OBSERVATION AND MODELLING OF SMALL-SCALE ENERGETIC TRANSIENTS IN THE SOLAR ATMOSPHERE

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ABSTRACT

SOHO and TRACE give new opportunities for studying phenomena on rapid time-scale variability, such as the UV transition region transients, e.g., microflares, explosive events or blinkers.

These events are localised regions with small spatial extent that show sudden enhancements of line intensities associated with strong non-Gaussian broadenings at wide temperature ranges. We argue these events may serve as the building blocks of the operating heating mechanism(s) in the solar atmosphere.

The present work describes the progress made on their observations and numerical modelling based on a reconnection-type physical process. MHD simulations are performed to explore the properties of these micro-scale events.

In order to assess the physical model involved the numerical results of MHD simulations are converted into observable UV line profiles in non-equilibrium ionization. The confrontation of theoretical studies with observational data show an excellent agreement between theory and SOHO observations.

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

1. INTRODUCTION

High resolution ultra-violet (UV) spectra taken with the High Resolution Telescope and Spectrograph (HRTS) reported transient brightenings, often referred as explosive events (Brueckner & Bartoe 1983, Dere et al. 1989). Observations carried out by SMM UVSP also reported small-scale transient line broadenings (e.g., Porter et al. 1987).

With the launch of SOHO new opportunities have become available for studying short-time scale variability phenomena, such as explosive events. In July 1996, we obtained data with SUMER (Wilhelm et al. 1995).

For the data obtained on July 14, 1996 we used the 1 x 120 arcsec2 slit. Both 1st and 2nd orders are superimposed on the detector, with the dispersion in wavelength varying from 45 mÅ/pixel (1st order) to 22.5 mÅ/pixel (2nd order) at 800 Å to 41.8 mÅ/pixel and 20.9 mÅ/pixel at 1600 Å. The detector (see Siegmund et al. 1994) has 1024 spectral pixels and 360 spatial pixels. The central area is coated with KBr which increases the quantum efficiency by an order of magnitude in the range 900 Å to 1600 Å.

The dataset were obtained on 14 July 1996 in a northern coronal hole with the centre of the image at X=2 arcsec, Y=909 arcsec. Thus the end of the slit extended to the limb. The experiment was designed so as to record C IV 1548 Å using a 20 sec integration time. After each integration, the slit was moved 1 arcsec eastward, accumulating a 30 x 120 arcsec2 image in 10 minutes.

1.1. Explosive events in C IV observed by SOHO

The sequence in Fig. 1 lasts 220 sec. In the first two time-frames we see a broadening of the C IV line centred at 909 arcsec north of disk center. By the third time-frame we see a sudden blue-shifted component. For the next 40 sec, the line is mostly blue-shifted although there is a weak red-shifted feature. At 120 sec after the start, we see another sudden injection of energy resulting in a large blue and red-shifted plasma. By this stage the center of the feature has drifted southward by three to four arcsec. The latter three time-frames show mostly a blue shifted plasma. The size of the explosive event in the north-south direction is ~5 arcsec. The time-frames in Fig. 1 are separated by 1 arcsec (moving eastward), thus the feature is visible over area of 5 x 9 arcsec2. The maximum velocity of both the blue and red-shifted plasma is ~ 120 km s⁻¹.

The main features derived from the explosive events studies can be summarised as follows: spatial scales associated with explosive events are very small, although not point-like (~ 2 arcsec). In fact some even
Figure 1. A time series for an explosive event observed in C IV 1548 Åin a northern coronal hole on 14 July, 1996.

showed considerable spatial structures. All however showed a sudden enhancement in the ultraviolet line intensity associated with strongly broadened non-Gaussian line profiles. These Doppler broadenings were detected in lines produced by ions formed at temperatures between 20,000–200,000 K. The average maximum velocity was 110 km s\(^{-1}\) with a full width at half maximum along the slit of 1600 km. These events were observed in both the quiet Sun and in coronal holes, the birthrate being somewhat less in coronal holes. The life time distribution of observed explosive events ranges between 20 - 200 s with an average value of ~ 40 s and a peak in the distribution around 20 s (Dere et al. 1989, Perez et al. 1999).

The objective of the present work is to compare observations with results obtained via numerical modeling (see also Sarro et al. 1997, Sarro et al. 1999).

2. HYDRODYNAMICAL SIMULATIONS

Explosive events are interpreted as the response of the solar atmosphere to a sudden release of energy (e.g., 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, H\(_\alpha\) observations and magnetograms suggest a connection with emerging magnetic flux (Brueckner et al. 1989). 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 video-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, Mariska 1992, Sterling et al. 1993, Sarro et al. 1997, Erdélyi et al. 1998, Sarro et al. 1999). 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. Gravity forces, \(g(s) = g_0 \cos \alpha\), are taken into account, where \(g_0 = g_{1,0, s} = 2.7 \times 10^{2} \mathrm{m/s^{2}}\) and \(\alpha\) denotes the angle between the component of gravity along the loop at the point \(s\), and the gravity vector downwards. The governing equations of physical processes in the loop can be written in the form:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial s} = 0, \tag{1}
\]

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

\[
\frac{\partial E}{\partial t} + \frac{\partial (E + p)v - \frac{\partial T}{\partial s}}{\partial s} = -\rho g(s) - L + S, \tag{3}
\]

where

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

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 \(3.6 \times 10^{-4}\) ergs cm\(^{-3}\) 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. On both foot-points, the temperature and the pressure are fixed at 10,000 K and 2.1 dyne cm\(^{-2}\) respectively. Typical results are shown in Figs. 2-3.

Now we describe the dynamical response of the loop model to an energy perturbation obtained for the parameter set the total energy injected \(E/\sigma = 2.5 \times 10^{5} \) erg cm\(^{-2}\); the point of energy deposition around which the spatial distribution is centered \(x_0 = 1.3 \) Mm; and the time during 90% of the total energy is deposited \(\Delta t = 300\). 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 rough 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 2 it is readily seen how, at
the explosion site, the plasma is heated up to coronal temperatures as it expands due to the increased pressure. As a consequence of the temperature rise, new narrow regions at transition zone temperatures are created at both sides of the evacuated region. At the same time, the expansion produces two oppositely directed plasma flows centered roughly in the middle of the two new transition zones (see Figure 3). Therefore, these new transition zones move at opposite velocities thus contributing to the integrated flow profile with the corresponding Doppler shift. The plasma flows—which during the first 4 s are of the same order of magnitude despite the effect of the asymmetric gravity force—will soon be characterised by different flow speeds due to the original asymmetry in the physical conditions on both sides of the evacuated region: while the up-flowing stream encounters a medium of decreasing density, on the opposite side, hydrodynamical equilibrium governs the run of density with depth and thus, the medium consists of an increasingly denser chromosphere that prevents the development of fast down-flows towards the foot-point of the loop.

At t = 5.0 s the up-flowing material reaches the position of the transition zone originally placed 200 km above the explosion site and, as a result of this interaction, two pressure waves develop. It is at this point that the asymmetry between the oppositely directed flows becomes more dramatic. The two waves have different propagation speeds. One is a slow pressure wave that propagates with the same kinematic speed of the cool dense plasma originally situated between the explosion site and the original coronal and the second is a fast pressure wave of smaller magnitude that accelerates, compresses and heats the plasma while it develops into a shock. In Figures 2–3 for the sake of clarity we have only shown the computed solution at 10 s intervals. Therefore, this process is not shown in detail, but the resulting pressure waves can be seen in the solution at t = 10 s.

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, 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. Shortly before the end of the simulation, a reverse shock is easily discernible travelling back to the loop apex and decelerating the previously accelerated plasma. Though not shown in the plots, we also find two density condensations, the first corresponding to the original plasmoid and the second to the enhanced density produced by the compression of the chromosphere by the shock wave. At the point where the pressure increase (associated with this second density condensation) approaches the boundary of the loop we end the simulation for this parameter set.

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.,

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

(5)

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). Because of explosive events in Fig. 1 appear in the resonance line of C IV at 1548.2 Å we selected Carbon as the atom whose ion populations is going to be determined. 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. Due to the lack of space we cannot represent here a careful study of this deviation. We refer the detailed analysis of the evolution of the fractional ion populations with respect to the equilibrium values to a recent paper (Sarro et al. 1999, Sarro et al; private communication) devoted entirely to the study of the evolution of the ionisation state of several species in a loop subject to this kind of energy perturbations. Note, another not yet presented set of simulations have also been developed recently to perform similar studies with Oxygen and Neon resonance lines involved.

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 by using the standard from

\[
E_{\lambda} \propto \frac{hc \Omega N_1 N_{\text{ion}} N_{\text{elem}}}{\lambda \omega N_{\text{ion}} N_{\text{elem}} N_{\text{H}} N_{\text{e}} \exp \left( \frac{E_W}{k_{\text{B}} T} \right) \phi(\lambda)}
\]

Given a distribution of emissivities along the loop, the total intensity can be calculated as

\[
I_{\lambda} = \int E_{\lambda} ds
\]

where \(s_e\) is the total length of the loop.

4. Results

Fig. 4 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 0° 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 \(E_T/\sigma = 2.5 \times 10^{57} \text{ erg cm}^{-2}\) as the low energy case, and \(E_T/\sigma = 6.25 \times 10^{57} \text{ erg cm}^{-2}\) as the high energy case.

In general, the radiative output of the simulations, and the corresponding line profiles shown in Figure 4, can be described as a very rapid and short-lived enhancement of the line intensity followed by the appearance of Doppler shifted components. As the energy injection rate decreases we find an increase in the relative intensity and in the rate of change of the different profile components.

For the low energy cases the intensity increases abruptly while the line profile splits into two components. Then, the up-flowing component decreases in intensity while the Doppler shift reaches a maximum and subsequently diminishes. In the simulation with \(x_0 = 1.3\) the blue component has not yet returned to the rest wavelength when \(\tau = 55\ \text{s}\), while in the case with \(x_0 = 1.45\) the plasma is heated up to temperatures where no C IV can be present and, thus, the blue component disappears from the profiles.

In the high energy case with \(x_0 = 1.3\), the initially up-flowing plasma reaches the loop apex well before the end of the simulation and thereafter flows downwards towards the foot-point opposite to the explosion site. This is observed in the line profiles as a displacement of the component initially associated to up-flowing material from blue-shifts to red-shifts. At the point where its wavelength coincides with the characteristic wavelength of the down-flowing material both components merge thus increasing the relative intensity. In the case with \(x_0 = 1.45\) we see again the effect of the increased conductivity at high temperatures. In this simulation, the plasma reaches temperatures where the conductive energy transport becomes so efficient that the heating of the cool plasmoid above the C IV formation temperature occurs before the end of the simulation. Nevertheless, though not visible in C IV, the plasmoid crosses the loop apex and travels downwards towards the foot-point opposite to the explosion site. The maximum blue-shifts are of the order of \(100 \text{ km s}^{-1}\). On the contrary, in these simulations the crossing of the cool plasmoid past the loop apex and its arrival to the ‘second’ chromosphere increase the maximum redshift up to values of the order of 60-70 km s\(^{-1}\).

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
Figure 4. C IV line profiles obtained for the set of simulations characterised by $\Delta t$ equal to 300 s. From left to right and from top to bottom, the top row of plots corresponds to $E_T/\sigma = 2.5 \times 10^9$ erg cm$^{-2}$ and $x_0 = 1.0$, $x_0 = 1.3$ and $x_0 = 1.45$. The last two plots in the bottom row correspond to $E_T/\sigma = 6.25 \times 10^9$ erg cm$^{-2}$ with $x_0 = 1.3$ and $x_0 = 1.45$. 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.

As mentioned before, all the plots shown in Figure 4 have been computed assuming that the loop is located at Sun centre and aligned with the equator. A full exploration of the (predictable) behaviour of the line profiles as functions of the position of the loop (given by its latitude, longitude and rotation angle with respect to the parallel circle that passes below its apex) is far beyond the scope of this paper. Nevertheless we have included three examples of the dependence of the line profiles on the positioning angles for one of the simulations shown in Figure 4. These examples are shown in Figure 5 where the latitude is measured as usual and the longitude is zero at Sun centre and $-\pi/2$ in the western limb. The inclination angle represents the clockwise measured angle between the parallel circle that passes beneath the loop apex and the loop itself.

Figure 5 shows how different positions of the loop on the solar disk can result in very different phenomenologies for the same underlying processes. The original asymmetry between red and blue shifts observed in the exploration of the parameter space when the loop was placed at Sun centre—in the sense that blue-shifts are always higher in absolute value than red-shifts—is thus less significant as it depends very strongly on the three positioning angles.

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 of the observed volume, 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.

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