THE FINE TEMPORAL STRUCTURE OF THE EV LACERTAE FLARE ON FEBRUARY 6, 1986 AT THE C IV (λ1550 A) RESONANCE LINE

II. INTERPRETATION

M.M.Katsova

Sternberg State Astronomical Institute,
University of Moscow, 119899 Moscow, USSR

M.A.Livshits

Institute of Terrestrial Magnetism, Ionosphere
and Radio Wave Propagation, Academy of Sciences
Troitsk, 142092 Moscow Region, USSR

ABSTRACT. Flare optical continuum with duration above one minute is emitted by a gas condensation with $T \approx 10^4$ K, which may form in a gas-dynamic process. The light curve slope implies that this flare consists of several elementary events. The features of the initial C IV line burst during one elementary event are determined by numerical simulation. The comparison of theoretical intensity and duration of the C IV burst with the observations of the EV Lac flare on February 6, 1986 shows that the observed elementary event in the C IV line is consistent with the formation of a radiative shock wave with an explosive evaporation of the chromosphere. The possibility of the appearance of C IV doublet emission, accompanying the entire process, is also discussed.

1. THE OBSERVATIONS

In Paper I Burnasheva et al. (1988) report on a flare with amplitude of about 3 mag (U-band) and 10-15 min duration, which was observed on February 6, 1986. The ASTRON integral channel 1700-6500 Å showed noticeable emission for more than 50 seconds. The light curve slope implies that this flare consisted of several elementary events. The C IV line emission, with average flux at Earth of about 3×10^{-11} erg cm^{-2} s^{-1}, started simultaneously with white light radiation enhancement. The flux at Earth on the C IV line was $\approx 1.8\times10^{-9}$ erg cm^{-2} s^{-1}, and was due to one single bin of 0.61-s duration, 50 s after the flare onset.

2. THE GAS-DYNAMIC MODEL

The gas-dynamic model of stellar flares (Katsova et al. 1981; Katsova and Livshits, 1983, 1987, 1988) has been developed in the framework of Kostyuk-Pikel'ner (1974) model. Our numerical simulation was carried out to study the effect of the primary energy release. The general features of the gas-dynamic process has been discussed both for solar (Livshits et al. 1981; Fisher 1986) and stellar flares. During the impulsive heating of large masses of chromospheric gas, two disturbances propagate upwards and downwards from the formed high-pressure region. During the course of powerful events, the downwards shock wave is formed in less than about 1 s and this process must be accompanied by a short and intense radiation burst of the EUV-lines in the range 1000-2000 Å. In between the shock wave front and the downwards moving temperature jump, a gas condensation with density $\geq 10^{15}$ cm^{-3} and temperature $T \approx 10^4$ K arises. This condensation becomes the source of line and continuum optical emission. The typical lifetime of this chromospheric condensation may reach up to 1 minute. The character of the upwards outflow of the hot gas is different for mild evaporation regime (small or slowly growing energy fluxes in the chromosphere) and for explosive events.

3. THE IMPULSIVE C IV BURST

A short and intense C IV burst was observed with ASTRON during the EV Lac flare on February 6, 1986. Theoretically, the C IV flux maximum must occur at the onset of an elementary gas-dynamic event. Shown in Fig.1 is the temperature distribution versus column depth in the atmosphere, according to the numerical simulation of the stellar flare by Katsova et al. (1981). The emission source with $T \approx 10^5$ K arises simultaneously with the beginning of the heating if a rectangular time profile is assumed for the heating energy flux, e.g., for an accelerated electron beam. Then, a moving downwards shock wave rapidly forms. The temperature behind its front falls from $> 10^5$ K to 6×10^4 K within 0,4 s after the flare onset. The electron density n_e at this time rises up to $(1.5-2) \times 10^{13}$ cm^{-3}. The optical depth in the centre of the stronger line of the C IV doublet first remains sufficiently large, ($\tau \approx 1.5 \times 10^{-10}$, $\Delta\xi \approx 6 \times 10^5$) and subsequently decreases very sharply. Just this is the cause of the short duration (≤ 1 s) EUV-burst, which must accompany this process.

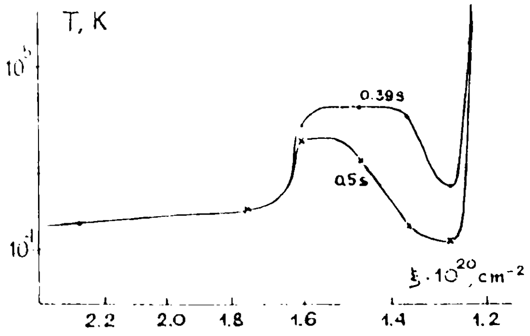

Figure 1. Temperature distribution versus column depth in the region of formation or a downwards shock wave, 0.39 s and 0.5 s after the turn-on of the heating flux $F_0 = 10^{12}$ erg cm^{-2} s^{-1} (from numerical simulation by Katsova et al. 1981). Temperature jump and coronal layers are to the right. ξ is the column depth measured from the corona base.

To calculate the flux in the C IV line, we use the theoretical result of Ivanov (1973), with a source function close to the Planck function for optical depths $\tau >> (1 - \Lambda)^{-1}$, where Λ is the probability of proton escape in one scattering. The value $(1 - \Lambda) = C_{21}\, n_e / A_{21}$, with C_{21} being the de-excitation rates and A_{21}, the probability of spontaneous transitions, is 2.4×10^{-3} in our case due to the high efficiency of inelastic collisions, so that the condition $\tau >> (1 - \Lambda)^{-1}$ is satisfied.

Assuming that the flare has area S, luminosity $L = S \pi I$, and emits like a blackbody in the solid angle 2π, we shall use, thereinafter, the following relation between the fluxes at Earth (F) and the emission intensity (I):

$$F = L / 2\pi D^2 = S \pi I / 2\pi D^2 \approx S B_\lambda(T) / 2 D^2 \qquad (1)$$

where D is the star distance.

The radiative flux is estimated from (1) for both lines of the C IV doublet, when $I = 2 B_\lambda(T) \Delta\lambda$. For $T \approx 10^5$ K, $S \approx 3 \times 10^{17}$ cm^2 (see below) and taking into account the result by Naghirner (1975) that, for an optically thick layer, the width of the line $\Delta\lambda$ is equal to $3 \Delta\lambda_D$, we obtain $F = 1.8 \times 10^{-7}$ erg cm^{-2} s^{-1}.

The time resolution of the observation (0,61 s) is in this case close to ≈ 0.5 s, i.e., to the lifetime of the emission source. Therefore, the intensity of the observed burst must be close to the theoretical estimate. The agreement of both the intensity and the duration of the C IV line burst with our theoretically estimates may give evidence for the turn-on of an impulsive evaporating regime, which occurred 50s after the flare onset. We may conclude that, in this case, the formation of a radiative shock wave, due to an elementary event producing explosive evaporation in the chromosphere, was observed for the first time. The absence of a similarly powerful short-lived burst of the C IV lines at flare onset is not completely clear, but may be connected with the different slope of the rising part of the flare light curve.

4. LONG-DURATION OPTICAL CONTINUUM AND WEAK C IV EMISSIONS

Optical continuum and weak C IV emissions are observed to last longer than 1 minute. The UV-continuum flux in the range at 2420-2448 Å does not exceed 1.7×10^{12} erg cm^{-2} s^{-1}, the flare onset excluded. From the ratio of the fluxes in the ASTRON integral channel 4 (1700-6500 Å) and UV-channel (2420-2448 Å), by assuming blackbody radiation and equal area of the emitting regions in both spectral ranges (for optical depth $\tau > 1$) and by using equation (1), we find that the temperature of the flare is $\leq 10^4$ K. The absolute flux of the flare optical continuum corresponds to a flare area $S \approx 3 \times 10^{17}$ cm^2. It should be noted that the same temperature was derived for another powerful impulsive flare observed with ASTRON on EV Lac on February 24, 1984 (Gershberg and Petrov, 1986), and for other flares showing optical continuum emission.

Thus, there are sufficient arguments to correlate the 1-minute optical continuum emission with the radiation of the gas condensation, which is developed in gas-dynamic processes.

Tentatively, the weak emission at 1550 Å may be considered to be radiated by a plasma that is optically thin in the C IV line. Using the parameters of the C IV ion and of the corresponding transitions, from Katsova (1982) we have:

$$1.8\times10^{-22}\ EM = 2\pi\ D^{2}\ F \tag{2}$$

from where, with $F \approx 3\times10^{-11}$ erg cm^{-2} s^{-1}, we obtain the volume emission measure $EM \approx 3\times10^{50}$ cm^{-3}. This value may be somewhat underestimated due to the hypothesis of optically thin plasma. For a flare with area $S \approx 3\times10^{17}$ cm^{2}, we obtain $EM \approx 10^{51}$ cm^{-3}, which is a factor of 10 larger than the value of EM derived by Fisher (1986) for the flaring transition region of a typical solar event. Certainly, a source emitting at $T \approx 10^{5}$ K, e.g. a loop, can develop. Further observations with high temporal resolution of additional transition region lines can allow us to study this possibility in detail.

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