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MODIFIED CLOUD METHOD VALIDATION BY DETERMINATION OF PHYSICAL PARAMETERS OF THE SOLAR FLARE ON JUNE 26, 1999

Abed-Alkader Abseim*, Mohamed Semeida, Magdy Saleh***,****, Shahinaz Youssef***, Penka Stoeva*****, Alexey Stoev*******

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Abstract

The studied moderate solar flare on June 26, 1999 was observed in Hα line using the multichannel flare spectrograph (MFS) at the Astronomical Institute in Ondřejov, Czech Republic. To fit the Hα line profiles, we use a new technique, proposed by Liu and Ding [1]. It is different from the classical cloud model and avoids using the background profile. The five parameters of the flare chromosphere, namely: 1) the source function, 2) the optical thickness at line center, 3) the Doppler shift, 4) the Doppler width and 5) the downward flow velocity for the Hα line profiles, are obtained. The theoretical asymmetry profiles derived by the modified cloud model are in good agreement with the observed ones. The new results are useful for a better understanding of the solar flare dynamics.

Key words: Sun, chromosphere, solar flare, Hα spectra, modified cloud model

Introduction. The mechanism of the solar flares and their dynamic characteristics, cool and hot flare loops and other eruptive events associated with them have been extensively studied by many authors [1–3]. Spectral analysis is an important means of studying solar flares. The essential problems in the analysis of disturbed line profiles is the determination of the physical quantities, which are related to that part of the atmosphere where the line is formed. Some basic parameters, such as Doppler width, Doppler shift of the line under consideration, optical depth, and line source function, etc. in solar flare loops may be obtained by spectral analysis.

The "cloud model" (CM) method of Beckers [4] has been extensively used for investigation of chromospheric absorption features seen in the Balmer lines as well as the "Differential Cloud Models" (DCM1 and DCM2), which were proposed by Mein and Mein [5] and take into account a realistic background profile. These models are again suitable only for symmetric profiles. The basic scenario of chromospheric condensation has successfully explained the asymmetric profiles of disk flares [6], but it is unsuitable for limb flares. To solve this problem, Gu et al. [7] proposed a "multi-cloud model" (MCM) method based on the CM, DCM1 and DCM2 methods. The MCM method has been applied to many asymmetric profiles of flares, prominences, surges, etc. Liu and Ding [1] used for the first time a technique different from the classical cloud model to fit the Hα line profile. They have obtained parameters of Hα post-flare loops using the modified cloud model (MoCM) method that eliminates the use of the background profile, which is usually hard to determine. In the present work the MoCM method is used for analysis of the Hα profiles in flaring regions and a special attention is paid to the origin of the line asymmetry. The five parameters of the flare's chromospheres, namely: 1) the source function, 2) the optical thickness at line center, 3) the Doppler shift, 4) the Doppler width and 5) the downward flow velocity for the Hα line profiles, are obtained.

Observations and data analysis. In the present study, the Hα spectra of the moderate flare on June 26, 1999 was taken by Ondřejov multichannel flare spectrograph (MFS) and used during the observation time interval from 07:23:33 UT to 08:05:51 UT in the active region NOAA 8598 located at N20 E09. According to Solar Geophysical Data, this solar flare (SF) began at 07:18E UT, ended at 08:19:09 D, reaching its maximum at 07:23 UT. According to GOES, it is with Hα importance and soft X-ray class C 7.0. The observed frame spectra involved Hydrogen Balmer lines Hα and Hβ, and the infrared strongest Calcium triplet line 8542 Å. The observed frame spectra have been analyzed and stored in a digital form. The duration of registered observations of this flare is about 42 min from its beginning to its end. The three emission spectral lines (Hα, Hβ and the infrared strongest Calcium triplet line 8542 Å) appeared clear. This flare is clearly visible, unstable, with complicated morphology and good features.

Method of computation. The classical cloud model (CM) adopts a mean profile over the quiet chromosphere as a background profile. However, for flares it is not feasible because of the large fluctuations in the active-region background. Here we use a technique avoiding the use of a background profile – modified cloud model (MoCM) method [1, 8–10]. In the cloud model (CM), the line intensity is given by

$$I(\Delta\lambda) = I_0(\Delta\lambda)e^{-\tau(\Delta\lambda)} + S_0\left[1 - e^{-\tau(\Delta\lambda)}\right], \tag{1}$$

where the source function S_0 is assumed to be constant and frequency independent, $I_0(\Delta\lambda)$ is the background intensity and $\tau(\Delta\lambda)$ is the optical thickness which is expressed as follows:

$$\tau(\Delta\lambda) = \tau_0 H(a, x). \tag{2}$$

Here $H(a, x)$ is the Voigt profile given by:

$$H(a, x) = \frac{a}{\pi} \int_{-\infty}^{+\infty} \frac{e^{-y^2}}{a^2 + (x - y)^2} \, dy, \tag{3}$$

where

$$x = \frac{\Delta\lambda - \Delta\lambda_I}{\Delta\lambda_D}, \tag{4}$$

$$a = \frac{\Gamma \lambda_0^2}{4\pi c \Delta\lambda_D}. \tag{5}$$

In the above equations $\Delta\lambda_D$ is the Doppler width and Γ is the damping constant (this parameter has no essential impact on the other parameters to be fitted, thus in the computations Γ is fixed to be a value of 5×10^9 s^{-1}, considering both the radiative damping and the collisional broadening).

The four unknown parameters are the source function S_0, the optical thickness at line center τ_0, the Doppler shift $\Delta\lambda_I$ and the Doppler width $\Delta\lambda_D$, which are assumed to be constant throughout the perturbed layer.

Below the perturbed layer, the Hα line profile is assumed to be symmetric, namely,

$$I_0(\Delta\lambda) = I_0(-\Delta\lambda), \tag{6}$$

$$I(-\Delta\lambda) = I_0(\Delta\lambda) e^{-\tau(-\Delta\lambda)} + s_0 \left[1 - e^{-\tau(-\Delta\lambda)}\right]. \tag{7}$$

Subtraction of $I(-\Delta\lambda)$ from $I(\Delta\lambda)$ leads to an asymmetry profile

$$\Delta I(\Delta\lambda) = [I_0(\Delta\lambda) - s_0] \left[e^{-\tau(\Delta\lambda)} - e^{-\tau(-\Delta\lambda)}\right]. \tag{8}$$

From equation (1) and equation (8) we can eliminate the background profile $I_0(\Delta\lambda)$. Then, for the asymmetry profiles we get:

$$A(\Delta\lambda) \equiv \Delta I(\Delta\lambda) = [I(\Delta\lambda) - s_0] \left[1 - e^{\tau(\Delta\lambda) - \tau(-\Delta\lambda)}\right]. \tag{9}$$

Using the above formula, we have tried to fit the obtained asymmetry profile to the observed one by utilizing an iterative least square procedure of the Levenberg–Marquardt method for nonlinear functions. To check the validity of this method, we have constructed theoretical asymmetry profiles by choosing different sets of the four parameters, which can in most cases be recovered using this method.

The initial values of the parameters for the iteration are taken in the following way:

- The intensity near the Hα continuum for the source function.
- One for the optical thickness at the line center.
- 1 Å for the Doppler shift.
- 0.4 Å for the Doppler width.

It should be emphasized that the computation converges rapidly and varying the initial values has almost no influence on the finally converged data.

Results and discussion. The modified cloud (MoCM) method described above has been applied to the selected observed Hα line profiles, which show red asymmetries through the course of observation time from 07:23:43 to 08:05:51, while the line center is nearly not shifted.

Table 1 gives a sample of the physical parameters, the source function, the optical thickness, the Doppler shift, Doppler width and the downward velocity for the Hα line profiles which are obtained by using the (MoCM) method. Figure 1a, b shows a typical Hα line profile with a red asymmetry along with the observed asymmetry profiles $A(\Delta\lambda)$ defined by equation (9). The asymmetry profiles from observations were well fitted to those computed by the used modified cloud (MoCM) method, the effect of other spectral lines has been eliminated.

Table 1

Sample of physical parameters derived from the Modified Cloud Model (MoCM) Method for the studied flare on June 26, 1999

Observation Time hh:mm:ss	Source Function	Optical Thickness	Doppler Shift (Å)	Doppler Width (Å)	Downward Velocity (km/s)
07:23:43	0.5928543	0.5367020	0.45258802	0.8709010	20.688
07:23:53	0.7031969	0.3681597	0.84653234	0.4256746	38.696
07:24:03	0.7664037	0.3103667	0.62571308	0.3504658	28.602
07:24:13	0.3526420	0.3125118	0.49404880	0.6233073	22.583
07:24:23	0.4251473	0.1886744	0.67215744	0.2915751	30.684
07:24:33	0.7633807	0.3272861	0.60422462	0.4253648	27.620
07:24:42	0.5155367	0.3308460	0.67910068	0.3715049	31.043
07:25:02	0.6715556	0.3126849	0.65045152	0.4213607	29.733
07:25:13	0.4800384	0.5204152	0.63299933	0.2557439	28.935
07:26:22	**0.5822429**	**0.3546404**	**0.95216906**	**0.5595285**	**43.525**
07:26:34	0.4732430	0.3362687	0.63058246	0.2839212	28.825
07:26:43	0.7469670	0.1882107	0.76014791	0.3663345	34.747
07:27:55	0.5927181	0.2914919	0.62732576	0.2439510	28.676
07:28:05	0.4907898	0.3538631	0.62153232	0.1870236	28.411

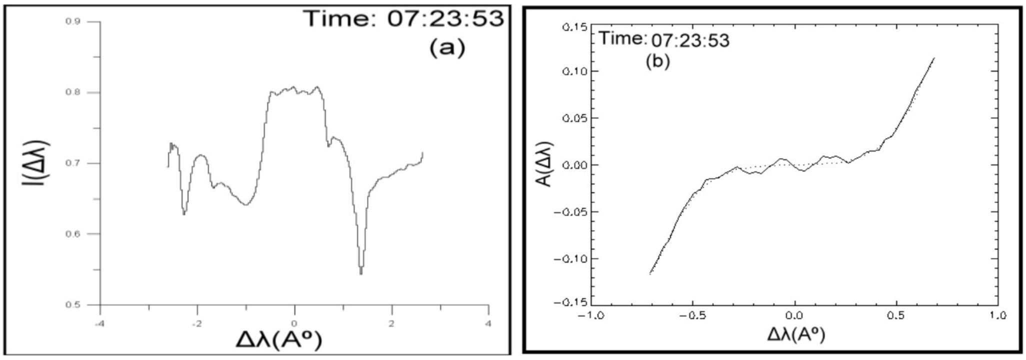

Fig. 1. (a, b) Typical Hα line profile with asymmetry in the flaring region at 07:23:53 UT. (b) A comparison between observed asymmetry profile (solid line) and that computed by the help of the modified cloud model (MoCM) method (dotted line). The intensity is normalized to the continuum near the Hα line

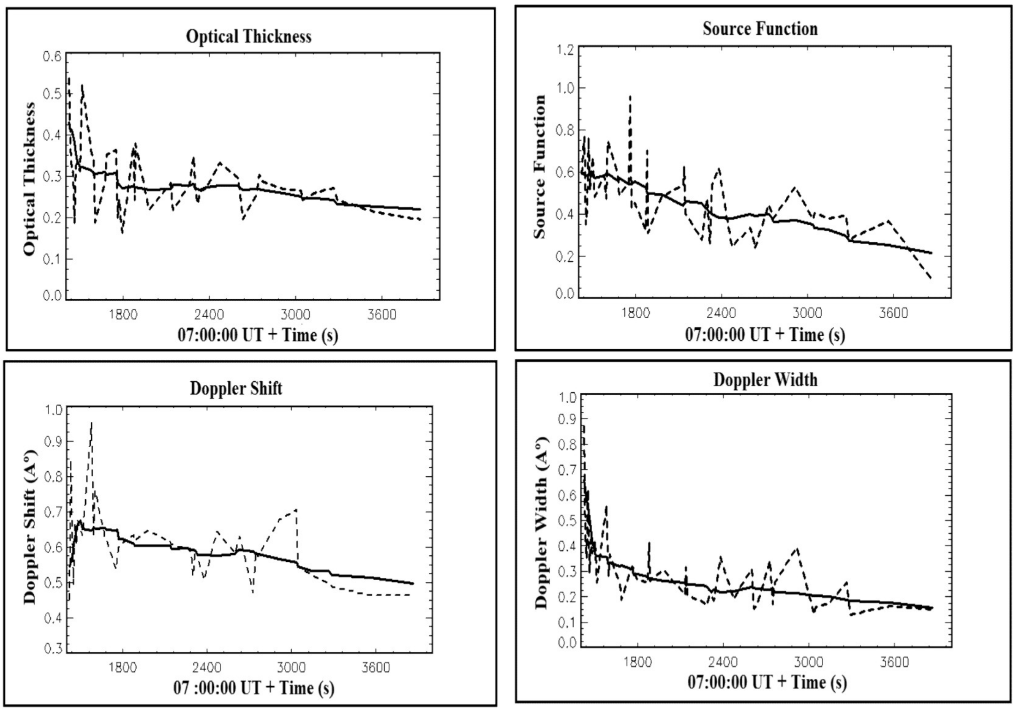

Fig. 2. The average temporal variation of the optical thickness, source function, Doppler shift and Doppler width (dashed line), and the smoothed ones (solid line) for the Hα line profiles of the studied flare on June 26,1999. Zero time corresponds to 07:00:00 UT

Figure 2 illustrates the average temporal variation of the physical parameters – the source function, the optical thickness, Doppler shift and the Doppler width of the Hα line profiles of the studied flare on June 26, 1999. This figure shows that the four parameters exhibit an approximately similar behaviour and evolution; it seems that they reach their maximum at the onset of the flare and then decrease. This result looks reasonable taking into account the fact that the Doppler width and source function increase when the energetic electron beams hit the flare atmosphere and decrease when the electron beams weaken. This figure also shows that the flare reaches its maximum at different moments. It is computed by converting the values of the Doppler shift into velocity in units of km/s. It ranges from about 20 km/s to 44 km/s with a mean average value of about 28 km/s. This value is less than the maximum velocities obtained by Ichimoto and Kurokawa [11], Zarro et al. [12] and Wulser and Marti [13], but it is reasonable, in good agreement, and comparable with those of Canfield et al. [14], Liu and Ding [1], and Berlicki [15]. The conspicuous downward motion in the flare emitting region with velocities up to 45 km/s can be found at the early stage of the impulsive phase of the flare. The evolution of the downward motions fluctuated very fast during the first 3 min reaching its maximum velocity at 07:26:22 UT, then it suddenly decreased by about 18 km/s. The downward motions slightly fluctuated for the next 20 min. Finally, it gradually decreased with decreasing the maximum intensity of the Hα line emission. Such chromospheric down flows would be most probably associated with the dynamics of chromospheric condensations. In spite of the numerical simulations, prediction that the lifetime of the condensation is of order of one minute, the velocities derived from Hα line profiles of this studied flare remained large even in the later phase, which are consistent with previous observations of Ichomoto and Kurokawa [11] and Liu and Ding [1]. This has been interpreted by Fisher [16] as a result of superposition of several condensations within an unresolved region. Wang et al. [17] showed in their study that the emission in the wings of Hα line profile could also exhibit high frequency fluctuations which was interpreted as a signature of fine structures related to elementary bursts; thus, the net line emission and velocity derived from the line could be fairly large even in the later phase.

An important conclusion can also be derived from the shape of the asymmetry of the observed profile. The observed Hα line profile seems to consist of two components. The core of the observed profile is generally unchanged and has no shift, while the shifted one produces profile with a red asymmetry. Comparing source function and Doppler width (Fig. 2) we can notice a correlation between them. The source function in the cloud model is not a free parameter, but depends on the Doppler width, as many authors mention. In the present work, the obtained results support such a conclusion.

To understand the impact of the condensation on the line profiles, the intensity profile irradiating the perturbed layer from below, $I_0(\Delta\lambda)$, a typical observed profile with red asymmetry, and the mean undisturbed profile near the flaring region are plotted in Fig. 3 as an example. The first one is constructed from eq. (1) using the four parameters derived above. $I_0(\Delta\lambda)$, is assumed to be symmetric as mentioned above with noticing that when fitting the asymmetry profile, $A(\Delta\lambda)$,

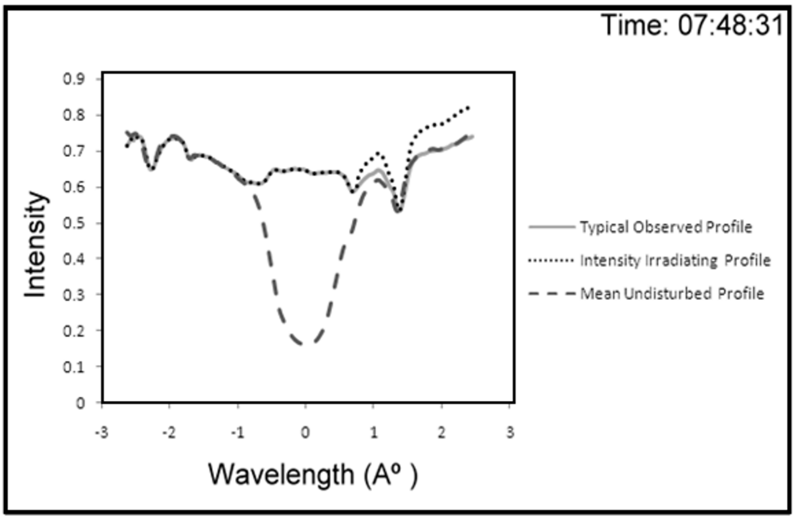

Fig. 3. Comparison of the mean undisturbed profile at 07:48:31 UT near the flaring region (dashed line), the typical observed asymmetry profile (solid line), and the intensity irradiating the perturbed layer from below (dotted line). Line intensity is in units of $I_{\text{continuum}}$. It shows emission excess in the red wing, while exact fitting is obtained in both, the line center and blue wing

the influence of other lines in the wing should be excluded, while the profile of $I_0(\Delta\lambda)$ is recovered using an extended wavelength window.

It is very interesting to note that this profile exhibited a large extent of emission compared to the undisturbed profile. This indicates that the atmosphere below the condensation could be heated substantially through various ways, which is in agreement with the flare dynamic models. Also, the heating may be caused by bombarding of high energy particles, possibly radiative back warming by the condensation, and irradiation by EUV and soft X-rays. Figure 3 reveals an important fact that the observed profile in the flaring region shows emission excess in the red wing compared to the profile just below the condensation. This implies that the source function finally determined from the Modified Cloud Model (MoCM) method is greater than $I_0(\Delta\lambda)$ near the line core which is consistent with the fact that the observed profiles show red asymmetry. This also implies that the atmosphere below the condensation may also be heated through different mechanisms.

Conclusion. We have used a modified cloud method (MoCM) to derive the physical parameters – the source function, the optical thickness at line center, the Doppler shift, the Doppler width and the downward velocity – of the Hα line profiles of the chromospheric moderate flare observed on June 26, 1999 with the multichannel flare spectrograph (MFS) at the Astronomical Institute in Ondřejov, Czech Republic.

The average temporal variation of the flare characteristics (Fig. 2) shows that the five parameters exhibit an approximately similar behaviour and evolution; it seems that they had reached their maximum at the onset of the flare and then had decreased. This result looks reasonable because of the fact that the Doppler width and source function increase when the energetic electron beams hit the flare atmosphere and decrease when the electron beams weaken.

The average temporal variation of downward velocity for the Hα line profiles of the studied flare is obtained by the modified cloud model (MoCM). It is computed by converting the values of the Doppler shift into velocity in units of km/s. It ranges from about 20 km/s to 44 km/s with a mean average value of about 28 km/s. This value is less than the maximum velocities obtained by Ichimoto and Kurokawa [11], and Wulser and Marti [13], but it is reasonable, in good agreement and comparable with those of Liu and Ding [1], Gu and Ding [2], Canfield et al. [14] and Berlicki [15].

The observed Hα line profile seems to consist of two components, the core of the observed profile is generally unchanged and has no shift, while the shifted one produces the profile red asymmetry.

We have obtained a good correlation between source function and Doppler width. This result supports the fact that the source function in the cloud model is not a free parameter. It depends on the Doppler width and many authors consider this fact, in the present work, the obtained results support such a conclusion, the observed profile in the flaring region shows emission excess in the red wing compared to the profile just below the condensation. This implies that the source function finally determined from the Modified Cloud Model (MoCM) method is greater than $I_0(\Delta\lambda)$ near the line core, which is consistent with the fact that the observed profiles show red asymmetry. This also implies that the atmosphere below the condensation may also be heated through different mechanisms.

Solar flares affect all layers of the solar atmosphere (photosphere, chromosphere, and corona), when the plasma medium is heated to tens of millions kelvins and the cosmic-ray-like electrons, protons, and heavier ions are accelerated to near the speed of light [18–20]. These studies are important as it is believed that changes of the solar activity can have a major impact on terrestrial physical and biological processes, i.e. on the space weather and space climate [21–24].

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*National Board for Technical and Vocational Education
*Faculty of Civil Aviation Technology and Meteorology
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*****Institute for Space Research and Technology
*Bulgarian Academy of Sciences
Stara Zagora Department
P.O. Box 73
6000 Stara Zagora, Bulgaria*
e-mails: penm@abv.bg
stoev52@abv.bg