Dynamic Solar Flare Model Atmospheres

William P. Abbott & Suzanne L. Hawley

Michigan State University, Dept. of Physics and Astronomy, East Lansing, MI 48824-1116, USA

Abstract. A dynamic theoretical model of a flare loop from its footpoints in the photosphere to its apex in the corona is presented, and the effects of non-thermal heating of the lower atmosphere by accelerated electrons and soft X-ray irradiation from the flare heated transition region and corona are investigated. Important chromospheric transitions are treated in non-LTE.

1. Introduction

A solar flare is believed to be the result of a sudden release of free magnetic energy at a localized point in the solar corona. Exactly how this energy is liberated into the solar atmosphere is not well understood, but its effects include the rapid acceleration of charged particles along lines of magnetic field. The peak energy deposition of a strong flux of non-thermal electrons will occur in the upper chromosphere, triggering downward moving condensations along with explosive evaporation of chromospheric material to coronal temperatures (Fisher et al. (1985), Zarro et al. (1988), Fisher (1987)). White light continuum emission is observed to emanate from localized areas around the footpoints of flare loops, and this emission tends to be both spatially and temporally correlated with the hard X-ray radiation (Hudson et al. (1992)). This suggests that the emission occurs at the point where the accelerated electrons impact the pre-flare chromosphere.

It is the response of the chromosphere to the deposition of flare energy that ultimately determines the characteristics of the excess optical line and continuum radiation. Since the radiation field is often decoupled from local conditions in the chromosphere, and since mass motions and strong velocity gradients develop as material is rapidly accelerated through atmospheric plasma, the formalism of non-LTE (non-local thermodynamic equilibrium) radiation hydrodynamics is required to properly model the structure, energetics, and optical emission of the atmosphere.

We model a magnetically confined flare loop from its coronal apex to its footpoints in the photosphere. We introduce a flux of energetic, accelerated electrons at the top of the loop, and compute the dynamic, energetic, and radiative response of the atmosphere to this non-thermal heating. Soft X-ray irradiation...
tion of the lower atmosphere due to the flare heated corona is self-consistently included in the models.

2. Methodology

A modified version of the non-LTE radiative hydrodynamic code of Carlsson & Stein (1997) is used to obtain the simultaneous solution of the plane-parallel equations of mass, momentum, and internal energy conservation along with the level population equations, and the equation of radiative transfer. The equations of radiation hydrodynamics, together with the charge conservation equation, are solved implicitly on an adaptive grid via Newton-Raphson iteration. Advected quantities are treated using the second-order upwind technique of van Leer (1977). The adaptive mesh follows the prescription of Dorfi & Drury (1987), and is of critical importance when modeling the dynamics of the lower atmosphere during flares. Features in the chromosphere, such as strong shocks and compression waves, develop quickly and require dense spatial distributions of grid points in order to be properly resolved.

We use the method of Hawley & Fisher (1994) to calculate the energy deposition rate at each height in the atmosphere due to thick target heating from a flux of energetic, non-thermal electrons introduced at the loop apex. To model the soft X-ray flux, we use the optically thin, thermal emission spectra of Raymond & Smith (1977) along with the temperature and electron density stratification of the atmosphere to calculate the emitted power per wavelength band at each atmospheric layer. The soft X-ray flux incident on any other portion of the atmosphere due to the aggregate contribution of the emitting regions is then calculated using a plane-parallel approximation if an emitting region is nearby, and the point source approximation of Gan & Fang (1990) if the emitting region is distant. Once the flux is determined, the heating rate is calculated as in Hawley & Fisher (1992).

The total flare heating at each level of the atmosphere is a sum of the thermal contribution from soft X-ray irradiation and the non-thermal contribution of the accelerated electrons. The flare heating is included in the equation of internal energy conservation as an external source, ensuring detailed energy balance at all depths in the atmosphere and at all times during the flare.

An important part of the model atmosphere calculation is the non-LTE treatment of the radiation field. Atoms important to the chromospheric energy balance are treated in non-LTE: a six-level hydrogen atom, a six level singly ionized calcium atom, a nine level helium atom and a four level singly ionized magnesium atom. Complete redistribution is assumed for all lines. For the Lyman transitions, the effects of partial redistribution are mimicked by truncating the profiles at ten Doppler widths (see Milkey & Mihalas (1973)). Other atomic species are included in the calculation as background continua in LTE using the Uppsala opacity package of Gustafsson (1973). Optically thin radiative cooling due to bremsstrahlung and coronal abundances of carbon, oxygen, neon, and iron is included in the calculation of the total radiative loss rate.

Two basic methods can be used to model the initial, pre-flare state of the solar chromosphere. They have been dubbed by Ricchiazzi & Canfield (1983) as the “semi-empirical” approach and the “synthetic” approach. Semi-empirical
models ignore energy transport in the atmosphere in favor of a fixed temperature and density stratification which reproduces observed optical emission from static solutions to the equations of statistical equilibrium and radiative transport. Synthetic models differ in that the atmospheric structure is produced as a result of a self-consistent solution of the basic equations of hydrodynamics and radiation transport. One advantage inherent in using a synthetic pre-flare model rather than a pre-existing semi-empirical state is that dynamic effects not directly related to the influx of flare energy are eliminated from the flare simulation. For this reason, we generated a synthetic pre-flare state to use as the initial starting atmosphere for the dynamic run.

![Graph](image)

Figure 1. The temperature stratification as a function of log column mass (g cm$^{-2}$) for the three model atmospheres PF1, VAL3C, and MF1ME.

To generate the pre-flare state, a transition region and corona were added to the initial state of Carlsson & Stein (1997) and this starting approximation was allowed to relax to a state of hydrostatic and energetic equilibrium. During this procedure, the upper boundary (the apex of a symmetric coronal loop) was held at 10$^6$ K, and an assumed amount of non-radiative quiescent heating per unit mass was applied to several grid zones adjacent to the lower boundary in order to fix the gradient of the temperature at the base of the photosphere. No other external driving mechanism or source of heating was provided. The resultant temperature and electron density stratification of the relaxed state (hereafter referred to as the PF1 atmosphere) is shown in Figure 1, and is compared to the standard semi-empirical VAL3C chromospheric model of Vernazza et al. (1981)
and to the semi-empirical active atmosphere of Metcalf (1990) (MF1ME) that was used as the pre-flare atmosphere of Hawley & Fisher (1994). We see that PF1 is not as active as the pre-flare state MF1ME, and is somewhat quieter than the VAL3C quiescent state.

Figure 2. The F10 atmosphere. The solid line represents the log of the temperature, $T$ (K), as a function of height above $\tau = 1$, $z$ (megameters), at time $t$. The dotted line denotes the pre-flare temperature structure (PF1).

3. Impulsive Phase Dynamics

To investigate the properties of the lower atmosphere during the impulsive phase of a moderately strong solar flare, we consider a constant electron energy flux of $10^{10}$ ergs cm$^{-2}$ s$^{-1}$ (hereafter called run F10) applied to the PF1 atmosphere for seventy seconds. The F10 run can be described as having two distinct dynamic phases, each with a definite observational signature: a gentle phase, characterized by stages of near-equilibrium, and an explosive phase characterized by large material flows, and strong hydrodynamic waves and shocks. These features are illustrated in Figures 2 & 3 which show the temperature and electron density evolution of the atmosphere. Figure 3 also shows the beam heating profile. The gentle phase is represented in the first panels of each figure, while the explosive evaporation is shown in panels four through six. The last two panels depict the
new flare-heated atmosphere with a deeper transition region and hotter corona than the pre-flare state.

To understand this behavior, we follow the progress of the beam heating process in the lower atmosphere. The accelerated electrons initially deposit energy in the upper chromosphere, and rapidly heat a broad region to $\approx 10^4$ K (see the first frame of Figure 2 at 0.2 seconds, and note the region between $\approx 1.1$ and 1.5 Mm). At this temperature, atomic transitions between excited states of hydrogen efficiently radiate away a majority of the non-thermal energy input, and the atmosphere enters a short-lived state of near-equilibrium. However, in the localized region where non-thermal energy deposition is highest (corresponding to the penetration depth of 20 keV electrons), the temperature continues to climb. Figure 3 shows that after 0.2 seconds of flare heating, this point is located approximately 1.1 megameters above the height where $\tau_{5000} = 1$.

![Figure 3](image)

> Figure 3. The F10 atmosphere. The solid line represents the log of the electron density as a function of height, $z$ (Mm), at time $t$ (log $n_e$, $[n_e]=$cm$^{-3}$). The dotted line denotes the pre-flare electron density, and the dashed line is the log of the non-thermal electron heating, scaled so that it will fit on the plot (log $Q_{e^{-}}+11.5$, $[Q_{e^{-}}]=$ergs cm$^{-3}$ s$^{-1}$).

Although the local temperature minimum close to the lower boundary of the chromospheric plateau (seen in the first frame of Figure 2) looks like a chromospheric condensation, it is not the same phenomenon. During the gentle phase, this temperature minimum develops without a substantial increase in the local gas density, and without the downward motion and steep velocity gradients usually associated with a fully developed condensation. Thus, the optical
line emission formed in this region is not significantly Doppler shifted, and the profiles remain essentially symmetric about their nominal central wavelengths.

The increasing number of collisional ionizations throughout the temperature plateau elevates the density of protons in the region. This effects a change in the thermalization depth of energetic electrons, since it is considerably more likely for a high energy electron to undergo a Coulomb interaction and thermalize in regions where proton densities are high. Thus, even though there is little material flow in this region, in time the non-thermal heating profile broadens slightly, and the point of maximum energy deposition slowly moves upward toward the corona.

By 0.3 seconds, a significant fraction of hydrogen in the upper chromosphere is ionized, and the bulk of the flare energy can no longer be effectively radiated away. The plasma in the upper chromosphere rapidly heats to \( \approx 10^5 \) K where collisionally excited resonance transitions of abundant metal ions dominate the radiative cooling (eg. C iv), and the radiative loss function attains its maximum value. The atmosphere then enters a second, longer-lasting state of near-equilibrium (see panel 2 of Figure 2), and once again, the energy input of the flare electrons is balanced by radiative losses. The development of two distinct temperature plateaus (rather than a single plateau at \( \approx 10^5 \) K) is characteristic of the gentle phase, and is a direct result of the upward drift of the non-thermal heating profile in response to variations in the hydrogen ionization fraction.

The gentle phase persists until the atmosphere is no longer able to effectively radiate away the non-thermal energy input. In the F10 run, this occurs after approximately 27 seconds of impulsive heating, at which time the atmosphere proceeds to the explosive phase. During this phase, the bulk of the energy from the accelerated electrons can no longer be radiated away, and instead is able to do work in the atmosphere. Material is forced away from the point of maximum flare heating, forming a shock front that moves rapidly upward into the corona, and a narrow compression wave that propagates downward into the chromosphere (see panel 5 of Figure 2 at 1.4 and 2.3 Mm). Within the downward moving wave, high gas densities lead to increased radiative cooling, and a local temperature minimum appears, forming a chromospheric condensation. Note that although the non-thermal electron energy flux in run F10 is a factor of three below the explosive limit of Fisher et al. (1985), the atmosphere eventually undergoes explosive evaporation.

Much of the excess optical emission during the explosive phase originates in the high density condensation (and fast upward-moving evaporation). The emergent intensity reflects the material motion and steep velocity gradients of these regions; the observed line profiles are highly Doppler shifted and are asymmetric about their nominal central wavelengths.

4. Continuum Emission

Figure 4 shows the flare continuum emission at the early and late stages of the F10 run, and Figure 5 shows the light curve of the continuum at 5000 Å and in the near wings of Hα. Notable features include an initial reduction in the continuum intensity (eg. the top panel of Figure 5 during the first second of
flare heating) which is not mirrored in the Hα line wings. Later in the flare, the 5000 Å continuum undergoes a one percent brightening over its pre-flare value. This effect is much more pronounced when the electron energy flux is an order of magnitude higher than in run F10.

This behavior can be qualitatively understood as follows. The influx of flare energy from the non-thermal electrons increases collisional rates in the upper chromosphere, thus elevating the population densities of high-energy bound states of hydrogen. The number of photoionizations from the upper states then increases, and photons from the photosphere that normally would escape and be seen as continuum radiation get absorbed high in the chromosphere. This results in a decrease in the observed continuum intensity as shown in the first panel of Figure 4.

![Graphs showing normalized irradiance over wavelength](image)

Figure 4. *Solid* lines show the Balmer and Paschen continua (normalized to the gradual phase maximum) for the F10 run. The *dotted* line is the continuum emission of the pre-flare atmosphere.

However, this population excess is short lived. The high number of photoionizations liberates electrons into the continuum, quickly depopulating bound states of the hydrogen atom. The number of photoionizations is thus reduced, just as increases in the electron density cause a sharp rise in the number of recombinations in the same region. The net result is a switch over between the dominance of photoionization absorption and recombination emission in the region of the low temperature ($\approx 10^4$ K) plateau.

The excess emission in the near wings of Hα originates in the same region, but begins almost immediately after the onset of non-thermal heating (the radia-
tive balance in this case being controlled by the relative strength of the non-local radiation field, and the local value of the Planck function). Thus, the time lag that occurs between H$\alpha$ wing emission and the Paschen brightening is almost entirely controlled by the amount of time it takes for recombination radiation to dominate the chromospheric plateau. We note that a time lag similar to this has been observed in the strong white light flare of March 7, 1989 observed by Neidig et al. (1993).

By late in the explosive phase (the dynamics of which are shown in the lower panels of Figures 2 & 3), the hydrogen ionization fraction in the upper chromosphere is approximately two orders of magnitude greater than during the early gentle phase. The increase in electron density throughout the upper chromosphere and the elevated gas density within the chromospheric condensation both contribute to high levels of hydrogen recombination radiation emanating from the upper chromosphere. We discuss in detail the formation of the continuum and line emission during the explosive phase in Abbett & Hawley (1998).

![Figure 5](image)

Figure 5. Continuum intensity (normalized between the preflare value and the maximum value at 25.0s) at 5000 Å (solid line) for the F10 run. The normalized H$\alpha$ line wing intensities are shown at +2.5 Å (dashed line) and -2.5 Å (dotted-dashed line). For this case, the lag between the 5000 Å continuum brightening and the H$\alpha$ wing brightening is $\approx$ 1.0s.
5. Conclusions

The numerical simulations support the hypothesis that a sudden flux of non-thermal electrons is a major factor in the appearance of optical continuum emission at the footpoints of magnetic loops during strong flares, and that this emission originates throughout a broad temperature plateau formed locally in the upper chromosphere immediately after flare onset. Specifically, the primary conclusions of this analysis are the following:

- An impulsive event can be described as having two phases, a gentle phase characterized by a state of near equilibrium, and an explosive phase characterized by large material flows, and strong hydrodynamic waves and shocks.

- Hydrogen recombination radiation from the chromospheric plateau (gentle phase) and the chromospheric condensation (explosive phase) is the primary cause of the white light continuum brightening observed during strong flares.

- The time lag between the brightening of the Paschen continuum and the brightening of the near wings of Hα is controlled by the amount of time it takes for electron densities in the plateau to become high enough, and the densities of hydrogen atoms in high energy bound states to become low enough, to allow recombination radiation to dominate the region.

Acknowledgments. This work was funded in part by NSF grants AST 96-16886 and AST 94-57455. The computations described here were partially supported by the National Computational Science Alliance and utilized the NCSA SGI/CRAY Power Challenge Array. Additional computations were carried out on the SUN Enterprise-6000 parallel computing facility at Michigan State University. We would like to thank Mats Carlsson and Viggo Hansteen for their invaluable assistance during the initial stages of this project, and we would like to acknowledge Bob Stein and George Fisher for their many helpful discussions during the course of this work.

References


