SOFT X-RAY EMISSION FROM ELECTRON-BEAM-HEATED SOLAR FLARES

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ABSTRACT

Using time-dependent numerical simulations and Solar Maximum Mission (SMM) observations of a solar flare on 1985 January 23, we examine the ability of an electron-beam-heating model to reproduce the rise phase of a flare as observed in soft X-ray lines of Ca xix. The electron beam is parameterized by a peak flux, a low-energy cutoff, and a spectral index, and has a time dependence similar to the observed hard X-ray burst. We find that for a spectral index of 6, only models with a low-energy cutoff of 20 keV reproduce the observed peak emission in the Ca xix line complex. All models with a low-energy cutoff of 15 keV produce too much emission, while all models with a 25 keV cutoff too little emission. None of the models reproduces the temporal behavior of the soft X-ray emission. We conclude that the electron-beam-heated component may only represent a small fraction of the energy released in the impulsive phase of this flare.

Subject headings: Sun: flares — Sun: X-rays

1. INTRODUCTION

Observations of solar flares during the impulsive phase generally show rapidly fluctuating hard X-ray emission, which is thought to be produced by collisional degradation of a high-energy electron beam (e.g., Canfield et al. 1986). This electron beam is one of the major manifestations of the sudden release of magnetic energy that probably begins the impulsive phase. In addition, if we assume a model for the hard X-ray source, thick-target for example, then the hard X-ray spectral measurements provide an estimate of the total energy in the electrons (e.g., Tandberg-Hanssen & Emslie 1988). Whether this energy is sufficient to produce the impulsive-phase atmospheric response observed at soft X-ray, UV, and visible wavelengths is an unsolved problem of flare physics.

Because the physics of the electron beam heating and subsequent evolution of the flaring plasma are quite complex, numerical simulations are necessary to predict the observational consequences of this heating mechanism. In the last few years a number of these calculations have been performed (Nagai & Emslie 1984; MacNeice et al. 1984; Mariska & Poland 1985; Fisher, Canfield, & McClymont 1985a, b, c; Peres et al. 1987; Mariska, Emslie, & Li 1989). In general, all of the simulations show roughly the same hydrodynamic evolution. Moreover, comparison with the general evolution of the emission measure and, to some extent, the total emission in selected UV and soft X-ray emission lines, also show reasonably good agreement with average flare properties.

Detailed attempts to model data from individual well-observed flares have, however, been limited. Only a single flare observed by the Solar Maximum Mission (SMM) on 1980 November 12 at 17:00 UT has been modeled using an electron-beam heated simulation (Peres et al. 1987). That analysis concluded that locally heating a preflare loop near the apex resulted in a better fit to the soft X-ray emission line observations. Only an extremely soft (spectral index of 8) electron beam with a low-energy cutoff of 10 keV and a time profile that did not follow the hard X-ray timing provided a reasonable fit to the data. This set of parameters required significantly more total energy in the electron beam than was indicated by the hard X-ray observations, and thus was not consistent with the observations. In addition, it failed to reproduce even the average velocity properties of the Ca xix resonance line.

In this paper using an electron-beam–heated model, we attempt to analyze the impulsive phase of a second flare observed with SMM. Our goal is to reproduce the observed time behavior of the Ca xix emission line complex near 3.17 Å.

2. OBSERVATIONS

While all of the numerical simulations of solar flares assume that the entire event takes place within a single magnetic loop, the Sun is not usually so cooperative. Typically, only the weaker class M flares have simple enough time behavior and spatial structure to satisfy the single loop assumption of the model. For example, Peres et al. (1987) analyzed a well-observed class M1.4 flare in their comparison with numerical simulations.

For our analysis, we have chosen a GOES class M1 flare which began at 0725 UT on 1985 January 23 in NOAA active region 4617 at S10 W55. This event has been studied by Zarro & Lemen (1988), who found evidence for gentle chromospheric evaporation during the cooling phase. Simultaneous observations were made in hard X-rays with the SMM Hard X-Ray Burst Spectrometer (HXRBS; Orwig, Frost, & Dennis 1980) and in soft X-rays with the Bent Crystal Spectrometer (BCS) and Flat Crystal Spectrometer (FCS) of the X-Ray Polarimeter (XRP; Acton et al. 1980).

The HXRBS is a full-Sun field-of-view instrument with 15 channels that span the energy range ~24–308 keV (Orwig et al. 1980). Figure 1 shows the variations in the total intensity in the Ca xix line complex observed with the BCS and in the 24–308 keV energy band of the HXRBS for this flare. Our study concentrates on the impulsive phase of this flare, which was characterized by two intense hard X-ray bursts lasting ~2
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Time (min since 07:00 UT)

Fig. 1.—Light curves of the 1985 January 23 flare. The hard X-ray emission has a time resolution of 128 ms, while the Ca xix emission has a time resolution of ~7 s. The data gap at ~0729 UT corresponds to a short pause when the XRP onboard computer switched the FCS to spectroscopic mode.

minutes and by the initial rapid increase in Ca xix emission. After this initial burst, there was additional hard X-ray emission at a lower intensity level and a more gradual rise in the Ca xix, followed by an extended cooling phase, which was the subject of the analysis by Zarro & Lemen (1988).

We infer spectral parameters of the hard X-ray observations by approximating the HXRBS spectra by a single component power-law functional form $I(e) = a(e/50)^{-\gamma}$ (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$), where $a$ is the hard X-ray amplitude and $\gamma$ is the spectral index. The count rates in each of the HXRBS channels are binned over 5 s averages and a least-squares deconvolution technique is used to determine the values of the power-law parameters that are most consistent with the measured counting rates. Assuming a thick-target model for hard X-ray production, we use the fitted parameters to infer the thick-target electron spectral index $\delta = \gamma + 1$ and the power $P_{20}$ in energetic electrons above a reference cutoff energy $E_c$ (see Hoyng, Brown, & van Beek 1976). Figure 2 shows the variations of $\delta$ and electron power $P_{20}$ above a 20 keV cutoff during the interval 0726:30-0728:30 UT, the period of maximum impulsive hard X-rays. The peak $P_{20}$ during this interval is $2 \times 10^{28}$ ergs s$^{-1}$. For cutoff energies of 15 and 25 keV, the corresponding powers are $6.8 \times 10^{28}$ and $6.5 \times 10^{27}$ ergs s$^{-1}$, respectively. During the impulsive phase, $\delta$ shows a soft-hard-soft evolution between values of 6.2 and slightly above 7.

The SMM FCS obtained a 5' x 5' map of AR 4617 in the Mg xi resonance line at 0707 UT (18 minutes before the impulsive phase). This map shows two bright points of emission separated by ~14'. Assuming these emission peaks correspond to the footpoints of a semicircular preflare loop, we obtain a characteristic half-length for the loop of $8 \times 10^8$ cm. Using velocity measurements in the Mg xi line during the early cooling phase and a simple conductive-evaporative cooling model, Zarro & Lemen (1988) estimated that the flaring loop had a cross sectional area of $1.5 \times 10^{17}$ cm$^2$. This half-length and area are uncorrected for any possible projection effects due to the flare's location on the disk, and are thus lower limits. Applying a correction for the location (S10, W55) yields upper limits for the half-length and cross-sectional area of $1.4 \times 10^9$ cm and $7.9 \times 10^{17}$ cm$^2$, respectively.

Table 1 summarizes all of the observational constraints on this flare. Along with the parameters discussed above, we have included rough estimates of the preflare coronal temperature based on the Mg xi/O viii ratio, and a preflare coronal pressure calculated using the Rosner, Tucker & Vaiana (1978) scaling law and the temperature and loop lengths listed.

3. NUMERICAL MODEL AND INITIAL CONDITIONS

To simulate the impulsive phase, we use a numerical model which solves the time-dependent equations for mass, momentum, and energy conservation for a solar plasma confined within a one-dimensional magnetic flux tube. This model includes flux-limited thermal conduction, optically thin radiative losses, and electron beam energy deposition. The basic numerical model has been described in detail by Mariska et al. (1982). Details of the modifications made in the model for electron-beam-heated flare calculations have been reported in Mariska et al. (1989).

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed Values*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop half length (cm)</td>
<td>8.0-14. (8)</td>
</tr>
<tr>
<td>Cross sectional area (cm$^2$)</td>
<td>1.5-7.9 (17)</td>
</tr>
<tr>
<td>Spectral index</td>
<td>6.2-7.0</td>
</tr>
<tr>
<td>Peak power in energetic electrons (ergs s$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>15 keV cutoff</td>
<td>6.8 (28)</td>
</tr>
<tr>
<td>20 keV cutoff</td>
<td>2.0 (28)</td>
</tr>
<tr>
<td>25 keV cutoff</td>
<td>6.5 (27)</td>
</tr>
<tr>
<td>Mg xi/O viii preflare temperature (K)</td>
<td>3. (6)</td>
</tr>
<tr>
<td>Scaling law preflare pressure (dyn cm$^{-2}$)</td>
<td>6.1-3.5</td>
</tr>
</tbody>
</table>

* Numbers in parentheses are powers of 10.
We begin with a magnetic flux tube, whose length is determined by the observational constraints of the flare, bent into a semicircular half-loop. By symmetry, only one side of the loop needs to be considered, and we incorporate a reflecting upper boundary to simulate material passing from one side of the loop to the other. Within this configuration we construct an initial equilibrium atmospheric model. At the base of the model is a 5000 km thick chromospheric region in hydrostatic initial equilibrium. At the base of the transition region we are constrained by the temperature gradient vanish at the top boundary of the half-loop. A complete initial model is specified by setting the length from the base of the transition region to the top of the half-loop and the pressure at the base of the transition region. The model solution then provides the value of the background constant volumetric heating rate necessary to maintain the initial configuration.

Our calculations were performed on a finite difference grid consisting of 450 computational cells of variable size. The first 4700 km of the loop were divided into 175 cells which decreased in size exponentially from 86 km at the base to 4 km at 4700 km above the base. Above this region were 100 cells, each 4 km in size. Finally, above this second region were 175 computational cells which increased in size exponentially from 4 km at the lower boundary of the region to ~ 200 km at the top of the half-loop. Changes in the length of the flaring loops were made by adjusting the length of this third region. During the course of a simulation, the middle portion of the grid was allowed to move in order to keep the steep temperature gradient associated with the chromosphere-corona transition region at a position 2/3 of the distance from the beginning of the middle region. As the flare evolved, this results in the cells in the first region becoming progressively smaller and the cells in the third region becoming progressively larger. The total number of computational cells was not changed during a simulation.

4. RESULTS

Using the observational constraints listed in Table 1 as a guide, we selected sets of parameters for a series of flare simulations in which the flare energy deposition was provided only by an electron beam. Simulations were run for each set of parameters and the results used to calculate the total emission in the Ca xix line complex between 3.17 and 3.21 Å. A simulation was judged to minimally satisfy the observations if the peak intensity in the Ca xix line complex agreed with the observed peak intensity. Our numerical approximation to the electron beam heating allows only even powers of the spectral index. Thus we selected a value of 6 for the beam spectral index in all of the calculations. This is the closest approximation to the observed values we can achieve. The number of parameters that must be examined was further limited by selecting a value for the length of the transition region and coronal portion of the initial loop of 10,000 km.

Since the time behavior of the hard X-ray burst is thought to follow the time behavior of the electron beam, we used piecewise linear fits to the hard X-ray light curve shown in Figure 1 to determine the time evolution of the electron beam. Our model flare began at 23.9 minutes and continued until the second impulsive spike ended near 28 minutes. While the electron beam was on for a total of 261 s, most of the energy was concentrated in the two impulsive spikes which lasted for less than 120 s. For each calculation the peak flux in the electron beam was determined by dividing the peak power in energetic electrons given in Table 1 by the cross-sectional area of the model flux tube.

Mariska et al. (1989) investigated the effects on the atmospheric response of changes in the peak electron beam flux, low-energy cutoff, and spectral index in a model flux tube of constant length and cross-sectional area. They were not constrained by observations of a particular flare and were thus able to vary each parameter separately. Because of the observational constraints listed in Table 1, we are not able to vary the parameters independently. For example, a decrease in the low-energy cutoff immediately implies a much larger peak energy flux for the same cross-sectional area. This is because extension of the power law for the power in nonthermal electrons to lower cutoff energies greatly increases the peak power and hence the flux. Similarly, the peak flux and the cross-sectional area of the flux tube are related. The hard X-ray observations provide only the peak power in energetic electrons. We have to assume a cross-sectional area to convert this to a flux. Thus any change in the assumed cross-sectional area implies a change in the peak flux.

Even with the spectral index of the beam set at 6, the available range of beam cutoff energies and peak fluxes is large. As an initial survey of the parameter space, we calculated two models for each cutoff energy, one with the largest allowable cross sectional area and one with the smallest. Each model was run for 300 s, which is well past the two impulsive spikes in the heating. The resulting physical conditions as a function of position and time in each calculation were then used to synthesize the spectrum of the Ca xix from 3.17 to 3.22 Å for comparison with the observations. The simulations labeled A–F in Table 2 summarize the parameters for the models and the resulting peak count rates in the Ca xix channel of the BCS.

Comparison of the calculated peak count rates with the observed peak count rate of 700–800 counts s$^{-1}$ shows that a large range of the available parameter space does not reproduce the observed peak count rates. All models with a cutoff energy of 15 keV will result in too much emission in the Ca xix line complex, while all models with a cutoff energy of 25 keV will result in too little emission. Only models with a cutoff energy of 20 keV produce Ca xix emission in the acceptable range.

Further model calculations with the low energy cutoff set at 20 keV showed that a peak beam flux near $3.5 \times 10^{10}$ ergs cm$^{-2}$ s$^{-1}$ reproduces the observed peak count rate in the Ca xix line complex. Figure 3 shows the calculated total count rates in Ca xix as a function of time for models with peak beam fluxes of $3 \times 10^{10}$, $3.5 \times 10^{10}$, and $4 \times 10^{10}$ ergs cm$^{-2}$ s$^{-1}$, along with the observed total count rate and the assumed time profile of the electron beam.

### Table 2

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Cutoff (keV)</th>
<th>Area (cm$^2$)</th>
<th>$F_{\text{max}}$ (ergs cm$^{-2}$ s$^{-1}$)</th>
<th>Pressure (dyn cm$^{-2}$)</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15</td>
<td>1.5 (17)</td>
<td>4.5 (11)</td>
<td>5.0</td>
<td>22,200</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>7.9 (17)</td>
<td>8.6 (10)</td>
<td>5.0</td>
<td>9430</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>1.5 (17)</td>
<td>1.3 (11)</td>
<td>5.0</td>
<td>2780</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>7.9 (17)</td>
<td>2.5 (10)</td>
<td>5.0</td>
<td>255</td>
</tr>
<tr>
<td>E</td>
<td>25</td>
<td>1.5 (17)</td>
<td>4.3 (10)</td>
<td>5.0</td>
<td>103</td>
</tr>
<tr>
<td>F</td>
<td>25</td>
<td>7.9 (17)</td>
<td>8.2 (9)</td>
<td>5.0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 3 clearly shows that the overall agreement between the model and the observations is poor. The only agreement between the two is that the peak count rates agree. The rise in the calculated Ca xix emission, however, begins later than it is actually observed and is more rapid. Once peak emission has been reached, the decay in emission is more rapid than is observed.

Consider first the problem of the rapid decay in the emission. Calculations A–F in Table 2 assumed that the time dependence of the energy deposition from the electron beam could be represented by a gradual rise followed by the double peaked structure seen in the hard X-ray burst. The hard X-ray burst shown in Figure 1, however, has emission at ~13% of the peak value from ~250 to 550 s after the start time of the calculations. When the electron beam energy deposition is continued at the 13% level for this time period and then terminated, the Ca xix line emission continues to rise throughout the time period from 250 to 550 s after the beginning of the simulation. This is shown in Figure 4, where we plot the results of three calculations that have this continued low level of beam heating. Each model line is marked with the peak beam flux in units of $10^{10}$ ergs cm$^{-2}$ s$^{-1}$ and the low-energy cutoff in keV. The curves shown in the figure demonstrate that continuing the electron beam at a low level will reproduce the gradual rise in the Ca xix emission that takes place after the data gap in the observations. The curves also show, however, that once that heating is removed, the emission again falls rapidly. Thus it is clear that additional heating is required throughout the decay phase to produce the observed gradual decrease in the Ca xix emission. In addition, while the overall agreement between the observed and calculated Ca xix emission, however, continues to be poor.

The problem of the more rapid rise in the calculated Ca xix emission compared with the observed emission is more difficult to solve with changes in the electron beam parameters. The observed hard X-ray emission does not support more electron beam energy input than the gradual rise from 0 to 250 s shown in Figures 3 and 4. There could, however, be gradual heating produced by an electron beam which produces hard X-rays with a flux just below the level of detectability of the HXRBS.
It seems clear from the figure that it would take a very high initial pressure to produce the initial rise seen in the Ca xix emission when the actual impulsive energy deposition took place. Moreover, the initial pressure would be so high that the preflare loop temperature would be almost at the level of a small flare. This would probably violate other observational constraints on the preflare loop.

5. DISCUSSION AND CONCLUSIONS

In the flare calculations described by Mariska et al. (1989), the electron beam had a rise time of only 30 s to roughly the same flux levels as those used in this work. This produced large increases in the temperature and density in the upper portions of the loop in very short times. For example, the temperature near the top of the loop reached a value of $10^9$ K in less than 20 s. This sudden rise was accompanied by upward mass motions with velocities of over 500 km s$^{-1}$ as a result of the pressure pulse created by the sudden deposition of energy in the upper chromosphere. Within 60 s, when the beam heating ended, the velocities had been damped to less than 200 km s$^{-1}$ everywhere in the loop.

Because the early phases of this flare are characterized by a gradual rise in the electron beam flux, the evolution of the flaring plasma is somewhat gentler in these calculations. Figure 6 shows the evolution of the temperature and electron density at a position 14,000 km from the base of the model (1000 km from the top of the loop) for the model shown in Figure 4 with a peak flux of $3 \times 10^{16}$ ergs cm$^{-2}$ s$^{-1}$ and a 20 keV cutoff. Roughly the first 150 s of the flare are characterized by a gradual increase in the coronal temperature from less than $3 \times 10^7$ K initially to near $10^7$ K. During this time the peak upflow velocity in the loop is less than 50 km s$^{-1}$. When the two spikes take place between ~150 and 260 s, the temperature and density in the coronal portion of the loop are already quite large. The additional energy in the first spike causes a rapid increase in the temperature to ~$1.8 \times 10^7$ K as the density continues to increase. Since the loop is already quite dense, however, the maximum upward velocity is much less than that seen in the earlier calculations. The peak value is never over ~300 km s$^{-1}$. It is important to note, however, that, though the velocities are not as large as those in the earlier calculations, they are easier to observe. This is because the density in the coronal portions of the loop has already been increased substantially by the gradual heating.

For this flare, none of the simple beam-heated models will reproduce the observed Ca xix emission. It is, of course, possible that this flare is unusual, and that many flares can be modeled with an electron-beam–heated atmosphere. The fact that both this flare and the one analyzed by Peres et al. (1987) were not well fitted with such models, however, suggests this may not be the case.

One possible explanation for this failure is that even in small M class flares such as this one there may be many loops participating in the event. In that case a model would have to be calculated for each individual loop and then the computed Ca xix emission from the individual loops would have to be combined. Without better spatial information on the geometry of the flaring plasma and some idea of which loops are being heated at any given time by the electron beam, it appears that this is not a useful approach at this time.

Another possible explanation for the failure of the calculated Ca xix emission to match the observations is that the heating function may be incorrect. The heating function assumes that the magnetic flux tube has a constant cross-sectional area, which means that there is no mirroring of the energetic particles. If the magnetic field converges from the coronal to the photosphere, some of the particles would mirror, resulting in more heating in the coronal portions of the loop and perhaps a different evolution.

Our electron beam parameters are based on using the observed hard X-ray fluxes and a simple cold target formula. As the ambient plasma begins to heat, however, the cold target approximation begins to break down for the lowest energy electrons. For example, a 10 keV electron has a velocity only about twice that of a $20 \times 10^6$ K electron. Our calculations assume a gradual cutoff in the electron beam below the cutoff energy listed in Table 2 (Mariska et al. 1989). Thus there are some low-energy electrons present. If these are significant contributors to the heating that produces the rapid rise in the Ca xix emission, then the cold target model upon which the electron beam parameters are based would be incorrect. The fact that the basic thermal evolution of our model is similar to that observed in calculations that have a sharp cutoff at energies greater than 10 keV (e.g., Emslie & Nagai 1984) suggests that this is not a problem. Given the disagreements between the models and the observations, however, it may be worthwhile to reexamine some of the fundamental assumptions that go into determining the parameters of the electron beam and its interaction with the ambient medium.

The problem of too rapid a decay in the soft X-ray emission after the flare heating is turned off is common to all numerical models of flare heating. Usually it is solved by assuming that there is an additional source of heating during the gradual phase, which maintains the heated plasma after the electron beam has decayed. There is, of course, also the possibility that some physical mechanism which we have not included in our model reduces the rate at which the flaring plasma cools. Near the end of the calculation whose physical variables are summarized in Figure 6, the radiative cooling time is ~780 s, while the conductive cooling time is ~375 s. Thus the heated plasma is cooling primarily by conducting energy to the base of the transition region where it can be efficiently radiated. Any
process that inhibits this conductive flow of energy would thus increase the decay time for the predicted Ca xix emission.

Calculations that include more sophisticated treatments of thermal conduction (e.g., Karpen & DeVore 1987) show that nonlocal thermal transport can alter the evolution of the flaring plasma. No detailed studies of how the flaring plasma cools under the influence of nonlocal thermal transport have, however, been undertaken. If energy transport by thermal conduction is severely limited, then the 780 s radiative cooling time scale would begin to control the cooling. This scale is still short compared to the decay times for many flares, suggesting that an additional heat source will always be required.

Our calculations are based on the premise that the electron beam originates at or near the top of a magnetic flux tube. There is, of course, the possibility that the electron beam originates in the chromospheric layers at one, or possibly both, of the footpoints of a loop. In that case more of the energy would be deposited in the chromospheric layers of the model. Since the density in those layers is high, radiation would tend to remove more of the deposited energy than is the case for the models we have computed. This would alter the rise phase behavior of the Ca xix emission, possibly leading to a more gradual rise in the emission. It would also alter the dynamics of the evolving plasma. We have not investigated this possibility, but believe that it merits further study. Once the plasma was heated to flare temperatures, the cooling phase would still be subject to the same problems we have already noted with our calculations.

It is interesting to note that there is a range of acceptable beam parameters for which the Ca xix emission is less than what is observed. In fact in one case, it was essentially zero. This means that an additional thermal energy source could be added to the model without violating the constraint that the simulated flare must reproduce the observed hard X-ray emission. This additional component could be initiated earlier and have a time dependence that would reproduce the observed Ca xix emission. The resulting two-component heating model would then give some indication of the relative importance of thermal and nonthermal energy deposition in the rise phase of a solar flare.

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