to motions directed toward the observer.

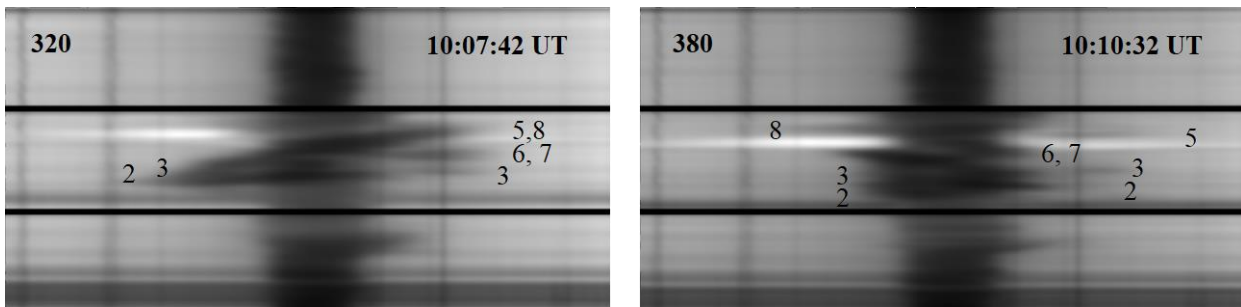


Figure 7: H $\alpha$ -spectra of the AR site. The numbers correspond to the surge numbers.

occurred simultaneously at all photospheric levels. Horizontal movement of matter took place near the EB area (panel d). Figure 5 shows that an increase the central intensity of all the studied photospheric lines was correlated in time with an increase of the emission intensity in the H $\alpha$  line wings (Fig. 3).

We obtained temporal Vlos variations in a wide interval (140 – 490 km) of photospheric heights for the area of EB development and its vicinity. At all photospheric levels predominantly upward motions were found (Fig. 6). At the same time, a noticeable decrease of the Vlos magnitudes was observed at the EB location. In the central part of the EB in the upper layer of the photosphere the Vlos varied between  $-0.5 \div 0.2$  km/s, in the lower layer  $-1.1 \div -0.1$  km/s. A similar Vlos distribution in the photosphere was obtained in (Pasechnik, 2019). Perhaps it is characteristic of EBs formed in the emerging magnetic flux region. The largest changes of Vlos occurred during the H $\alpha$ -ejection formation near the EB and which had signs of plasma vortex motions. At that time, downward matter flows with Vlos of 0.2 km/s were observed in the upper photosphere.

#### 4. H $\alpha$ -ejections

The features of the formation and development of all H $\alpha$  surges that existed in the AR site during our observations were investigated. Figure 1 shows the spectrum was obtained at the beginning of the observations. Surges 1 and 2 occurred on different sides near the pore, surges 4 and 5 – near and above the EB area development and surge 3 – in the middle part of the site. Surges 1, 3 and 5 consisted of one jet. Surges 2 and 4 consisted of two jets – dark details are visible in the blue wing and in the H $\alpha$  line core. Figure 8 shows the shape of the H $\alpha$  line profiles obtained for the places of maximum intensity of various surges on the 320 spectrum (Fig. 7). Depending on whether the upflows or downflows was observed in the surge, the surge profile was projected onto the blue ( profiles 2a, 3a) or red (profiles 3b, 6b) H $\alpha$  line wing. If the surge profile was projected onto the line core, there was H $\alpha$  profile distortion and a shift of its central part to the red or blue side (profile 2b, 6a, 5). Doppler shifts of these components were used to calculate the chromospheric matter Vlos in surges. The Vlos values in the L2 section did not exceed  $\pm 2$  km/s. Changes in Vlos

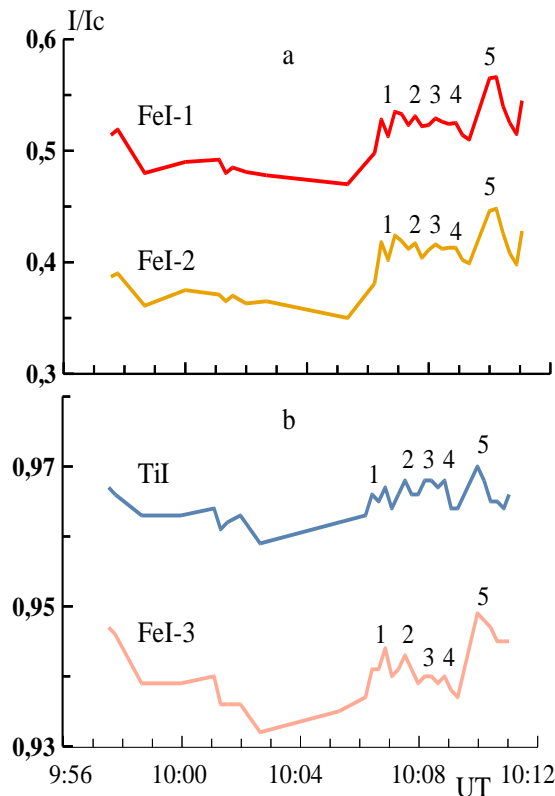


Figure 8: Temporal variations of the Fraunhofer lines central intensity, which are formed in the upper (a) and lower (b) layers of the photosphere for the EB central part.

of the chromospheric matter along the cross section at the surges maximum intensity site were determined. Figure 9 shows changes in the matter movement along a cross section in one of the surges. It can be seen that this surge was very structured. Most of the velocities change curves consisted of several segments. This means that the surge consisted of several smaller jets, that is, it had a multi-flow structure. The evolution of the surge looks like this: the surge appears with a high upward movement velocity up to  $-90 - -100$  km/s, over time the it decreases, but not uniformly, sometimes accelerating, then slowing down, surge reaches a certain height or the top of the magnetic loop and under the force gravity action returns along the same trajectory or along the second part of the loop. The 380 spectrum was obtained during the 5th highest intensity peak in the EB light curve (Fig. 7). The  $H\alpha$  line is very fibrous. Surges are visible in both line wings. The  $H\alpha$  line central part was completely covered by dark details, a system of arc-shaped  $H\alpha$ -ejections, the so-called Arch Filament System, was formed, under which the EB developed.

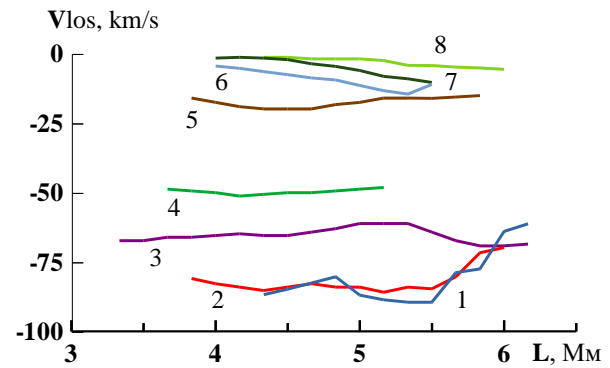


Figure 9: Changes in  $V_{los}$  along the cross-section of surge 3 at different moments of observation: 9:57:05, 9:57:19, 9:57:46, 9:58:16, 9:59:12, 10:01:06, 10:01:20, 10:02:31 UT - curves 1-8, respectively.

## 5. Conclusion

We obtained and analyzed new observational data for the Ellerman bomb and accompanying  $H\alpha$ -ejections: for the EB preheating phase; changes in chromospheric matter  $V_{los}$  along the cross section of the surges; followed the formation so-called Arch Filament System and studied the changes that occurred at the photospheric different levels under the influence EB.

The features of the change in the  $H\alpha$  line wings intensity as well as the chromospheric and photospheric matter  $V_{los}$  indicate that the EB and accompanying  $H\alpha$ -ejections, which arose and developed in the AR site under investigation, were the result of magnetic reconnections caused by the emergence of a new serpentine magnetic flux and its interaction with a pre-existing magnetic field or between the magnetic loops of the flux itself.

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