ISSN 1845–8319

ON LINE PROFILE ASYMMETRIES IN SOLAR FLARE

T. PROSECKÝ [1,2], P. KOTRČ [1] AND A. BERLICKI [3,4]

[1] *Astronomical Institute of the Academy of Sciences of the*
Czech Republic, Fričova 298, 251 65 Ondřejov, Czech Republic
[2] Astronomical Institute of the Faculty of Mathematics and Physics,
Charles University, V Holešovičkách 3, 180 00, Praha 8, Czech Republic
[3] Observatoire de Paris, Section de Meudon, France
[4] Astronomical Institute of the Wrocław University, Wrocław, Poland

Conference paper

Abstract. To detect vertical velocity fields from observed H_α profiles we analyze spectral line profile asymmetries in the flare on August 10, 2003. In addition to a bisector method we use a comparison of the observed and non-LTE calculated profiles. In most of the analyzed flare kernels we detect a weak blue asymmetry and interpret it in terms of a downward motion. Capacities and results of the two methods are compared and discussed.

Key words: Sun – solar flares – spectrum – line profile asymmetry

1. Introduction

Spectral lines in solar flares typically indicate the profile asymmetries. This phenomenon contains information on the velocity fields present in different depths of the solar atmosphere affected by abrupt heating or various non-thermal flare processes. As spectral lines of various chemical elements originate at different heights of the solar atmosphere they can be used for diagnostics of the spatial distribution and time evolution of velocity fields in the flaring atmosphere.

Asymmetry of a spectral line profile arises from mass motions of a flaring atmosphere. Therefore, detection of asymmetries can be used for study of such motions and for testing of different flare models. Most extensive data exist for the H_α line. Strong asymmetries (mainly red but also blue) have been detected during impulsive phase of a flare (Ichimoto & Kurokawa (1984), Canfield et al. (1990), Heinzel et al. (1994) and others). Usually the red asymmetry is interpreted as a consequence of downward motions of cool and dense plasma (*chromospheric condensation*) with velocities of the order of tens $\mathrm{km\,s^{-1}}$. Origin of these motions is most probably due to a fast heating of upper chromospheric layers (caused by particle beams) during impulsive phase of a flare. Quite different physical situation occurs during the gradual phase of a flare. Schmieder et al. (1987) observed small but long lasting blue shifts in the H_α line core in a two-ribbon flare and interpreted them as a consequence of upward mass motions with velocities up to 10 $\mathrm{km\,s^{-1}}$. They called this *a gentle evaporation*. During the impulsive phase of a flare the energy is transported by beams of non-thermal particles which proceed from the corona to the chromosphere and cause an explosive heating. However, if the energy flux (transferred by these particles) is low, the *gentle evaporation* takes place due to other heating and dynamical processes. One can assume that it arises after the primary energy release and after thermalization of electron beams. These physical conditions prevail during the gradual phase of a flare, see e.g. Berlicki et al. (2005).

2. Data

Observations of the flare on August 10, 2003, which are processed in this work, have been taken from archives of the solar department of Astronomical Institute of the Academy of Sciences of the Czech Republic in Ondřejov. Since 1958 till June 2004 there had been in operation the *Multichannel Flare Spectrograph* (*MFS*). Parameters of MFS can be found in Valníček et al. (1959), later upgrades are described by Kotrč (1997).

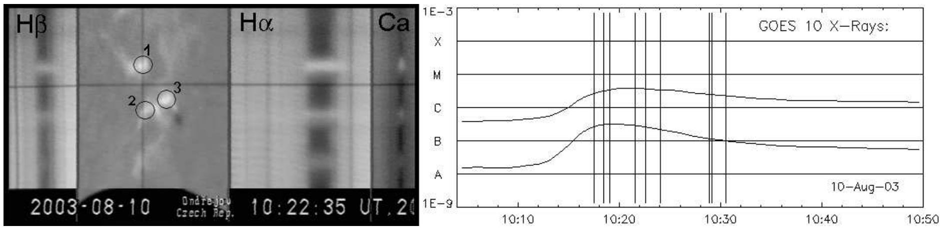

Figure 1: Images and spectra of NOAA 0425 taken by MFS (left panel, circles mark the kernels where the H_α line profiles of the flare were obtained). Right: time evolution of X-ray flux observed by GOES during the flare of August 10, 2003. Black vertical lines mean the times of observation by MFS.

Time of the MFS observation was 10:15 - 10:45 UT. Duration of the flare and time of its maximum from GOES were 10:11 - 10:31 and 10:20 UT, respectively. Position and importance of the flare according to NOAA (0425 active region) were S06, W36 and SF, respectively. Its class according to GOES was C3.5. Demonstration of the MFS record is given in Fig. 1. There is also shown a time evolution of X-ray flux observed by GOES.

3. Methods of analysis of line profile asymmetries

To investigate the line profile asymmetries two methods can be used. The first one is based on the *modeling of radiation transfer in flaring atmosphere and comparison of the observed and synthetic non-LTE profiles*, the second one is a 'direct' *bisector method*.

3.1. NON-LTE MODELS OF FLARES

To study the line profile asymmetries (which originate due to macroscopic mass motions) it is necessary to include velocities of these motions into non-LTE transfer calculations. In case of small velocities ($\leq 10\ \mathrm{km\,s^{-1}}$) which do not affect the plasma excitation and ionisation too much it is possible to use static non-LTE models for finding the atmospheric parameters and then to perform the formal solution of radiation transfer equation with prescribed velocity field (Nejezchleba, 1998). We used this approximation and followed the approach of Berlicki et al. (2005). In the first step a grid of static models of the flaring atmosphere was constructed by varying two parameters: m_0 (modification of the column mass scale of the reference atmosphere) and ΔT (modifies the temperature distribution of the reference atmosphere). Then each observed profile was compared with such grid of synthetic profiles by least-square method. For best fitted parameters of the static atmosphere another grid of synthetic profiles is constructed by the formal solution of radiation transfer equation with prescribed velocity field defined by

$$V(\tau) = \frac{2V_0}{1+\tau/\tau_m}\,, \tag{1}$$

where τ is optical depth and τ_m marks the line-center optical depth at which the velocity is equal to V_0. This velocity field was originally used for expanding atmospheres (Mihalas, 1970) and it is also suitable for description of flows in the flaring atmosphere (Nejezchleba, 1998; Berlicki et al., 2005). Positive values of the velocities mean the downward motion. Parameters of this second (velocity) grid are V_0 and τ_m. Finally, each observed profile is compared with this second grid by least-square method too. The parameters of these grids are the same as in Berlicki et al. (2005), but the velocity parameter V_0 is larger – from +10 to -10 km s^{-1}. More details about construction of these grids can be found in Berlicki et al. (2005).

K	T [UT]	χ_1^2	m_0 [g/cm^2]	ΔT [K]	χ_2^2	$\log \tau_m$	V_0 [km/s]
1	10:17:15	6.13	0.00100	-300	3.85	+1.0	+0.63
	10:19:01	9.39	0.00100	-250	5.45	+1.0	+2.50
	10:22:35	5.98	0.00095	-300	3.82	+1.0	+1.25
	10:24:05	4.02	0.00090	-350	2.82	+1.0	+0.63
	10:29:04	3.01	0.00085	-450	2.10	−0.9	+12.50
2	10:17:15	2.60	0.00030	-700	1.96	−0.8	−1.88
	10:19:01	2.38	0.00060	-700	2.05	−1.0	+9.38
	10:21:26	1.81	0.00055	-500	1.77	−0.6	+3.13
	10:24:05	2.85	0.00060	-400	1.87	−0.7	+6.25
	10:29:04	6.16	0.00035	-700	2.17	+1.0	+2.50
3	10:17:29	3.68	0.00090	-450	2.67	−0.9	+12.50
	10:18:34	2.66	0.00085	-450	1.94	−0.9	+12.50
	10:21:31	3.69	0.00070	-450	2.26	−0.7	+11.87
	10:22:41	2.84	0.00050	-550	1.60	+0.2	+3.75
	10:28:54	3.28	0.00060	-600	1.84	+0.3	+6.25
	10:30:38	4.65	0.00050	-700	1.54	+1.0	+5.63

Table I: Results of the fitting procedure. K means kernel, T means time; m_0 and ΔT are parameters of the static models deduced from the first step of the fitting of synthetic H_α line profiles with observed ones; τ_m and V_0 are parameters of the vertical velocity field deduced from the second step of the fitting procedure; χ^2-values are parameters of the preciseness of the first and second step of the fitting procedure, respectively.

We use the differences in 161 wavelength points for fitting procedure. These cover the interval between 6562.03 Å and 6563.63 Å (−0.8 Å to +0.8 Å from the line center) approximately. Synthetic and observed profiles exist for interval approximately ±2 Å, however, it has been necessary to cut off blends of terrestrial line of water 6564.206 Å. For this reason we take into

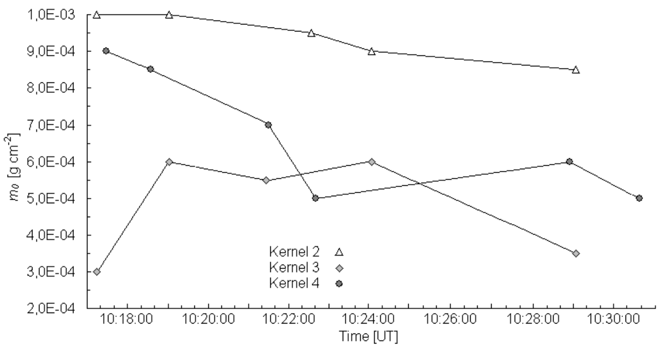

Figure 2: Time evolution of the parameter m_0 as determined from the fitting procedure.

account the range ±0.8 Å only. Parameters of the static flare atmosphere and resulting parameters of the vertical velocity field can be found in Table I. We assumed the velocity vector perpendicular to the solar surface. Therefore, the parameter V_0 was corrected for the position of the flare equivalent to $\cos\theta = 0.8$. Time evolution of m_0 parameter can be found in Fig. 2. Comparison of observed and best fitted synthetic profiles is given in Fig. 4. There is also a value of χ^2 divided by the number of fitted wavelength points in the Table I. This value from the second step of the fitting procedure must be lower or at least equal to the value from the first step. This condition was fulfilled for all of the profiles. Finally, vertical velocity field $V(\tau)$ was evaluated from parameters V_0 and τ_m according to formula (1). Results are given in Fig. 3.

3.2. Bisector method

Due to the complexity of the transfer solutions, the bisector method has been widely used for quantitative analysis of line profile asymmetries. Thanks to its simplicity it is still used. However, several problems arise in connection with this method.

Line bisector is defined as the locus of points midway between the equal intensity points to either side of the line profile. For practical use it is usually expressed as a distance from the line center in units of the velocity.

Next step is an allocation of the derived velocities to geometrical or optical depths in flaring atmosphere. However, first problems can be found

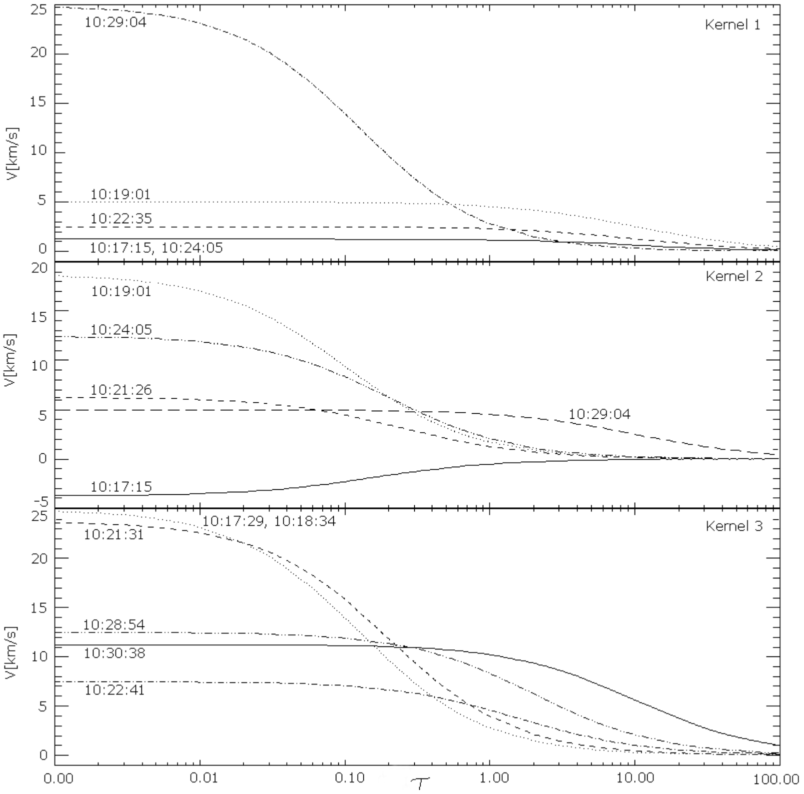

Figure 3: Vertical velocity of the plasma as a function of the H_α line-centre optical depth determined from fitting procedure (upper panels and lower left panel).

here. A high precision of such allocation is almost impossible. For an approximate allocation so called *contribution function* (CF) can be used. CF expresses the amount of radiation by which a given layer of the atmosphere contributes to the emergent monochromatic intensity. Hence, if the CF is single valued (it has one distinct peak) the velocities derived from the corresponding intensity can be ascribed to the movement of the atmospheric layer in which CF peaks. However, to use the CF the parameters of the flaring atmosphere have to be known and this requires the non-LTE calculation. In addition, this can be used only in case when the CF is not affected by velocity fields too much. Fortunatelly, according to Qu and Xu

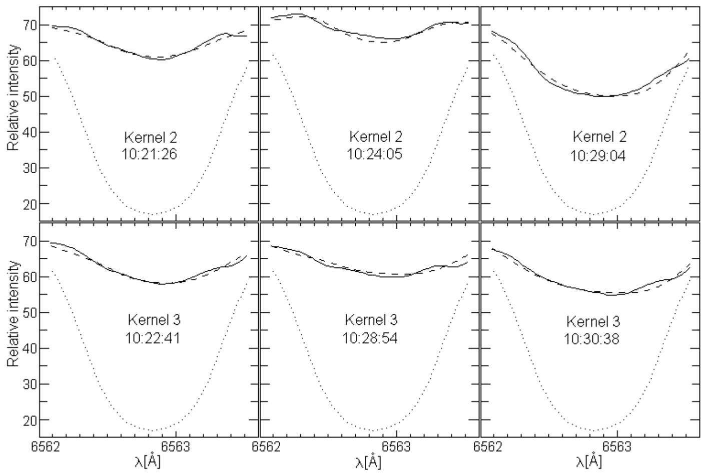

Figure 4: Examles of the observed (continuous lines) and fitted (dashed) H_α line profiles of the flare on August 10, 2003. Dotted line mean the reference profile of the quiet-Sun chromosphere for $\mu = 0.8$ taken from David (1961). Intensities are in % of continuum.

(2002) this condition is satisfied for diagnostically important lines (H_α, H_β or CaII 8542 Å). More details about CF can be found there.

Next problem of bisector method is its straigtforwardness – the origin of asymmetries could not be found. For example one can not distinguish if the origin of red asymmetry is due to emission of layers which move from the observer or whether the origin is in absorption of layers which move to the observer. Therefore, in some cases there can be a totally misleading interpretation of the results and in fact the sign of velocities can be oposite.

There can be problems with flat line profiles too. When we want to use bisectors for profiles where the emission totally fills the absorption profiles, the bisector method fails. This problem is sometimes solved by using the *difference profiles*, which means that profiles of the quiet Sun are subtracted from the flaring ones. However, this can be used only under some simplifying assumptions, e.g. when the source function $S = const.$ in a flare and when the optical depth $\tau < 1$ (see Ichimoto & Kurokawa, 1984). For the core of the H_α line this can not be used because $\tau > 1$ there.

Due to some flat profiles we could not use the bisector method for all of the observed profiles. But we could find velocities for 8 of 16 profiles.

Results derived for the line core can be found in Table II. It can be seen there that all derived velocity values are positive which means downward motion. As the line core we take the range ±0.2 Å around the line center. In this interval the bisector method has been used and averaged value of the velocity (rounded to one half of $\mathrm{km\,s^{-1}}$) has been taken as a result. This range of wavelengths has been taken according to CF of F1 flare model taken from Qu and Xu (2002). It would be better if this range has been taken according to CF of each profile, however this would require non-LTE computations which we try to avoid by using the bisectors.

4. Discussion and conclusions

Using the method of the non-LTE computation we established a pattern of the vertical velocity field versus optical depth in the center of the H_α line in the flare on August 10, 2003. In addition, velocities for some profiles were derived also by the method of bisectors. We found mostly positive values of Doppler shifts (downwards), only 1 of 16 analyzed profiles showed a small negative velocity value. In most of the analyzed flare kernels we detected a weak blue asymmetry (i.e. slightly increased intensity in the interval from -0.5 to -0.6 Å), while the line core displays a weak red shift. As was first shown in Heinzel et al. (1994) or in Nejezchleba (1998) and Berlicki et al. (2005), the blue asymmetry can be caused by the downward motion. We found the velocity parameter V_0 in the range from -1.9 $\mathrm{km\,s^{-1}}$ till +12.5 $\mathrm{km\,s^{-1}}$. These results do not correspond with the scenario of *gentle evaporation* for the gradual phase of the flare, where e.g. Kašparová et al. (1998) or Berlicki et al. (2005) interpreted a weak red asymmetry during the gradual phase as an upward plasma motion.

As we mentioned earlier, it is believed that this method is usable for small values of velocities occurring mostly in the gradual phase of flares. However, we applied the method for profiles from all the phases of the flare, even from its impulsive part. As stated earlier, maximum of the flare occurred at 10:20 UT. We can see from the Table I that the values of χ^2 are small and therefore the computed theoretical profiles are in a good agreement with the observed ones even for the beginning of the flare. A decrease of the m_0 parameter in time can be seen in the Figure 2, which is quite similar as it was found by Berlicki et al. (2005). It has to be noted that accuracy of the data is influenced by seeing and by the instrumental effects.

Kernel	Time [UT]	V_{non} [km/s]	V_{bis} [km/s]
2	10:17:15	-0.5	0.0
	10:19:01	+1.7	+6.0
	10:21:26	+1.3	+2.5
	10:24:05	+2.1	+5.5
	10:29:04	+4.5	+3.0
3	10:22:41	+4.6	+4.0
	10:28:54	+8.3	+6.5
	10:30:38	+10.2	+5.5

Table II: Comparison of vertical velocities determined for H_α line-centre optical depth $\tau = 1$ by fitting procedure (V_{non}) and bisector method (V_{bis}).

We estimated the broadening of the used lines and applied a convolution of the theoretical profiles with a gaussian of 0.2 Å halfwidth. As was stated earlier by Berlicki et al. (2005), quite large discrepancies appear when rather flat profiles are to be matched and processed. We tried to avoid these profiles and exclude them from processing.

In several works (Heinzel et al., 1994; Nejezchleba, 1998) we can find a statement that results of the bisector method can be misleading. Results which we got by the bisector method can be confirmed by a comparison with ones obtained from the modeling of the radiation transfer in flaring atmosphere. For this we use a rough approximation as follows. CF of the H_α line core rises mainly in a very narrow layer, thus we can assume that below this layer an optical depth $\tau > 1$ (optical depth appears in exponential function in the definition of CF, thus with the growing optical depth the CF will drop very quickly). It means that the optical depth should be around one somewhere in this layer. As a consequence, the velocities deduced from bisectors for the line core can be allocated at depths where $\tau \approx 1$. Results of the modeling method depend on the optical depth, so we need to use formula (1) only. Results of this approach can be found in Table II where we can see a relatively good agreement despite of the rough approximation. Consequently, the bisectors shoud not be cast away but it is necessary to work with them very carrefully. As was shown e.g. in Berlicki et al. (2005), blue asymmetry can arise because of downward mass motions – a blue peak can be seen in a profile but the line core is shifted to the longer wavelengts.

If the bisector method is used for the line core of this profile, we will get qualitatively suitable values of velocities. However, if the bisector method is used for difference profile (flare−quiet), it can be seen easily that results are inverse. Nejezchleba (1998) writes: 'Profile includes, besides the part of the profile directly affected by the moving material, also a static part of the profile. To use the bisector in terms of Doppler shift the static part should be somehow eliminated.' As we can see from the text above, for the H_α line it can not be done by automatical substracting of preflare profile.

Acknowledgements

This work was supported by the grant IAA3003203 of the Academy of Sciences of the Czech Republic and the project AV0Z10030501 of the Academy of Sciences of the Czech Republic.

References

Berlicki, A., Heinzel, P., Schmieder, B., Mein, P., Mein, N.: 2005, *A&A* **430**, 679

Canfield, R. C., Kiplinger, A. L., Penn, M. J., Wülser, J.-P.: 1990, *ApJ* **363**, 318

David, K. H.: 1961, *Zeitschrift für Astrophysik* **53**, 37

Heinzel, P., Karlický, M., Kotrč, P., Švestka, Z.: 1994, *Sol. Phys.* **152**, 393

Ichimoto, K., Kurokawa, H.: 1984, *Sol. Phys.* **93**, 105

Kašparová, J., Kotrč, P., Heinzel, P., Nikulin, I.F., Rudawy, P.: 1998, *IAU Coll.167*, *ASP Conf. Ser.* **150**

Kotrč, P.: 1997, *Hvar Obs. Bull.*, Vol. **21**, 97.

Mihalas, D.: 1970, *Stellar Atmospheres.* W. H. Freeman, San Francisco.

Nejezchleba, T.: 1998, *A&A* **127**, 607

Qu, Z. Q., Xu, Z.: 2002, *Chin. J. Astron. Astrophys.* **2**(1), 71

Schmieder, B., Forbes, T. G., Malherbe, J. M., Machado, M.E.: 1987, *ApJ* **317**, 956

Valníček B., Letfus V., Blaha M., Švestka, Z., Seidl, Z.: 1959, *Bull. Astron. Inst. Czechosl.* **10**, 149