Modeling of Explosive Events in the Solar Atmosphere

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Abstract:
High-resolution ultraviolet (UV) spectra show transient brightenings — often referred to as explosive events — in the solar atmosphere. The present work describes the progress made on their numerical simulations. Using semi-circular magnetic flux tubes we find that thermal energy perturbations drive flows along the flux tube. The time evolution of our simulations first shows a sudden rise in temperature at the perturbation site followed by the ejection of cool dense gas bullets and the generation of sound waves. This is then followed by the appearance of “new” transition regions moving at different velocities.

Our computational results are converted into UV line profiles in (non)-equilibrium ionization. Observational signatures (e.g., emission measures) are calculated as a function of time at different locations on the solar disk.

1. Introduction

High resolution ultra-violet (UV) spectra taken with the NRL High Resolution Telescope and Spectrograph (HRTS) (Brueckner & Bartoe 1983) show transient enhancements of the wings of lines formed in the solar transition region often referred to as explosive events resulting in highly non-Gaussian line profiles. Similar observations have been done by SMM UVSP which observed line broadenings in “hotter lines” (see e.g., Porter et al. 1987); and more recently by SUMER (see companion paper by Perez et al. 1998).

The most complete statistical description to-date of explosive events can be found in Brueckner & Bartoe, 1983 and Dere et al., 1989. The main conclusions derived from these studies can be summarized as follows:

- the observed velocities range between $\pm 250 \text{ km s}^{-1}$ and $\pm 50 \text{ km s}^{-1}$;
- a particular explosive event may present different time histories with distinct activity episodes. The life time distribution ranges between $20–200 \text{ s}$;
- the maximum line of sight velocity is independent of latitude, suggesting an isotropic distribution of velocities at the explosion site.

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The present work describes the progress made on their numerical simulations. In section 2 we describe the numerical simulation of the response of the solar atmosphere to a sudden energy deposition and in section 3 and 4 the extraction of observational consequences suitable for comparison with real data is discussed.

2. Hydrodynamical Simulations

- Explosive events are simulated in one-dimensional semi-circular rigid magnetic flux tubes (see e.g., Sterling et al. 1991)
- 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 are taken into account

The equations governing the structure and evolution of the loop are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \cdot v)}{\partial s} = 0, \quad (1)$$

$$\frac{\partial (\rho \cdot v)}{\partial t} + \frac{\partial (\rho \cdot v^2)}{\partial s} = -\rho \cdot g(s) - \frac{\partial \rho}{\partial s}, \quad (2)$$

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

where

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

Here $L$ denotes the radiative loss function and $S$ denotes the volume heating rate. For the radiative loss function, $L$, we use the analytical expression given by Rosner et al. (1978) modified as in Sterling et al. (1991) while for the input heating rate, $S$, we take a constant value per unit volume of $3.6 \times 10^{24}$ ergs cm$^{-3}$ s$^{-1}$ that yields the desired loop length.

An initial solution is perturbed introducing an additional exponentially decaying energy deposition heating term ($\sim 10^{24}$ ergs) localized 200 kilometers below the upstream transition region that generates upward and downward velocities along the loop as well as the rise in temperature illustrated in Figure 1 and sound waves that subsequently develop into shocks. As a result, new transition regions moving at opposite velocities are created whose signatures are investigated in section 4.

3. Ion Populations

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

$$\frac{\partial N_i}{\partial t} + \frac{\partial (N_i \cdot v)}{\partial s} = N_e(N_{i+1} \alpha_{i+1} + N_{i-1} S_{i-1} - N_i (\alpha_i + S_i)) \quad (5)$$
where $\alpha_i$ and $S_i$ are the recombination and ionization coefficients respectively of ionization stage $i$ and $N_i$ is the volume density of ion $i$. In our case, we have selected Carbon as the atom whose ion populations we intend to calculate, following Arnaud & Rothenflug (1985) in the computational of the recombination and ionization coefficients.

Figure 2 shows the ionic fractions of Carbon from $N_{\text{C}i}/N_{\text{Ctot}}$ to $N_{\text{Cvii}}/N_{\text{Ctot}}$ in a region that comprises the explosive event location at $s = 1,300$ km and the initial transition region at $s = 1,500$ km. These ion populations are used

Figure 1. Time evolution of the first half of the loop. Solid lines correspond to $t = 5$ s, dotted lines to $t = 15$ s and dashed lines to $t = 25$ s. The top panel shows the logarithm of the electron density ($\text{m}^{-3}$), the middle panel the plasma velocity ($\text{m s}^{-1}$) and the bottom panel, the plasma temperature (K) assumed to be equal for electrons and ions. The x axis represents distance along the loop(km).
in combination with the thermodynamic variables in the loop to compute and predict the line profiles.

Figure 2. Ionic fractions at $t = 0$ s, $t = 5$ s, $t = 15$ s and $t = 25$ s. For clarity, only $N_{Cl}/N_{Ctot}$ (dotted line) and $N_{CV}/N_{Ctot}$ (dashed line) have different line styles.

4. Line Synthesis

The emissivity of a given emission line per unit interval of wavelength in an optically thin, collisionally excited resonance line is given by

$$E_\lambda \propto \frac{hc}{\lambda} \frac{N_1}{\omega} \frac{N_{ion}}{N_{elem}} \frac{N_{elem}}{N_H} \frac{N_H N_e}{\sqrt{T}} \exp \left( -\frac{W}{K_B T} \right) \phi(\lambda)$$

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where $h$ is the Planck constant, $c$ is the speed of light, $\Omega$ is the collisional strength, $\omega$ is the statistical weight of the lower level, $N_1/N_{\text{ion}}$ is the ratio of ions responsible for the emission in the ground state relative to the total number of ions per unit volume, $N_{\text{ion}}/N_{\text{elem}}$ is the relative population of the ion, $N_{\text{elem}}/N_H$ is the element abundance, $N_H$ is the proton density, $N_e$ is the electron density, $W$ is the energy difference between the upper and lower levels, $K_b$ is the Boltzmann constant, $T$ is the temperature, and

$$\phi(\lambda) = \frac{\exp\left(-\frac{(\lambda - \lambda_0 - \lambda_s)^2}{\Delta\lambda_0}\right)}{\Delta\lambda_0 \sqrt{\pi}}$$

(7)

In the definition of $\phi(\lambda)$, $\lambda_0$ is the rest wavelength of the line, $\lambda_s = \left(\frac{\lambda_0}{c}\right)v_p$ is the Doppler shift corresponding to the velocity of the plasma projected on the line of sight ($v_p$), $\Delta\lambda_0$ is the Doppler width of the line

$$\Delta\lambda_0 = \frac{\lambda_0}{c} \sqrt{\frac{2K_bT}{m_i}}$$

(8)

and $m_i$ is the mass of the ion.

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

$$I_\lambda = \int_0^L E_\lambda ds$$

(9)

where $L$ is the total length of the loop. Figure 3 shows the results of these
calculations as applied to the 1548Å resonance line of C IV. The profiles show
the integrated emission along the loop, computed at times $t = 0$ s, $t = 5$ s,
$t = 15$ s and $t = 25$ s for a structure at latitude $0^\circ$ and placed at the solar
meridian.

In the first 5 seconds, C IV ions are created at the explosion site while the
plasma is evolving from chromospheric to coronal densities, the line intensity
undergoes a dramatic enhancement followed by a progressive shift towards the
blue part of the spectrum and a simultaneous decrease in the intensity. We also

![Graph showing line profiles]

Figure 4. Synthesized line profiles for time $t = 0.5$ s (solid line),
$t = 10$ s (dotted line) and $t = 18$ s (dashed line) for an energy input of
$3 \times 10^{25}$ erg. Units are J m$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$.

show in Figure 4 line profiles resulting from a somewhat higher energy input
($3 \times 10^{26}$ erg). The profiles correspond to $t = 0.5$ s, $t = 10$ s and $t = 18$ s, and
show a qualitatively different behaviour.

The initial burst of emission is also present but, as the explosive event de-
velops, two different components (one blue-shifted and one red-shifted) appear.
The life time of the blue-shifted emission is relatively short, whereas the red-
shifted component persists and evolves from a maximum Doppler shift of about
40 km s$^{-1}$ towards the rest wavelength of the line.

5. Discussion

Early results indicate a sudden deposition of energy below the transition region
on one side of the loop resulting in the ejection of cool, dense gas bullets, plus
the generation of sound waves. Following, the interactions between the cool
gas bullets and sound waves (which develop into shock waves), we have the
appearance of “new” transition regions, moving at different velocities. A detailed comparison with observational data is underway.

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