IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

Dynamics of the chromospheric flares(*)

A. Falchi

Osservatorio Astrofisico di Arcetri - Largo E. Fermi 5, 50125 Firenze, Italia

(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — In this paper, I describe how chromospheric observations of a flare are used to locate the footpoints of the flaring loops and to analyse the response to the energy release during a flare. In particular, a red asymmetry in chromospheric lines is often observed during the impulsive phase of flares and is explained as due to Doppler-shifted emission of downward-moving chromospheric plasma. Using flare dynamic models that simulate in detail the physical conditions within the chromosphere, observables such as the response time, the duration and the peak value of the downflow velocity can yield information on the flare energetics. Moreover, this downward velocity is a chromospheric signature present in major events as well as in micro-flares, and seems to be a very distinctive characteristics of the flare process, more than the increasing intensity itself.

PACS 96.60.-j – Solar physics.
PACS 96.60.Na – Chromosphere and chromosphere-corona transition; spicules.
PACS 96.60.Rd – Flares, bursts, and related phenomena.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The dynamics of chromospheric flares can be an important probe of the flare energetics and of the transport mechanism of energy from the corona to the chromosphere. I will present a brief history of observational work on the dynamics of flares together with an illustration of the updated observations. I will discuss the hydrodynamic models that simulate the response of chromosphere for both thermal and non-thermal heating to stress the meaning of the expected observables. The open problems from observational and from theoretical point of view will be summarized.

(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.

2. – Observations

Flares at chromospheric levels have been generally observed in the Hα line because variations in this spectral range can be measured easily. The Hα emission varies during the flare development and the Hα line profile might turn from absorption in a quiet region into emission in a flaring one. The time dependence of the emission in the Hα center is very similar to the one of the soft–X-rays emission: it reaches its maximum simultaneously with the soft X-rays and decreases slowly afterwards. It does not have the impulsive character, common to almost all flares, of hard X-rays and microwave emission.

Švestka *et al.* [1] analyzed the spectra of 92 flares, observed both in the center and at the limb of the solar disc, with a spatial resolution of about 10$''$ and a temporal resolution from about 30 s up to 1 minute. The 80% of these flares showed line profiles with red asymmetry lasting for a few minutes within the maximum phase of the flare and the 23% of these show a blue asymmetry at the very onset of the flare lasting less than 1 minute. The red asymmetry is observed for the Balmer lines, for He lines and for metallic lines. Švestka *et al.* [1] and Fritzová [2] found that the asymmetry decreases from the center towards the limb, while Severny [3] found that the asymmetry at the limb was very similar to the one at the center.

Many hypotheses have been put forward to explain the temporal dependence of the asymmetry but still in 1976, Švestka [4] wrote in his book that an explanation for the asymmetry was still unknown, even if there were indications of some connection between the occurrence of the asymmetry and the flare energy transport from the corona to the chromosphere.

Ichimoto and Kurokawa [5] analyzed the spectra of 30 flares taken with much higher spatial and temporal resolution. They found that for almost all flares occurring near the disc center the Hα line shows red streaks at the impulsive phase of the microwave bursts. The typical size is less than 1$''$ and the lifetime is less than 40 s. They did not find any evidence of blue asymmetry at the onset of a flare as noted by [1] and [3]. From the analysis of the Hα line profile they interpreted the red asymmetry in terms of a downward motion in the chromospheric region with a maximum velocity of about 40–100 km s^{-1} attained a little before the impulsive peak of the microwave burst. In the following years many other observers (amongst others [6-9]) confirmed essentially these properties for the red asymmetry. No systematic observations of center and limb flares have been performed since the '60s, and hence nothing new about the center-to-limb behaviour of the asymmetry has been added to what debated between Švestka *et al.* [1] and Severny [3].

In these more recent observations a blue asymmetry of Hα line has been observed sporadically:

– in the case of an erupting filament before the flare (*i.e.* [8, 10]);

– during the impulsive phase confined to small structures that sometimes also showed red asymmetry during the maximum phase [8, 11]. In some particular case, the reported blue asymmetry during the impulsive phase [12] refers to a Hα profile with a strong central self-absorption and a blue peak enhanced with respect to the red one. This line profile has been matched by modeling the atmosphere with a downward directed mass motions, that can absorb the radiation of the red peak [13, 14], giving the striking result of a blue asymmetry produced by a downflow.

The emission in the Hα wings generally shows impulsive episodes simultaneously with the impulsive episodes observed in hard–X-ray emission. The association between the wing emission and the hard X-ray can help to understand the mechanisms responsible for the transport of energy from the corona to the chromosphere [15, 16].

In the years 1980-1990, plasma motions have been observed at coronal levels during the impulsive phase of flares. Instruments onboard of P78-1 and SMM and Hinotori [17-19] detected non-thermally broadened and blue-shifted emission lines of Ca XIX, S XV and Fe XXV ions. The lines are broadened by turbulent non-thermal motions, corresponding to a velocity of about 200 $\mathrm{km\,s^{-1}}$, constant before and during the hard–X-ray burst. On the other hand, the blue-shifted emission, corresponding to an upward velocity of 100–500 $\mathrm{km\,s^{-1}}$, peaks simultaneously with the hard–X-rays burst and decreases afterward. The blue shift is nearly absent in limb flares, suggesting that the motion is perpendicular to the solar surface. Antonucci *et al.* [18] interpreted the data in terms of turbulent upflow of chromospheric plasma and this phenomenon is generally referred to as "chromospheric evaporation".

3. – Hydrodynamic simulations

The interpretation of these velocity fields observed at different layers of the flaring atmosphere can be derived using dynamic models of a flare. Most of the existing dynamic models refer essentially to the coronal component and consider the chromosphere just as a boundary layer. I briefly review here only the results of hydrodynamic simulations which consider in detail the physical conditions in the chromosphere.

Two models of how the flare energy is released into the atmosphere are generally accepted.

The *non-thermal* model assumes that the flare energy is released into acceleration of energetic non-thermal electrons, which produce the observed hard–X-rays emission and ambient heating through collisions with ions and electrons, respectively.

The *thermal model* assumes that the flare energy is released by heating some coronal plasma to $\approx 10^8$ K temperature and that this energy is then transported to the lower atmosphere through the propagation of a conduction front.

Hydrodynamic simulations of the response of the chromosphere have been computed for both mechanisms of energy release solving self-consistently both the equations of hydrodynamics and radiation transport (see [20-22] for the non-thermal case and [23-25] for the thermal case).

I discuss how the observable parameters predicted by these models can help to better understand the processes at work during a flare.

When the flux of non-thermal electrons with energies over 20 keV is weak ($\leq 10^{10}\mathrm{erg\ cm^{-2}s^{-1}}$) the chromosphere is moderately heated and responds to the temperature increase by expanding upward.

On the other hand, when the electron flux is $> 10^{10}\ \mathrm{erg\ cm^{-2}s^{-1}}$ the chromospheric plasma is heated beyond its ability to radiate and the chromospheric temperature jumps to coronal values causing what is named "explosive evaporation". The overpressure of this gas drives material both upward at coronal levels (blue-shift) and downward at chromospheric levels (red-shift).

Therefore the upward or downward direction of the velocity in the chromosphere can be an important signature to establish if the flux of non-thermal electrons is larger or smaller of the threshold value $10^{10}\mathrm{erg\ cm^{-2}s^{-1}}$.

Also for the thermal case, the response of the atmosphere to the impulsive heating is the formation in the chromosphere of a downward-moving condensation, but with a different response time. In the case of heating by non-thermal electrons the downward motion is established within 1–2 s, while in the case of heating by a conduction front the response time is ≥ 10 s. Therefore the response time of the chromosphere with respect to the hard–X-ray burst is an important observable that can help to distinguish between the two energy transport mechanisms.

The condensation moves downward driven by the pressure excess due to evaporation and its motion has been studied by Fisher [24]. An important characteristic of the condensation is that the velocity is constant within the condensation. The peak velocity, reached at the beginning of the chromospheric response, is proportional to $F_{\rm evap}/\rho_{\rm chrom}{}^{1/3}$, where $F_{\rm evap}$ is the fraction of the energy flux driving chromospheric evaporation and $\rho_{\rm chrom}$ is the preflare chromospheric mass density. The duration and the decay of the downflows are insensitive to the details of flare heating and depend on the preflare pressure scale height of the chromosphere and on the peak velocity.

A new class of simulations has been introduced by Abbet and Hawley [26]. They simulated the response of the atmosphere to the non-thermal electrons and to the thermal soft–X-rays irradiation. With respect to the previous models, the radiative transport is treated in much more detail and the "quiet" pre-flare atmosphere is given by the initial atmosphere of Carlsson and Stein [27] (with added a transition region and corona). The major difference between the latter, and a classical semiempirical atmosphere is the lack of chromospheric temperature rise. For these simulations each event progresses in two dynamic phases: a gentle phase for which no motions are measurable in chromospheric lines and an explosive phase with significant motions starting after 4–30 s. Although interesting, these models do not give the opportunity of comparing the two possible mechanisms of energy deposition for a flare.

4. – Observations *vs.* simulations

I try to summarize the major arguments to support or disprove the hydrodynamic simulations.

4˙1. *Gentle evaporation.* – As said above, for a weak flux of non-thermal electrons ($\leq 10^{10}$erg cm^{-2}s^{-1}) one expects gentle evaporation, *i.e.* upward velocity at chromospheric level. An upward velocity is instead very rarely observed, and sometimes with high values of the flux. Not only, a downward velocity is observed also for microflares with fluxes $\leq 10^{9}$erg cm^{-2}s^{-1} [28-30].

Even if predicted [22], gentle evaporation during the impulsive phase has not been observed yet. Hence the direction of chromospheric velocity cannot help to establish the threshold value of the flux of non-thermal electrons. The lack of a such an observable seems to favor the results of Abbett and Hawley [26] that foresee unmeasurable motions in the first dynamic phase of a flare, independently of the magnitude of flux of non-thermal electrons.

4˙2. *Explosive evaporation.* – The hydrodynamic simulations explain the general framework of chromospheric and coronal observations with a downward-moving chromospheric condensation and a chromospheric ablation causing the upward motion observed in coronal lines during the impulsive phase of many flares. Since the overpressure of the evaporated gas is responsible for the dynamics of the flare the momentum of downward-moving chromospheric plasma (observed for example in Hα) should be equal to the momentum of ablating plasma as revealed by the blue-shifted emission in coronal lines. The equality of the two momenta has been proved within a factor of 2–6, consistent with the uncertainties of the measurements, for a few events for which chromospheric and coronal observations are available during the impulsive phase [31-33]. It must be noted that the coronal line observations are spatially unresolved and in these cases the location of the blue-shifted plasma has been inferred to be the same of the red-shifted chromospheric material.

If the chromospheric evaporation is the process responsible for the plasma emitting soft X-rays an important issue would be proven: is the location of the chromospheric red-shifted material the actual footpoint of the brightest soft–X-rays loops?

A response to this question was given by the new-generation instruments as the CCD imaging spectrograph at Mees Solar Observatory and the instruments on Yohkoh that have high sensitivity and high spatial and spectral resolution. Wülser *et al.* [34] studied the flare of 15 November, 1991 with such a combination of ground-based and space instruments. They obtained simultaneous observations in the early phase of the flare, before the main hard–X-ray burst. They compared the Hα wing difference image with the images obtained in soft– and hard–X-ray emission (SXT and HXT on Yohkoh). Their fig. 2 clearly shows that the two kernels of red emission excess, *i.e.* of chromospheric downflow, coincide with the soft–X-ray loop footpoints, presumably the places of energy deposition. The BCS spectra of Ca XIX show a blue-shifted component for which was obtained the velocity of the upflowing plasma and the emission measure. The upward momentum and the downward momentum, computed for the two Hα red kernels, are equal within the statistical errors. For this flare is then demonstrated that the up and down momenta are *equal* and originate in the same locations.

This strongly supports the chromospheric evaporation hypothesis and is an important general issue coherent with the hydrodynamic simulations described in sect. **3**.

4˙3. *Response time.* – The measure of the delay of the chromospheric velocity with respect to the hard–X-ray emission is a difficult task. In fact, only small kernels in the flare area experience the downward velocity and it is rare to have the spectrograph slit just in the right position. Not only, but what is needed is a very high temporal resolution $\leq$2 s. Therefore the delay has been often measured using the intensity of the Hα red wing or the difference between the Hα wings, obtained with interferometric filters, as a proxy for the downward velocity.

Rolli *et al.* [35] studied the flare of 20 August 1992 with the imaging spectrograph at Locarno-Monti, in Switzerland, and the SXT and HXT telescopes on Yohkoh. During the first episode of the flare three kernels are clearly visible in the Hα and SXT images, while only two kernels are present in the HXT images (see their fig. 2). The very high temporal resolution of their spectra of about 2 s allows to study the cross-correlation between the measured downward velocity and the hard–X-ray emission. The chromospheric velocity shows a delay of 1–2 s for the two kernels emitting in the range 14–23 keV, where presumably the non-thermal electrons impact, and a delay of 12 s for the third kernel emitting only in the soft X-rays, where the energy is transported by a conduction front.

This seems to confirm that the delay of the chromospheric dynamic process with respect to the hard–X-ray emission is a good indicator of which heating process is going on.

4˙4. *Dependence of downward velocity on time.* – The motion of the condensation was simulated considering constant the velocity within the condensation but the observations indicate otherwise (see [9, 11, 34]).

The downward velocity is expected to peak at the time of the first response of the chromosphere and to decrease afterward. The observations show on the contrary a very complicated scenario:

– Cauzzi *et al.* [11] found a downward velocity that continues to increase after the end of the hard–X-ray emission (see their fig. 6);

– Wülser *et al.* [33] found a velocity approximately constant during the impulsive and the decay phase (see their fig. 2);

– Rolli *et al.* [35] found a velocity that nearly follows the time dependence of the hard–X-ray emission for both the impulsive and the decaying phase (see their fig. 5).

It seems to me that this topic needs a more accurate analysis from both the theoretical and observational point of view. The hypothesis of constant velocity within the condensation, used to simulate the motion, is not confirmed by observations, and the time dependence of the velocity is different from one event to another. From the observational point of view it would be very important to establish if different behaviours correspond to different classes of events.

4˙5. *Before the impulsive phase*. – If the chromospheric evaporation, due to both thermal or non-thermal heating, is the main process responsible for the observed motions, none shoud be observed before the hard–X-ray emission. In the last years evidence has been found that motions characteristic of chromospheric evaporation are present before any observed hard–X-ray emission.

Culhane [36] reports an upward velocity, before the first observed hard–X-ray emission, that remains approximately constant during the first burst (see his fig. 6). Silva *et al.* [37] observed an upward velocity of about 400 $\mathrm{km\,s^{-1}}$, 2 minutes prior to the hard–X-ray emission peak, that decreases down to 100 $\mathrm{km\,s^{-1}}$at the emission peak time (see their fig. 4). Moreover Alexander *et al.* [38] examined 10 flares and found in most cases that the non-thermal velocity peaks prior to the first significant burst of hard X-rays and then decays (see their fig. 2).

These observations suggest that the upward motion and/or the non-thermal velocity may be a direct consequence of the flare energy release rather than a by-product of the energy deposition associated with the production of hard–X-ray emission. If this is the case, it would be very important to search for the chromospheric counterpart to better understand the acting process.

5. – Conclusions

The dynamics of flares at chromospheric levels is a very important diagnostic tool for better understanding the energy deposition and transport mechanisms.

The downward velocity is an important characteristic of flares, from major ones to micro flares, during the impulsive phase of hard–X-ray emission. The motion is observed not over all the flare area but only on small regions with sizes of a few arcsec, possibly the footpoints of the soft emitting loops and the places of the energy deposition.

The velocity increases rapidly as a response to the energy deposition for both thermal and non-thermal mechanisms. It is the time delay Δt between the downward velocity and the hard–X-ray emission, that can help to distinguish between the two: $\Delta t \approx 1$–2 s means heating by non-thermal electrons; $\Delta t \geq 10$ means heating by a conduction front. The dependence of velocity on time varies with flares and is different from what expected by models. This is an important issue that deserves a more accurate analysis from the modeling point of view.

The evaporation seems to be responsible for the upward and downward motion during the hard–X-ray burst. Recent observations show upward motion at coronal level well before the hard–X-ray burst but there are no observations for the chromospheric counterpart. Therefore it would be very important to obtain spectra of chromospheric lines immediately before the flare but we know that it is a difficult task to observe with a spectrograph in the right position and at the right time. The suitable instrument for this kind of observations is an imaging spectrograph that allows simultaneous spectra over all the flare area.

REFERENCES

[1] Švestka Z., Kopecký and Blaha M., *Bull. Astron. Inst. Czech.*, **13** (1962) 37.
[2] Fritzová L., *Bull. Astron. Inst. Czech.*, **12** (1961) 254.
[3] Severny A. B., *Nobel Symp.*, **9** (1968) 71.
[4] Švestka Z., *Solar Flares* (Reidel Publishing Company) 1976.
[5] Ichimoto K. and Kurokawa K., *Solar Phys.*, **93** (1984) 105.
[6] Wülser J. P., *Solar Phys.*, **114** (1987) 115.
[7] Wülser J. P. and Marti H., *Astrophys. J.*, **341** (1989) 1088.
[8] Canfield R. C., Kiplinger A. L., Penn M. J. and Wülser J. P., *Astrophys. J.*, **363** (1990) 318.
[9] Falchi A., Falciani R. and Smaldone L. A., *Astron. Astrophys.*, **256** (1992) 255.
[10] Graeter M. and Kucera T., *Solar Phys.*, **141** (1992) 91.
[11] Cauzzi G., Falchi A., Falciani R. and Smaldone L. A., *Astron. Astrophys.*, **306** (1996) 625.
[12] Graeter M., *Solar Phys.*, **130** (1990) 337.
[13] Heinzel P., Karlický M., Kotrč P. and Švestka Z., *Solar Phys.*, **152** (1994) 393.
[14] Gan W. Q., Rieger E., Fang C., *Astrophys. J.*, **416** (1993) 886.
[15] Kurokawa H., Takakura T. and Ohki K., *Pub. Astron. Soc. Jpn.*, **40** (1988) 357.
[16] Qiu J., Falchi A., Falciani R., Cauzzi G. and Smaldone L. A., *Solar Phys.*, **172** (1997) 171.
[17] Doschek G. A., Feldman U., Kreplin R. W. and Cohen L., *Astrophys. J.*, **239** (1980) 725.
[18] Antonucci *et al.*, *Solar Phys.*, **78** (1982) 107.
[19] Tanaka K. and Zirin H., *Astroph. J.*, **299** (1985) 1036.
[20] Fisher G. H., Canfield R. C. and McClymont A. N., *Astrophys. J.*, **289** (1985) 414.
[21] Fisher G. H., Canfield R. C.and McClymont A. N., *Astrophys. J.*, **289** (1985) 425.
[22] Fisher G. H., Canfield R. C. and McClymont A. N., *Astrophys. J.*, **289** (1985) 434.
[23] Fisher G. H., in *Radiation Hydrodynamics in Stars and Compact Objects*, edited by D. Mihalas and K. H. Winkler, *Lecture Notes in Physics*, **255** (1986) 53.
[24] Fisher G. H., *Astrophys. J.*, **346** (1989) 1019.
[25] Gan W. Q., Fang C. and Zhang H. Q., *Astron. Astrophys.*, **241** (1991) 618.
[26] Abbett W. P. and Hawley S. L., *Astrophys. J.*, **521** (1999) 906.
[27] Carlsson M. and Stein R. F., *Astrophys. J.*, **286** (1997) 787.
[28] Canfield R.C. and Metcalf T. R., *Astrophys. J.*, **321** (1987) 586.
[29] Cauzzi G., Falchi A. and Falciani R., *Solar Phys.*, **199** (2001) 47.
[30] Cauzzi G., Falchi A., Falciani R., Smaldone L. A. and Shine R., this issue, p. 735.
[31] Zarro D. M., Canfield R. C., Strong K. T. and Metcalf T. R., *Astrophys. J.*, **324** (1988) 582.
[32] Canfield R. C., Zarro D. M., Metcalf T. R. and Lemen J. R., *Astrophys. J.*, **348** (1990) 333.
[33] Wülser J. P., Zarro D. M. and Canfield R. C., *Astrophys. J.*, **384** (1992) 341.

[34] Wülser J. P., Canfield R. C., Acton L. W., Culhane J. L., Phillips A., Fludra A., Sakao T., Masuda S., Kosugi T. and Tsuneta S., *Astrophys. J.*, **424** (1994) 459.
[35] Rolli E., Wülser J. P. and Magun A., *Solar Phys.*, **180** (1998) 361.
[36] Culhane J. L., *Adv. Space Res.*, **17** (1995) 29.
[37] Silva A. V. R., Wang H., Gary D. E., Nitta N. and Zirin H., *Astrophys. J.*, **481** (1997) 978.
[38] Alexander D., Harra Murnion L. K., Khan J. I. and Matthews S. A., *Astrophys. J.*, **494** (1998) L235.