MULTIWAVELENGTH OBSERVATIONS (SOHO, TRACE, La Palma) AND MODELLING OF EXPLOSIVE EVENTS

R. Erdélyi1 B. De Pontieu2 & L.M. Sarro3

1Space & Atmosphere Research Center, Department of Applied Mathematics
University of Sheffield, S3 7RH, Sheffield, England (UK)
tel.: +44-(0)114-2223832, fax: +44-(0)114-2223739, e-mail: Robertus@sheffield.ac.uk
2Lockheed Martin Solar and Astrophysical Laboratory,
3251 Hanover St., O/L9-41 Bldg. 252, Palo Alto, CA 94304, (USA) e-mail:bdp@lmsal.com
3LAEFF, INTA, P.O.Box 50727, Madrid, E-28908, Spain e-mail:lsb@laeff.esa.es

ABSTRACT

Explaining the high temperature of the solar corona has given rise to many suggestions. Perhaps one of the most interesting of these is the idea that the corona is heated by numerous small localised events which (Parker 1988).

Using the unique opportunity offered by SOHO a series of test observations was carried out as regards the explosive events (e.g., Perez et al. 1999). Preliminary results suggested it is crucial to consider and determine the changes in the magnetic field topology associated with these events. Inspired by these observations an extension/modification of SOHO's JOPs 33, 69, 79 and 103 was undertaken on 1 June 1999 to take advantage of the unique spatial and temporal resolution of the TRACE instrument combined with high-resolution ground-based observations in Hα with SVST (La Palma). These joint observations at disk center are used to study the relationship between explosive events and the underlying geometry in Hα.

We compare these preliminary observational results with results from numerical simulations (see, e.g., Roussev et al., this Volume) on micro-scale heating mechanisms (e.g., explosive events, microflares, blinkers). We also discuss their contribution and relevance to coronal heating. Results of these theoretical (numerical) studies are further converted into observable UV line profiles, assuming non-equilibrium ionisation.

Key words: explosive events; transition region; coronal heating; SOHO; TRACE

1. EXPLOSIVE EVENTS: WHAT ARE THEY?

The heating of the solar corona is a longstanding problem of fundamental solar and astrophysical importance. When the response of the solar corona consists of slow motions on a time scale long compared to the Alfvén transit time the mechanism is called DC. The magnetic fields undergo a slow evolution and magnetic energy is gradually built up by shearing motions until the fields relax or reconnect to a lower state of energy. Part of the released energy can be converted into heat. Currents that are dissipated in reconnection models of, e.g., microflares, explosive events, blinkers, and nanoflares are DC currents.

High resolution ultra-violet (UV) spectra taken with the High Resolution Telescope and Spectrograph (HRTS) reported transient brightenings, often referred to as explosive events (Brueckner & Bartoe 1983; Dere et al. 1989, 1991; Porter et al. 1987; Innes et al. 1991; Chae et al. 1998; Erdélyi et al. 1997, 1999; Erdélyi & Sarro 1999; Perez et al. 1998, 1999).

Explosive events are spatially very small regions, although not point-like. In fact some events showed considerable spatial structures. There characteristic spatial size is ≈ 2 arcsec ≈ 1,500 km, showing sudden enhancements of line intensities associated with strongly broadened non-Gaussian line profiles. These line profiles also show strong Doppler broadenings with a maximum velocities ≈ ± 250 km s⁻¹. These Doppler broadenings were detected in lines produced by ions formed at temperatures between 20,000–200,000 K. The life time of explosive events is found to be between 20 - 200 s with an average of ≈ 40 s. The peak of their life time histogram distribution is at 20 s (Dere et al. 1989, Perez et al. 1999). It has also been found that the maximum line of sight velocity of explosive events is independent of latitude.

Further, Hα observations complemented by jointly taken magnetograms suggest a connection of explosive events to an emerging magnetic flux. This observation is crucial as it can give as a first insight into the fine structure of one of the smallest observable dynamical phenomena in the Sun's atmosphere.

With the launch of SOHO and TRACE new opportunities have become available for studying short-time scale variability phenomena, such as explosive events. In particular, high-resolution observations can be made to derive the underlying photospheric
magnetic flux.

We have planned a joint observation program (JOP 79) involving SOHO and TRACE for 25 August 1998, however SOHO was 'lost' for this period. In June 1999, when SOHO was 'back' we carried out a small observational campaign and obtained data with SUMER (N V 1238.8 Å (10^5 K), O V 529.7 Å (2.5 x 10^5 K), Mg X 624.9 Å (10^6 K)); TRACE (171 Å (0.5 - 1.5 x 10^5 K)); and SVST La Palma (Ca II K 3933 Å (6 x 10^3 K), Hα 6563 Å - 6535/700 mÅ (10^4 K)).

The Plate (at the end of the paper) shows snapshots of a time sequence (part of a 10 minutes sequence) in 9 different wavelengths of a small subarea (13”x17”) of AR 8552 (N24,W27) on June 1, 1999. Several explosive events are visible in the SUMER N V and O V lines, e.g. at 150-180 s in the Plate. Some of the explosive events are accompanied by brightenings in the TRACE 171 Å passband (see the arrows in the Plate) despite being invisible in Mg X 624.9 Å. This may indicate low-temperature contribution (O VI) in the TRACE 171 Å passband.

The particular sequence shown on the Plate (and labelled as Fig. 1b and Fig. 1d) lasts 140 sec (starting at t₀ = 150s of the whole sequence). In the two time-series of N V and O V we see a broadening of the lines, meanwhile there is no broadening at higher temperatures (Mg X). We also found some explosive events occurring in the vicinity of Hα jets, visible in Hα-700 mÅ: see the arrows on the Plate. At 240 sec (e.g., at t₀ + 90 s) after the start, we see a sudden injection of energy resulting in a large blue and red-shifted plasma. By this stage the center of the feature has drifted northward by two to three arcseconds. The last snapshot at 270 s shows mostly a blue shifted plasma. The size of the explosive event in the north-south direction is ~5 arcsec. The snapshots are separated by 30 sec. This might be a little bit too high for explosive events, however in Hα we could not obtain better resolution. The maximum velocity of both the blue and red-shifted plasma is 150 – 200 km s⁻¹.

The objective of the present work is to model explosive events and compare observations with results obtained through a numerical modelling (see also Sarro et al. 1997, Sarro et al. 1999, Roussev et al. 1999).

2. HYDRODYNAMICAL SIMULATIONS

We support the idea of prevalent occurrence of small-scale energetic transients (e.g., micro/nanoflares) taking place somewhere in the TR causing explosive events. Explosive events are interpreted as the release of the solar atmosphere to this sudden release of energy (e.g., via reconnection). However, the ultimate origin of the input energy that drives the flow of material detected in the explosive events has not yet been established. The strongest explosive events have been associated with the He I dark points which coincide with X-ray bright points in the corona (Porter et al. 1987). X-ray bright points are the observational signature of the hot tops of magnetic bipoles made up of smaller loops (see, e.g., Krieger et al. 1971 or Sheeley & Golub 1979). At the same time, Hα observations and magnetograms suggest a connection with emerging magnetic flux (Brueckner et al. 1988). In a recent paper Chae et al. 1998 conclude, based on a sample of 163 explosive events observed simultaneously with SUMER on board SOHO and with the Big Bear Solar Observatory multi-magnetograph, that this type of phenomena occur preferentially in regions of mixed polarity and not in the interior of strong flux concentrations and that the majority of explosive events are associated with photospheric magnetic flux cancellation.

In the present work explosive events are simulated in one-dimensional semi-circular rigid magnetic flux tubes (see, e.g., Sterling et al. 1991, 1993; Mariska 1992; Sarro et al. 1997, 1999; Erdélyi et al. 1998, 1999). Thermal energy perturbations represent the small-scale energetic transients which drive flows along the flux tube. The distance along the loop is s, with s = 0 fixed at the left boundary of the tube. The length of the loop is taken to be 13,000 km, with a chromosphere 1,500 km thick at both ends of the loop. The governing equations of physical processes in the loop can be written in the form:

\[
\frac{\partial p}{\partial t} + \frac{\partial (pv)}{\partial s} = 0, \quad (1)
\]

\[
\frac{\partial (pv)}{\partial t} + \frac{\partial (pv^2)}{\partial s} = -\rho g(s) - \frac{\partial p}{\partial s}, \quad (2)
\]

\[
\frac{\partial E}{\partial t} + \frac{\partial}{\partial s} \left[ (E + p)v - \kappa \frac{\partial T}{\partial s} \right] = -\nabla g(s) - L + S, \quad (3)
\]

where

\[
E = \frac{1}{2} \rho v^2 + \frac{p}{\gamma - 1}. \quad (4)
\]

Here L denotes the radiative loss function and S denotes the volume heating rate. For the radiative loss function we use the analytical expression given by Sterling et al. (1991), while for the input heating rate we take a constant value per unit volume of \(3.6 \times 10^{-4} \text{ergs cm}^{-3} \text{s}^{-1}\).

Equations (1) – (3) are solved using the Fortran 90 code EMMA.D (De Sterck et al 1998) based on high resolution shock capturing schemes and an approximate Riemann solver. We use a fixed grid spacing corresponding to 13 km per grid cell. The code is implemented with solid wall boundary conditions. At both foot-points, the temperature and pressure are fixed at 10,000 K and 2.1 dyn cm⁻², respectively. Fig. 1 is time evolution between t=0 s and t=120 s of the velocity distribution in the loop derived from equations 1–3. The x axis represents the normalised spatial coordinate along the loop, and the different plots, which correspond to time increments of 10 s, have been shifted upward by 50 km s⁻¹. Here the total energy injected is \(E/\sigma = 2.5 \times 10^5 \text{erg cm}^{-2}\); the point of energy deposition around which the spatial distribution is centered is \(x_0 = 1.3 \text{Mm}\); and the time during 90% of the total energy is deposited is \(\Delta t = 300\). Plots shown in this section are normalised in the spatial coordinate so that the loop starts at \(s = -1\) where \(x = 0\) km and ends at \(s = 1\) where \(x = 13,000\) km.
The qualitative description of the evolution followed by the loop after the onset of the energy deposition is in agreement with previous studies. A common feature for any given set of parameters is that, during the first few seconds of the simulation, most of the energy injected goes into internal energy, thus increasing the temperature and pressure at the explosion site. In Figure 1 it is readily seen how the expansion produces two oppositely directed plasma flows centered roughly in the middle of the two new transition zones (see Figure 1). Therefore, these new transition zones move at opposite velocities thus contributing to the integrated line profile with the corresponding Doppler shift.

The subsequent evolution of the loop can be divided into three stages: during the first stage, both the pressure shock and the plasmoid travel along the loop and cross the loop apex; in the second stage, the preceding shock wave approaches the second chromosphere placed on the loop-leg opposite to the explosion site and compresses the plasma in between. Finally, in the third stage it is the cool plasmoid that reaches the second chromosphere giving rise to a complex mixture of pressure and density waves.

3. OBSERVATIONAL CONSEQUENCES

In order to calculate the ion populations along the loop for a given time we have to integrate the ionisation equations, i.e.,

\[ \frac{\partial N_i}{\partial t} + \frac{\partial (N_i \cdot v)}{\partial s} = \eta_e (N_{i+1} \alpha_{i+1} + N_{i-1} S_{i-1} - N_i (\alpha_i + S_i)) \]  

where \( \alpha_i \) and \( S_i \) are the recombination and ionisation coefficients of ionisation stage \( i \) and \( N_i \) is the volume number density of ion \( i \) (see, e.g., Arnaud & Rothenflug 1985). Solutions for the resonance line of C iv at 1548.2 Å are shown for, e.g., the first few seconds in Fig. 2.

![Figure 1](image1.png)

**Figure 1.** Time evolution between \( t=0 \) s and \( t=120 \) s of the velocity distribution in the loop derived from equations 1-3. The \( x \)-axis represents the normalized spatial coordinate along the loop. The successive plots are shifted upwards by an amount equivalent to 50 km s\(^{-1}\).

![Figure 2](image2.png)

**Figure 2.** C iv ionic fraction in three portions of the loop at TR temperatures for e.g., the, e.g., first four seconds. Solid line: ion populations out of equilibrium; and dashed line: values derived under the assumption of ionisation equilibrium.

This offers an easy comparison of explosive events' observations (see also Erdélyi et al. 1997,1998) and numerical predictions of time evolution of observational signatures. Analysis shows that it is evident that strong deviations from the equilibrium values of the ion populations occur.

Once the ion populations are computed, the emissivity of a given emission line per unit interval of wavelength in an optically thin, collisionally excited resonance line can be obtained.

4. Results

Fig. 3 shows the results of these calculations as applied to the 1548 Å resonance line of C iv. The profiles represent the emission integrated along the whole loop length for a structure at latitude 9° and placed at the solar meridian and normalized to the intensity emitted by the whole loop before any energy injection takes place. The plots are constructed from individual line profiles computed every 0.5 seconds and any structure below this time resolution will be due to perspective effects. In the horizontal plane, \( x \) and \( y \) represent wavelength in velocity units and time in seconds. Positive velocities represent blue-shift whereas negative velocities should be interpreted as red-shifts. Changes in perspective were necessary to provide visibility of as many profile components as possible. Hereafter and for the sake of clarity we shall refer to the energy input \( E_T/\sigma = 2.5 \times 10^8 \) erg cm\(^{-2}\) as the low energy case, and \( E_T/\sigma = 6.25 \times 10^8 \) erg cm\(^{-2}\) as the high energy case.
Figure 3. C IV line profiles obtained for the set of simulations characterised by Δt equal to 300 s. From left to right and from top to bottom, the top row of plots corresponds to $E_T/\sigma = 2.5 \times 10^9 \text{ erg cm}^{-2}$ and $z_0 = 1.0$, $z_0 = 1.3$ and $z_0 = 1.45$. The last two plots in the bottom row correspond to $E_T/\sigma = 6.25 \times 10^9 \text{ erg cm}^{-2}$ with $z_0 = 1.3$ and $z_0 = 1.45$. The x axis shows wavelength in velocity units (km s$^{-1}$) and the y axis corresponds to time in seconds. Positive velocities represent blue-shift whereas negative velocities should be interpreted as red-shifts. Changes in perspective are necessary in order to facilitate the follow up of the different profile components.

In general, the radiative output of the simulations, shown in Figure 3, can be described as a very rapid and short-lived enhancement of the line intensity followed by the appearance of Doppler shifted components. In the low energy cases ($E_T/\sigma = 2.5 \times 10^9 \text{ erg cm}^{-2}$), a blue shifted component is clearly visible whose maximum Doppler shift increases as the energy deposition is placed closer to the original transition region (1,500 km above the foot-point). In these low energy cases, the maximum red-shift is attained during the first 5 seconds of the simulations and diminishes thereafter. The blue-shift, on the contrary, increases with time, reaches the maximum shift and remains roughly constant until the end of the simulations except for the case with $z_0 = 1.45$ where the higher velocity attained implies that the up-flowing material is close to the loop apex at the end of the simulation. At the loop apex, the radial velocity vanishes and therefore the blue-shifted component tends to return to the rest wavelength as the material responsible for this emission approaches this point.

In the high energy cases ($E_T/\sigma = 5 \times 10^9 \text{ erg cm}^{-2}$), there is a marked difference between the simulations with $z_0=1.3$ and $z_0=1.45$. In the first case, the blue component initially increases in Doppler shift (and decreases in intensity) until it reaches a maximum of about 70 km s$^{-1}$. Then, it returns back to the rest wavelength (due to the curvature of the loop) thus merging with the red-shifted component. In the latter case the evolution takes place on a much faster time scale. The blue component has a very short lifetime and disappears from the line profiles due to the rapid heating of the plasma up to temperatures well above the C IV optimum formation temperature. Originally, the core of the cold plasmoid maintains temperatures below the C IV formation temperature ($T_{C\ IV}$) and is thus separated from the surrounding corona by a C IV emitting transition region. Given that, initially, this plasmoid is ascending along the loop-leg, this is the origin of the blue-shift in the profiles. Whenever heat conduction across the transition layers rises the temperature of the plasmoid above $T_{C\ IV}$ the emission from this part of the loop vanishes. The blue component actually disappears before showing hints of any decreasing trend in the wavelength shift. The red component shows a simi-
lar behaviour as in the former case where it reaches maximum shift right after the explosion and subsequently returns to the rest wavelength.

For this energy injection rate, the maximum blueshift can reach values of the order of 100 km s$^{-1}$ in the most extreme cases while the maximum redshift is always of the order of 20-25 km s$^{-1}$. These values, nevertheless, strongly depend on the positioning angles of the loop on the solar disk (Sarro et al. 1999).

5. Conclusions

In general, the observed trends can be summarised as follows: soon after the onset of the energy injection the line profile experiences a sudden increase in intensity and splits into two components with opposite wavelength shifts. The red-shifted component is produced by plasma moving in an ever increasing medium and therefore we interpret the monotonic decrease in the wavelength shift of this component as the manifestation of this deceleration process. The blue-shifted component, on the other hand, travels upward along the loop length surrounded by low density coronal plasma. The blue-shift will correspond to the net effect of two different factors: the natural hydrodynamic evolution of the velocity along the semicircular geometry prescribed in the simulations and the projection of this velocity along the line of sight. The intensity of each component will depend on the number of C IV ions at each velocity and this will, in turn, depend on the relative maximum and the width of the C IV ion population out of equilibrium and on the density in the region of emission.

One of the most prominent results derived from these simulations is the fact that the emission coming out from the loop after the explosion can outshine in more than two orders of magnitude the emission from the quiet loop. In general, the higher the total energy injected, the injection rate or the depth in the chromosphere of the injection point, the brighter the loop. In order to compare our results with observations of explosive events in the Sun, we first have to take into account that the plots shown in § 4. are normalized to the maximum intensity in the line profile emitted by the quiescent loop and only represent radiation coming from the perturbed loop. If the cross section of the loop is roughly equal to the field of view of our spectrograph it is then possible to compare directly its observations with the line profiles shown in this paper. If, on the other hand, one assumes that the perturbed loop belongs to an ensemble that occupies a given filling factor, then it is necessary to add to the synthetic line profiles a new component at the rest wavelength produced by the other, quiescent loops (see, e.g., Sarro et al. 1999).

It is evident that, under the simplifying assumptions made in this work, only partial agreement with observations can be achieved. In particular, no physical mechanism responsible for the energy injection has been put forward. But with the tools developed here for the analysis of the ionisation fronts in the solar atmosphere, this should allow us to explore more detailed scenarios such as two dimensional magnetic reconnection.

Acknowledgement R.E. is grateful to M. Kéray for patient encouragement. This work was also supported by the British Council - Ministry of Education and Culture of Spain, Acciones Integradas Program. R.E. also thanks the warm hospitality and financial support from LMSA during his visit in Aug. 1999, when part of this work has been produced.

REFERENCES

Erdélyi R. & Sarro L.M., 1999, in Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona, ESA SP-446, in press
Mariska, J. T., The Solar Transition Region, Cambridge University Press