Research Article

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Analysis and modeling of the dynamics of the glow of calcium and hydrogen lines in solar and stellar flares

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Abstract: We present intensity curves of solar flares obtained in the Hα hydrogen line and CaII H, CaIR 8542Å lines using multichannel spectrographs of Ondřejov Observatory (Czech Republic) for the period 2000–2012. The general behavior of observed intensity curves is practically the same for all flares and is consistent with temporal variations of X-ray emission. However, our results differ significantly from those obtained by other authors for selected flare stars, for example, AD Leo; EV Lac; YZ CMi. We tried to explain the difference in the behavior of Ca II and Hα radiation flux by appearance of a shock wave during a flare and slow heating of the plasma.

Keywords: flares spectrum, chromosphere, GOES flux

1 Introduction

The aim of this work was to study the behavior of the emission intensity curves in the Hα, H CaII and CaIR 8542 Å lines and to compare the results with the spectra of flare stars. The formation and temporal evolution of the Ca II line, which has a longer time for stellar flares, remains a mystery to this day. Perhaps this is due to the formation in the lower chromosphere and time-dependent, non-thermal model of electron heating at the moment of the impulsive phase, see Allred et al. (2006) or is the coronal X-ray reheat model described by Hawley et al. (1992). To determine the possible mechanisms of radiation intensity in the lines, the radiation flux was calculated under the assumption of a shock wave and, in the second case, a slow heating of the gas, which is stronger in this region than in neighboring regions.

2 Observations

All observational data on solar flares were obtained on two spectrographs of the Astronomical Institute of the Czech Academy of Sciences (Ondřejov). These are Multichannel-Flare-Spectrograph (MFS, 230 mm/13.5 m) and Horizontal-Sonnen-Forschungs-Anlage (HSFA-2, 500 mm/35 m), described in (Kotrč et al., 1992) and (Kotrč, 2009). Since the observations were carried out at two different instruments using analog and digital CCD matrices, the processing and calibration of the data differed. For the data obtained on HSFA-2 and MFS, we used the IDL software environment. We selected 25 class C, M flares with different positions on the solar disk for the period 2002–2012. The paper provides data for flares 2012-11-24 C3.3, 2002-08-20 M3.4, 2012-07-05 M1.8.

a) The 2012-11-24, C3.3, NOAA 11618 flare was observed on the MFS spectrograph with digital cameras. Its position on the disk and obtained spectra are shown in Figure 1. After data calibration, the intensity plots were plotted in absolute units as a function of time. The graph in Figure 2 also presents an X-ray flux (GOES 15).

b) The flare 2002-08-20 M3.4 in the active region NOAA 10069 was observed using an analog camera. We observed at the MFS simultaneously in three spectral lines. The position of the vertical line on the SJ fil-
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Figure 1. Flare 2012-11-24, 13:24:15 UT, from left to right: SJ, Hα, Ca 8542 Å.

Figure 2. Graph of the intensity of two flare nuclei in the lines: (+) Hα, (triangle) Ca 8542 Å, (rhomb) X–ray.

Figure 3. The image from MFS shows the flash spectra in lines: Hβ, Hα, CaIR. The position of the spectrograph slit is marked in the Hα (SJ) line in the filtergram. At the top of the image is a stepped attenuator.

Figure 4. Graphs of integrated radiation intensity and X-ray flux versus time.

+ Hα (1, 2); Δ – CaIR (1, 2); □ - xray GOES

(+) Hα ; ('') Hβ ; Δ – CaIR ; □– xray GOES

Figure 4. Graphs of integrated radiation intensity and X-ray flux versus time.

The results of solar flares analysis indicate the same change of the Hα and H CaII lines in time. Their impulse and gradual phases reach the same values at the same time.

Then we looked at the development of some stellar flares. (Kowalski et al., 2013) provide observational data from the Apache Point Observatory in southern New Mexico. As an example, note the evolution of the H CaII and Hα lines for the YZ CMi star flare (Figure 7) observed in 2011 Feb 24.

We also considered flares AD Leo observed in 2011 Feb 08 and EV Lac observed in 2010 Oct 11, see (Kowalski et al., 2013). For these three stars, the lag of the maximum for...
Figure 5. Flare 2012-07-05, 10:46:47 UT, from left to right: SJ, Hα, H CaII in AR NOAA 11515.

Figure 6. An example of calculating the integral flux $F$ for lines Hα and H CaII in solar flare. Emission profiles correspond to the flare region, absorption profiles – to the quiet Sun region. All intensities expressed in erg sr$^{-1}$ cm$^{-2}$ s$^{-1}$ Å$^{-1}$ units. Flux $F$ in Hα – $1.79 \cdot 10^8$ erg cm$^{-2}$ s$^{-1}$; $F$ in H CaII – $2.43 \cdot 10^8$ erg cm$^{-2}$ s$^{-1}$. The integration was carried out over the ranges: Hα – 6561.88–6563.79 Å, H CaII – 3968.09–3971.36 Å.

Figure 7. Radiation flux curves for YZ CMi. Figure from (Kowalski et al., 2013).

the K CaII line relative to the Hα line is within the range of 12–24 min.

### 3 Calculation of the Plasma Heating Models

The theoretical analysis of radiation in the observed lines is carried out within the framework of a model of a gas layer localized in the chromosphere and heated to a higher temperature than the environment at the same height. The proposed work considers two complementary heating mechanisms: a quasi-static increase in the energy supplied and a non-stationary radiative cooling behind the shock wave. In the first variant, the flux of energy carried by MHD waves from some confined region located under the photosphere is increased. The additional energy is transferred to the chromosphere where dissipation of waves leads to stronger gas heating. In this paper we assume the layer to be homogeneous with single temperature $T$, density $N$ and ionization state determined by balance equations. Due to the assumption of the layer homogeneity, the shock wave is a stationary one, that is, it moves on the undisturbed gas at a constant speed, designated $V$.

In the both variants, the stationary emission of the homogeneous layer and shock wave radiative cooling, the
following physical processes are taken into account: free-free, free-bound and bound-bound collisional and radiative transitions in the diluted black body radiation which temperature is \( T \) and dilution factor is \( 1/2 \). The layer is supposed to be transparent in the continuous spectrum but self-absorption in line frequencies is taken into account in the frame of the Biberman-Holstein escape probability method. Escape probability of photons in hydrogen lines was computed by integrating the Doppler and Holzmark convolution profile, and in metal lines is Voigt profile. In the case of hydrogen atom, all discrete levels allowed by the Inglis–Teller criterion are included (from 11 to 13, depending on the electron density), for the CaII ion – levels \( 4s^2S, 5s^2S, 3d^2D, 4d^2D, 5d^2D, 4p^2P^0, 6p^2P^0, 4f^2F^0, 5f^2F^0 \).

In the stationary heating model for each chemical element at specified parameter values, we calculate the ionization state and the excitation degree of the discrete levels. Parameters of the stationary problem are the size of the layer \( L \), the gas temperature, its density, and the black body temperature. The following parameters are taken into account:

\[
L = 1 \text{ km}; \quad N = 10^{15} \text{ cm}^{-3}; \quad T_r = 5500 \text{ K}; \quad (1) \quad 7000 \text{ K} < T < 8700 \text{ K}.
\]

The results of the calculations are listed in the Table 1. The first column shows the gas temperature, and the first row represents spectral line designations. The table body contains radiation fluxes expressed in units erg/(cm\(^2\) s). The third row of the table \( (T = 8000 \text{ K}) \) gives the best approximation to the flux values in the H\( \alpha \) and the CaII lines for stellar flares. Analysis of the table data allows the following highlights to be noted in the line emission of the layer.

1. Steep Balmer decrement. A large value of ratio \( F(\text{H}\alpha)/F(\text{H}\beta) \) is typical for hydrogen impact excitation at intermediate temperatures.

2. Comparable fluxes in hydrogen and calcium lines. Compensation for the large difference in the abundances of these chemical elements is due by the high excitation potential of the Balmer series and self absorption in the hydrogen lines.

3. Dependence \( r = F(3945 \text{ Å})/F(8542 \text{ Å}) \) of the CaII ion lines on the gas temperature. The infrared line is stronger at low temperatures, the resonant one is stronger at high temperatures. Such dependence \( r(T) \) is determined mainly by change in the probability of resonant radiation due to ionization of calcium.

4. Ratio of fluxes in the Hydrogen H\( \alpha \) and CaII resonant line increases with temperature. Within the parameter range \( (1) \), it passes through one at \( T = 8000 \text{ K} \).

In the frame of the shock wave model we solve the problem of the non-stationary cooling of the gas heated on the viscous jump. The equations describing radiative cooling downstream flux, and the methods of their solution are described by us in (Belova et al., 2014; Belova and Bychkov, 2018, 2019). The shocked gas becomes nonhomogenous because its temperature, density, excitation degree and the ionization state vary while it is cooling. The constant parameters are the density \( N_0 \) of the undisturbed gas and its speed \( V \).

The following ranges are taken into account:

\[
20 \text{ km/s} < V < 40 \text{ km/s};
\]
\[
3 \cdot 10^{12} \text{ cm}^{-3} < N_0 < 1 \cdot 10^{15} \text{ cm}^{-3}.
\]

### Table 2. Fluxes in the hydrogen and calcium lines in the shock wave model for the velocity \( V = 20 \text{ km/s} \).

| \( N_0, \text{ cm}^{-3} \) | H\( \alpha \) | Ca 3945 Å | Ca 8542 Å |
|-----------------|------------|-----------|-----------|
| \( 3 \cdot 10^{12} \) | 6.3 \cdot 10^5 | 2.0 \cdot 10^6 | 2.0 \cdot 10^5 |
| \( 1 \cdot 10^{13} \) | 1.9 \cdot 10^5 | 8.2 \cdot 10^5 | 1.4 \cdot 10^6 |
| \( 3 \cdot 10^{13} \) | 7.4 \cdot 10^5 | 2.1 \cdot 10^7 | 3.9 \cdot 10^6 |
| \( 1 \cdot 10^{14} \) | 4.5 \cdot 10^6 | 6.9 \cdot 10^7 | 1.3 \cdot 10^7 |
| \( 3 \cdot 10^{14} \) | 2.1 \cdot 10^7 | 1.6 \cdot 10^8 | 2.9 \cdot 10^7 |
| \( 1 \cdot 10^{15} \) | 6.8 \cdot 10^7 | 3.3 \cdot 10^8 | 5.6 \cdot 10^7 |

### Table 3. Fluxes in the hydrogen and calcium lines in the shock wave model for the velocity \( V = 40 \text{ km/s} \).

| \( N_0, \text{ cm}^{-3} \) | H\( \alpha \) | Ca 3945 Å | Ca 8542 Å |
|-----------------|------------|-----------|-----------|
| \( 1 \cdot 10^{13} \) | 2.3 \cdot 10^6 | 8.8 \cdot 10^5 | 5.3 \cdot 10^6 |
| \( 3 \cdot 10^{13} \) | 6.8 \cdot 10^6 | 1.7 \cdot 10^6 | 6.8 \cdot 10^6 |
| \( 1 \cdot 10^{14} \) | 2.0 \cdot 10^7 | 6.7 \cdot 10^7 | 6.1 \cdot 10^6 |
| \( 3 \cdot 10^{14} \) | 4.9 \cdot 10^7 | 1.6 \cdot 10^8 | 1.5 \cdot 10^7 |
| \( 1 \cdot 10^{15} \) | 1.2 \cdot 10^8 | 3.0 \cdot 10^8 | 3.6 \cdot 10^7 |

### Table 1. Fluxes in the hydrogen and calcium lines in the stationary model. Here CaII 3945 Å column represents total flux in H and K CaII lines. The second row of the table at \( T = 8000 \text{ K} \) is closest in terms of the fluxes in the H\( \alpha \) and Ca II lines for stellar flares.

| \( T, \text{ K} \) | H\( \alpha \) | H\( \beta \) | Hy | H\( \delta \) | Ca 3945 Å | Ca 8542 Å |
|-------|-------|------|-----|-------|-----------|-----------|
| 7000  | 2.31 \cdot 10^6  | 2.69 \cdot 10^5  | 7.45 \cdot 10^6  | 3.08 \cdot 10^6  | 3.85 \cdot 10^6  | 4.28 \cdot 10^6  |
| 8000  | 1.21 \cdot 10^7  | 1.42 \cdot 10^6  | 3.94 \cdot 10^6  | 1.63 \cdot 10^6  | 1.16 \cdot 10^7  | 8.91 \cdot 10^6  |
| 8700  | 5.56 \cdot 10^7  | 6.50 \cdot 10^6  | 1.82 \cdot 10^5  | 7.57 \cdot 10^6  | 1.93 \cdot 10^7  | 1.29 \cdot 10^7  |
The results of our calculations — the radiation fluxes in the Hydrogen Hα and resonant (3945 Å) and infrared (8542 Å) lines of CaII, expressed in units erg/(cm² s), — are listed in tables 2 and 3.

The data in the table show a marked correlation between the fluxes in lines and the velocity of the shock wave and the density of the undisturbed gas. Relative values of fluxes are varying widely what can explain their observed values. The values of flux calculated by the method given in section (c) are the values for the events: 2012-11-24 \( F_{\text{H\alpha}} = 6.18 \cdot 10^4 \), \( F_{\text{Ca}8542} = 1.97 \cdot 10^5 \) (erg cm⁻² s⁻¹); 2002-08-20 \( F_{\text{H\alpha}} = 6.35 \cdot 10^4 \), \( F_{\text{Ca}8542} = 2.05 \cdot 10^5 \) (erg cm⁻² s⁻¹) and correspond to the data calculated for \( V = 20 \) km/s (see Table 1) \( N_0 (\text{cm}^{-3}) = 3 \cdot 10^{12}, F_{\text{H\alpha}} = 6.3 \cdot 10^4, F_{\text{Ca}8542} = 2.0 \cdot 10^5 \) (erg cm⁻² s⁻¹).

At a speed \( V = 40 \) km/s for the 2012-07-05 flash, the flux values \( F_{\text{H\alpha}} = 1.79 \cdot 10^8 \), \( F_{\text{Ca}3945} = 2.43 \cdot 10^8 \) (erg cm⁻² s⁻¹), corresponding to the calculated values (Table 2) \( N_0 (\text{cm}^{-3}) = 1 \cdot 10^{15}, F_{\text{H\alpha}} = 1.19 \cdot 10^8, F_{\text{Ca}3945} = 3.03 \cdot 10^8 \) (erg cm⁻² s⁻¹).

4 Discussion and conclusion

The results of solar flares analysis indicate the same behavior of Hα and CaII lines in time. Their impulse and gradual phases reach the same values at the same time. These observations contradict those of other stars, for example, of the spectral type dMe. These individual types of stars demonstrate a significant delay in the emission of CaII (H, K) lines, relative to Hα (Kowalski et al., 2013). Possibly, in stars the flare causes sharp ionization followed by slow recombination. These issues have not been adequately studied yet. The authors are grateful to the Ondřejov observatory team for the opportunity to participate in joint observations.

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