UNDERSTANDING SOLAR FLARES FROM OPTICAL OBSERVATIONS: HOW PARTICLE BEAMS DO AFFECT THE LOWER ATMOSPHERE ?

P. Heinzel[1]

[1] *Astronomical Institute, Academy of Sciences of the Czech Republic, CZ-25165 Czech Republic*

ABSTRACT

During the impulsive phase of solar flares, both hard X-ray (HXR) and optical emissions exhibit fast temporal fluctuations detectable down to sub-second scales. This is usually ascribed to the propagation of beams of accelerated particles and to the dissipation of their energy in lower layers of the solar atmosphere. Although it is rather difficult to prove a temporal correlation between HXR and optical intensity variations, we discuss here some previous results and recent attempts. Namely in coordination with RHESSI observations, several ground-based observatories started to detect fast optical variations in the Hα line. In addition to this, we also mention a possibility of using some other diagnostically important lines. The proper interpretation of coordinated HXR and optical observations further requires robust tools for radiation-hydrodynamical (RHD) forward modeling. We briefly describe a new 'hybrid' code which consists of RHD part and particle-simulation part. Short-duration heating due to beam pulses is modeled which allows us to predict temporal fluctuations of HXR and selected optical and UV lines formed in chromospheric layers and in the transition region. Particularly the line asymmetries originating in a highly dynamical lower atmosphere of the flare can be used to diagnose the response of these layers to particle beams.

INTRODUCTION

Optical observations of solar flares have been carried out since many decades, using different types of instruments ranging from rather small but *dedicated* telescopes to largest tower telescopes equipped with high-resolution spectrographs. Before the space observations in X-rays were available, the focus on optical observations was very strong since they represented the main source of informations about plasma processes in the flaring atmosphere. However, as Zdeněk Švestka recently pointed to me, that period - viewed from today's perspective - could be characterized as an effort 'to reconstruct the whole dinosaur from analysis of his footprints'. Nevertheless, many important conclusions were drawn about the physics of *chromospheric flares* how the lower flare atmosphere is sometimes called.

Today we know that the solar flares are highly-energetic processes which take place mainly in the corona and what we observe in the chromosphere or photosphere is the response of the lower atmosphere to the energy transport of various kinds from primary energy-release sites. However, this should not be considered as some unimportant secondary effect, on the contrary, the chromospheric behaviour can serve as an important diagnostics of processes which originally take place in the hot flaring loops. Typical example is the propagation and dissipation of accelerated particle beams, where both hard X-rays (HXR) as well as optical emissions originate in the chromosphere (Karlický, 1997).

Here we will be concerned only with the so-called impulsive phase of flares during which the most energetic processes take place. Their understanding is the principal goal of the RHESSI mission (Ramaty High Energy Solar Spectroscopic Imager) and optical observations carried out *simultaneously* with RHESSI represent an important complementary diagnostics as we will discuss in this paper.

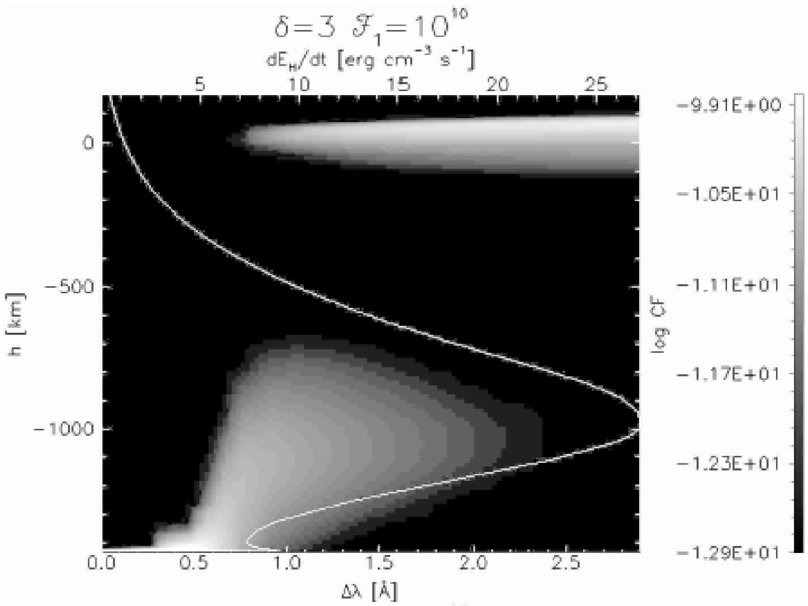

Fig. 1. Energy deposit dE_H/dt (white profile) and the Hα contribution function CF (gray scale). Hα wings are formed at heights h where the energy deposit has the maximum for parameters indicated on top of the figure. The line core is not much affected by the beam. From Kašparová and Heinzel (2002).

Hα LINE FORMATION

Most frequently observed optical line is hydrogen Hα which goes to emission during flares. We will briefly summarize our basic knowledge about the behaviour of this strong line. Other optical lines have similar properties and some of them (e.g. higher Balmer lines of hydrogen, CaII lines and others) have been used for complementary spectral diagnostics.

Avrett et al. (1986) showed three Hα profiles which correspond to three static *semiempirical models* of flares as constructed by Machado et al. (1980) (denoted as F1, F2 and F3 models). They are compared to a quiet-Sun profile. These models were frequently used to study the behaviour of the Hα line formation in static and dynamic atmospheres and in the presence of particle beams (electrons and/or protons). In particular, flare atmospheres F1 and F2 were perturbed by electron and proton beams and the effects of non-thermal collisional excitation and ionization of hydrogen were studied. The result is an enhancement of the Hα intensity in the presence of the beams (see reviews by Hénoux (2000) and Fang et al. (2000)). This has been recently confirmed by Kašparová and Heinzel (2001), although their results show somewhat different behaviour. The effect of electron beams with increasing flux F_{20} on first three Balmer lines formed in the F1 atmosphere is also shown in that paper. A similar study was performed by Fang et al. (1993) for CaII lines, but these lines are less sensitive to non-thermal processes. Quite recently, Gan et al. (2002) have demonstrated that the cut-off energy can be much higher than 20 keV and this may have significant consequencies on the above mentioned results.

To study the beam interaction with the lower atmosphere, we must understand at which depths the individual parts of the line profile are formed. This is normally described by the so-called contribution functions. Then the formation depths are to be compared with the depth-dependent energy-deposit function. Total energy loss from the beam has two components: direct Coulomb losses which convert the beam energy into the plasma heating, and the losses into hydrogen which leads to the non-thermal excitation and ionization. If for example the Hα line core is formed higher compared to the location of the maximum energy deposit into hydrogen, the line brightening will take place mainly in the wings (see Fig. 1).

FAST Hα FLUCTUATIONS

Rapid variations of the Hα line intensity have been reported in the literature and were compared with microwave and HXR fluctuations, in order to understand fast processes in particle beams. Certain degree of correlation was found, but in most cases on time scales larger than one second. Hα is mostly correlated with HXR, but the fine structure of fluctuations on subsecond time scales has not yet been firmly established. Previous measurements are presented in Dennis et al. (1987) and Kundu et al. (1989), here we mention some of the most recent studies.

Multiwavelength observations of two flares, using the imaging spectrographs at Locarno-Monti (Switzerland), were reported by Rolli et al. (1998a, 1998b). Hα spectra were obtained with the time resolution 2.3 sec and the imaging spectrograph obtained Balmer Hϵ and CaII H data with resolution up to 1.1 sec. Spectral data were correlated with soft X-rays (SXR) and HXR from Yohkoh and with radio observations. The authors found that the strongest footpoint emission in the optical lines does not coincide with the sites of the particle beam injection and these footpoints are thus heated by thermal conduction. A similar kind of analysis was recently done also by Asai et al. (2002). Using density-sensitive Hϵ line (its wings are strongly Stark-broadened), they analyzed the temporal evolution of the electron density in flaring footpoints. This electron-density variation correlates well in time with the HXR emission in one footpoint, while in another one the ionization seems to be predominantly of thermal origin.

Locarno-Monti Hα observations were also used to study fast and slow chromospheric responses to non-thermal particles during a HXR/γ-ray flare (Trottet et al., 2000). In this case the temporal resolution in Hα was 0.2 sec and high temporal resolution was also achieved in HXR (full-disk flux) with the PHEBUS instrument. A new idea is to model the Hα time variations using time profiles of HXR and then to compare them with the observed ones. The results of such a procedure demonstrate generally good correlation between HXR and Hα. From the HXR time profiles, one can infer the so-called *injection function* of the beam, which can be used in simulations of the Hα response. In Fig. 2 we show the correlation between Hα and HXR for one kernel during a short time interval.

The energy injection function was also evaluated by Kurt et al. (2000). Moreover, these authors have investigated correlations of fast Hα fluctuations (temporal resolution 0.27 sec) between different flaring kernels. Positions of correlated kernels were compared with the magnetic connectivity between footpoints of the flaring loops.

Finally, we mention the observations of Wang et al. (2000) obtained at BBSO with a narrow-band Hα filter tuned to the blue wing at 1.3 Å and with a cadence of 0.033 sec. The blue wing is supposed to be more sensitive to a beam-pulse energy deposit while the red wing typically responses to the motion of the chromospheric condensation (Canfield and Gayley, 1987). Hα time profiles were compared with HXR from BATSE, however, only 1 sec resolution mode was available for the flare under study. For the flare kernel which shows a good correlation with HXR, high-frequency fluctuations on a timescale of a few tenths of a second were found. Their amplitude exceeds the noise by a factor of three. Such observations correspond only to about 7 sec. In Fig. 3 we reproduce these observations taken in three different flare kernels. One can notice that indeed the highest amplitude fluctuations are seen in kernels where Hα correlates well with HXR.

The authors conclude that these fluctuations may be signatures of the Hα fine structure related to HXR elementary bursts. Based on these observations, the authors claim the evidence of Hα fluctuations on the subsecond time-scale which are above the noise level. However, it is not very clear what is the actual background intensity relative to which we do see such fluctuations. If the fluctuations correspond to emission enhancements only, then this level should be a curve connecting the minima. On the other hand, in their Fig. 7 Wang et al. (2000) show the fluctuations after subtracting a 10-point smoothed average. The minima seen in this intensity plot may correspond to fast variations of the beam energy deposit - we show this effect in the next section.

TIME-DEPENDENT SPECTRAL LINE FORMATION

In order to understand theoretically the relation between fast HXR (non-thermal bremsstrahlung in the low atmosphere) and Hα fluctuations, one can perform simplified numerical simulations, neglecting the dynamics. This is to some extent possible because the time scales on which the non-thermal processes

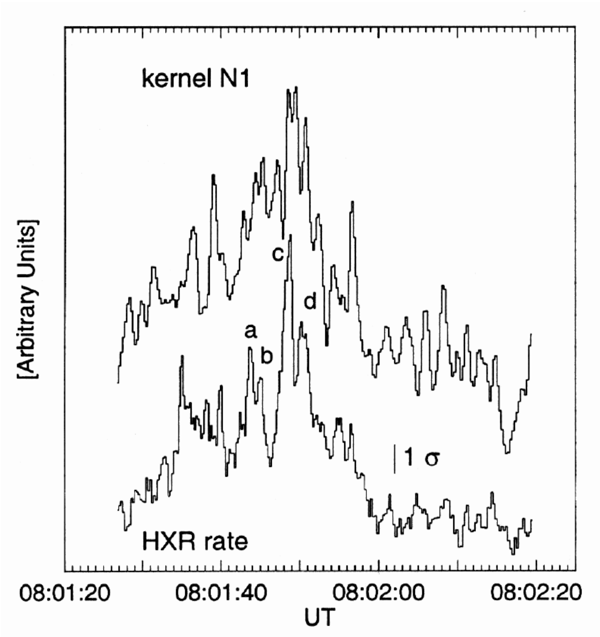

Fig. 2. Time evolution of the fast Hα intensity response (upper curve) to HXR rate (lower curve). HXR peaks a - d have corresponding ones in Hα. Note the significant Hα intensity drop just before the peak at time c. From Trottet et al. (2000).

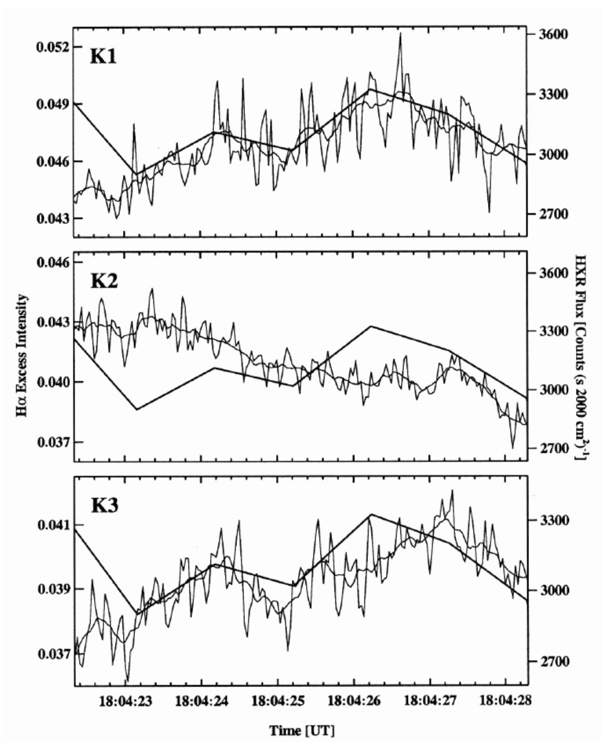

Fig. 3. Comparison of Hα–1.3 Å intensity (thin lines) and BATSE HXR flux (thick lines) for three flare kernels during 7 sec of the impulsive phase. For the Hα emission, both the raw data and a 10-point smoothed curve are plotted. From Wang et al. (2000).

influence the flare plasma are shorter compared to hydrodynamical time scales. To solve the time-dependent non-LTE line formation problem, we can start either with prescribed temporal variations of the temperature (Heinzel, 1991) or solve an approximate energy-balance equation (e.g. Ding et al., 2001).

Neglecting the dynamics, the time-dependent statistical-equilibrium equations can be written as

$$\frac{\partial n_i}{\partial t} = \sum_{j \neq i} (n_j P_{ji} - n_i P_{ij}), \tag{1}$$

where n_i is the population of i-th level (here we consider the hydrogen atom model) and P_{ij} is the total rate for transition $i \rightarrow j$. The rate P_{ij} consists of the radiative rate R_{ij} and collisional rate C_{ij}. The latter has the form

$$C_{ij} = n_e \Omega_{ij}(T) + C_{ij}^{nt}, \tag{2}$$

where n_e is the electron density, Ω_{ij} is the collisional cross-section for a given temperature T (see e.g. Mihalas, 1978) and C_{ij}^{nt} represents the non-thermal collisional rate, i.e. the collisional excitation and ionization induced by the beam particles. According to Fang et al. (1993), we can express the non-thermal rates as

$$C_{1j}^{nt} \simeq \frac{1}{n_1} \frac{dE_H}{dt}, \tag{3}$$

where n_1 is the ground-state population and dE_H/dt is the energy deposit from the beam into the hydrogen (by non-thermal excitations and ionization). Inverse thermal rates are obtained from the detailed balance, while inverse non-thermal rates are negligible. To obtain the radiative rates, one has to solve the radiative-transfer equation in the form

$$\mu \frac{dI_{\nu\mu}}{dz} = -\chi_{\nu\mu} I_{\nu\mu} + \eta_{\nu\mu}, \tag{4}$$

where $I_{\nu\mu}$ is the specific intensity and $\chi_{\nu\mu}$ and $\eta_{\nu\mu}$ are, respectively, the opacity and emissivity. A coupled set of these non-LTE equations, together with additional constraint equations, is then solved using the Crank-Nicholson time-difference implicit scheme (the resulting set of equations is linearized with respect to particle number densities). An efficient technique to solve this non-LTE transfer problem is so-called MALI-method (for more details see Heinzel, 2000).

In context of this approach, Heinzel (1991) has performed time-dependent simulations of the Hα line formation in the chromosphere bombarded by short-duration (sub-second) electron beams. Three important results have been obtained:
(i) for typical flare conditions, the electron-density variations do not follow the temperature ones because of substantial relaxation time for hydrogen recombinations;
(ii) there is a significant Hα response to beam pulses;
(iii) at the pulse onset, the Hα intensity drops down for very short sub-second period. The latter effect, which was also found in more sophisticated simulations (see below), has not been observationally proved yet, however, one could identify it in Fig. 2 where just before the HXR peak at time 'c', Hα drops down and this intensity drop is larger than the noise uncertainty (G. Trottet - private communication). In a similar way one could also interpret the negative minima in subsecond fluctuations reported in Wang et al. (2000).

Ding et al. (2001) performed similar simulations, solving a simplified energy-balance equation. They also found an instantaneous response of the Hα line intensity to the beam pulses of 0.2 sec duration and notable relaxation in the ionization balance of hydrogen, but they do not mention the intensity drops found in Heinzel (1991).

RADIATION-HYDRODYNAMICAL MODELS

First complex radiation-hydrodynamical (RHD) models of solar flares, which led to prediction of Hα variations, were developed by Fisher, Canfield and McClymont (1985). These models have revealed basic properties of the beam-heated atmospheric structure. However, they treated only beams with longer duration (several seconds) and the energy deposit was computed using a stationary approach of Emslie (1978). RHD models, which predict variations also in other optical lines, have been published by Abbett and Hawley

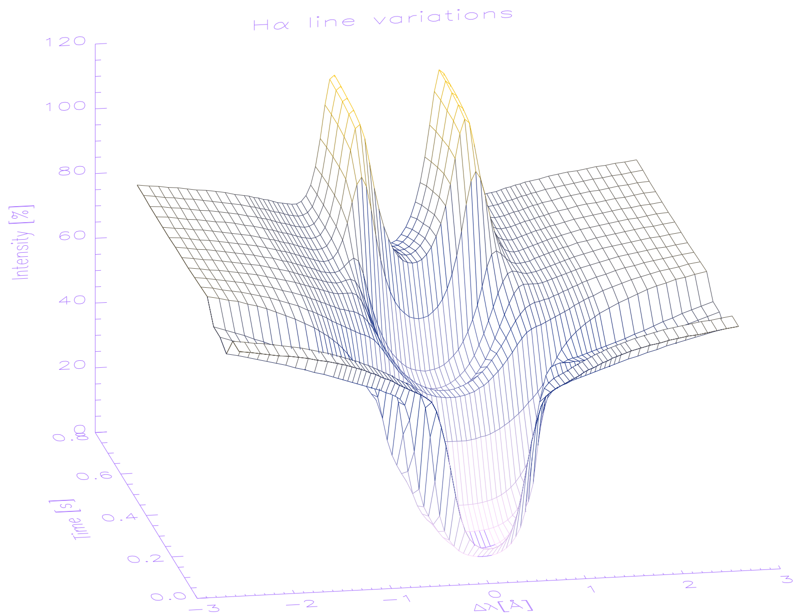

Fig. 4. Hα line-profile variations computed from RHD simulations of a sub-second electron beam pulse heating. The profile evolves from the quiet-Sun one at $t = 0$ sec into typically reversed emission profile. Note an intensity drop after the onset of the beam (for explanation see the text). In this example only a static transfer simulation is shown. From Varady et al. (2002).

(1999) who have used the RHD code of Carlsson and Stein (1990). A kinetic solution for an electron beam precipitation is described by Zharkova (2000), who considered the effects of the return current. On the other hand, Karlický (1990) and Karlický and Hénoux (1992) have developed so-called 'hybrid' code which is able to treat the beam propagation and energy deposit in a non-stationary way, taking into account the finite flight-time of the beam particles, their scattering, return current and other effects. This hybrid code computes the atmospheric response to a series of short-duration beam pulses (typically sub-second pulses), the beam being represented by numerical test particles with a mono-energetic or power-law distribution function. Atmospheric response is computed by solving the hydrodynamical and energy-balance equations. This code is now being coupled to time-dependent radiative transfer code based on the MALI technique (see previous section). An advantage of the particle description approach is that the fast transient phenomena are properly included and the hard X-ray emission can be computed directly.

By solving the time-dependent non-LTE problem for hydrogen, we theoretically predict the Hα-line intensity variations on sub-second time scales. Both computed hard X-ray fluxes and Hα wing intensities do exhibit a spiky behavior, consistent with short pulse-beam heating. At the onset of each beam pulse, the spikes in Hα are negative, i.e. the line intensity decreases for a very short time. This is due to a higher rate of the second-level hydrogen population as compared to that for the third level during the fast heating process at the onset of the beam energy deposition. These 'dips' are more pronounced when non-thermal rates are included, but appear also as a response to fast heating on subsecond scales. New RHD calculations performed by Ondřejov group (Varady et al., 2002) show the fast variations of the Hα line profile for one short electron beam pulse of a subsecond duration - see Fig. 4. The hybrid code was used, together with the time-dependent non-LTE transfer code based on the MALI approach. The next step is to simulate a stochastic series of beam pulses where the injection function can be supplied from the HXR observations.

LINE ASYMMETRIES AND FLARE DYNAMICS

Significant asymmetries are typically observed in strong optical lines and they are related to impulsive dynamics of the initial phases of flares. Usually one can detect the so-called 'red asymmetry' in the Hα line

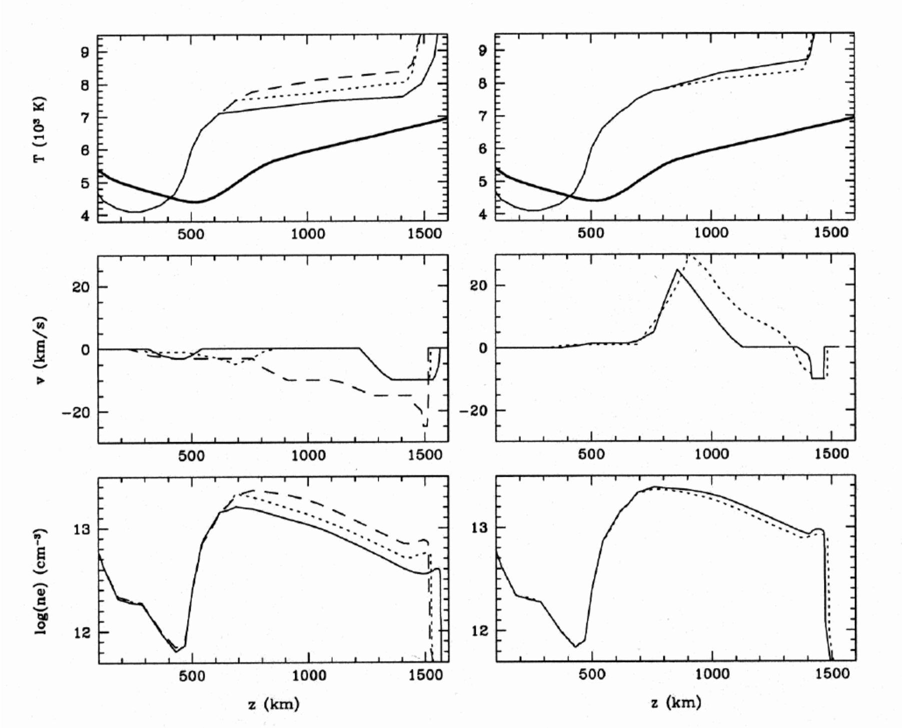

Fig. 5. Semiempirical flare models with velocity fields. Thick line in the temperature plot corresponds to the semiempirical VAL-3C model. In the left panels, three models are shown for three times prior to the HXR peak, while in the right panels another two models show the atmospheric behaviour after the HXR has peaked. Note significant downflows in the right panel. From Falchi and Mauas (2002).

and other Balmer lines, but at the onset of some flares, a blue asymmetry is also observed (for a review see Heinzel et al., 1994). Red asymmetry is typically represented by a strong emission enhancement of the red wing of the line, presumably caused by downward-moving chromospheric condensation (Canfield and Gayley, 1987). In CaII H and K lines, the red asymmetry is less pronounced (see e.g. Heinzel et al., 1994), but results of some numerical simulations do predict a strong red peak in the K line, well separated from the central emission profile (Abbett and Hawley, 1999). Blue asymmetry observations were reviewed in Heinzel et al. (1994), where the authors suggest that this type of asymmetry can be also produced by downward-moving plasma accelerated in upper layers of the chromosphere where the electron-beam energy is deposited (taking into account the return-current effects). When the flare atmosphere F1 is perturbed by downflows with a velocity gradient simulating the onset of a chromospheric condensation, the strongly reversed Hα profile becomes asymmetrical with a more intense blue peak. The computed profiles are consistent with those observed during initial phases of flares (see also Ding and Fang, 1997). Later on, during the impulsive phase, the Hα line goes to stronger emission and the coupling between still downward velocity field and the variations of the line source function leads to the red asymmetry.

Note, however, that some recent observations made simultaneously in the Hα line and the infrared CaII line at 8542 Å have shown the opposite asymmetries at the same time (Ding and Fang, 1996; Mein P. et al., 1997). This leads to a question how the velocity field in the flaring atmosphere is related to the run of the line source functions. The latter are dependent on the flare dynamics and therefore must be computed consistently with the velocity fields (e.g. Nejezchleba, 1998). This was done self-consistently in dynamical simulations of Fischer et al. (1985) and Abbett and Hawley (1999). However, a direct comparison of such simulations with temporal evolution of various lines is difficult and in fact was never done in detail. Instead, the 'snapshots' of the evolving atmosphere were modeled in terms of the semiempirical approach and the results were compared with the time evolution of spectral profiles of Balmer Hδ, CaII K and SiI 3905 Å lines, observed simultaneously with the HXR from BATSE (Falchi and Mauas, 2002). Upward flows were detected prior to the HXR peak, while after it the downward motions prevailed (Fig. 5). Note finally, that an interesting method was recently proposed by Liu and Ding (2001) who modified the so-called cloud model to derive empirically velocities from the peak asymmetries of the Hα and CaII 8542 Å lines observed during the impulsive phase.

REQUIRED OPTICAL DATA

In order to achieve further progress in understanding solar flares in their complexity, we need new high-resolution optical observations, obtained simultaneously with HXR and radio observations. Ideally, one would like to obtain temporal variations of spectral line profiles on subsecond time scales, in the whole 2D field-of-view (fov) where the flare is observed. Currently we use spectrographs with fast CCD's which can provide us with high-resolution spectra (both in wavelength and time), but spatial resolution is limited only to one dimension along the slit. Multiline data of this type can now be obtained for example at THEMIS, Sacramento Peak, Ondřejov (with a new multichannel scanning spectrograph - see Sobotka et al., 2001) and Nanjing. By using the scanning techniques, one can get time-dependent spectral information in 2D fov, but the temporal resolution is then correspondingly lowered. Imaging instruments which use various kinds of narrow-band filters give full 2D fov time evolution with usually high cadence (depending on CCD-type and storage capabilities), but normally this is done only in one wavelength. Various Hα telescopes routinely operated at several observatories are now used for detection of fast Hα variations (see e.g. recent BBSO observations reported by Wang et al. (2000)). Using two or even more wavelength positions with a given line (tunable filters) again lowers the time resolution, but for example the new ISOON telescope installed at Sacramento Peak can provide up to two images at two different line wavelengths within one second and this can be further improved by optimizing the readout of the large CCD used (D. Neidig - private communication). The instrument which can provide high temporal resolution in reasonably large 2D fov and still gets the full spectral information at each spatial position (but with limited spectral resolution) is the Multichannel Subtractive Double Pass spectrograph (MSDP) currently mounted on German VTT and French-Italian THEMIS telescopes on Tenerife (Mein P., 2002) and on Pic-du-Midi and Wroclaw university coronagraphs. We do not envisage any significant development of this kind of instrumentation within next few years, but a simultaneous usage of the above mentioned instruments, e.g. during specialized campaigns, will provide us with important optical data, provided that they are obtained *simultaneously and cospatially* with RHESSI observations. Rapidly fluctuating intensities which can be detected by these instruments are, however, mixed with intensity fluctuations due to seeing and this should be eliminated using such simultaneous data obtained by similar instruments. An important observational strategy is to point the telescope at preselected active region where the flare activity is expected and then record the data continuously until a flare appears - this guarantees that the onset of the flare is always catched (this is somewhat easier for full-disk telescopes). Note that RHESSI detects the full disk and thus will see all flares within the periods when the satellite can observe. Another quite important aspect of optical observations is that we usually concentrate ourselves on most intense optical lines like Balmer lines of hydrogen, CaII lines and some others. However, the flare emission appears also in many other lines of various species (see Švestka, 1976; Avrett et al., 1986) and this was investigated only marginally. In fact, having observed the time evolution of emission in such lines, one can diagnose much better the propagation and energy deposit of particle beams in the flaring chromosphere. Examples of a recent investigation of beam effects on metallic lines are studies by Ding et al. (2002) and Zharkova and Kosovichev (2002) of the NiI 6768 Å line formation during flares (this line is used by SOHO/MDI to measure the magnetic and velocity fields).

Finally, let us mention an increasing effort to detect an optical-line polarization (namely in the Hα line) which is expected to result from the beam collisions with hydrogen plasma - so called impact polarization. For a review of this special topic see Hénoux (2000).

CONCLUSIONS

As we saw in this paper (not a complete review - I appologize for many missing references), various attempts were made in the past to derive the physical conditions of the flare atmosphere from optical line observations. Based on spectral or imaging observations, various authors tried to diagnose the thermodynamic structure and velocity fields or quantify the relations between optical-line fast temporal fluctutions and the observed HXR bursts. Various aspects of the flare evolution are of course related to different time scales and thus the dynamics can for example be studied on longer time scales than fast (subsecond) energy deposit due to stochastically accelerated beams of particles. However, the final answer to questions how the flares originate and evolve must result from detailed comparison of time-dependent RHD simulations with high-resolution spectral observations not only in optical, but as well in IR, UV and EUV spectral bands. This must be done simultaneously and cospatially with HXR spectral observations for which RHESSI is now quite important mission.

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E-mail address of P. Heinzel pheinzel@ asu.cas.cz

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