I. INTRODUCTION

The most dynamic and least understood aspect of a solar flare is the impulsive phase. This phase occurs during the first few minutes or less of the flare, during which there is a rapid increase in emission of hard X-rays (HXR), microwaves, and transition-region lines. It is characterized by temperatures possibly as high as 10^6 K, large turbulent and/or expansion motions of approximately 200 km s^{-1}, and sometimes γ-ray emission. The impulsive phase observations of flares have been reviewed by Kane et al (1980), and some recent observations from the Solar Maximum Mission (SMM) satellite have been described by Poland et al (1982) and Woodgate et al (1983).

The current most popular model for the impulsive phase (see, for example, Brown 1976) begins with an active region loop on the solar surface. Magnetic instabilities at the top of the loop are thought to accelerate high-energy electrons which travel down the legs of the loop. These electrons produce HXR via collisional bremsstrahlung and heat the chromosphere via collisional heating, yielding enhanced transition region emission. This chromospheric heating causes a pressure imbalance which results in material moving up the loop, producing the observed expansion velocities.

The intimate link between HXR and transition region and chromospheric line emission during the impulsive phase of solar flares has been discussed by several authors. Kane and Donnelly (1971) obtained a good correlation between the amount of HXR emission (ergs s^{-1}) above 10 keV and the amount of UV emission (ergs s^{-1}) in the 10-1030 Â range, over the entire flare area, as measured by sudden frequency disturbances (SFD) in the Earth's ionosphere. They also found a center to limb variation in the ratio of HXR to UV emission, suggesting that the UV emission comes from a region below the corona. Woodgate et al. (1983) investigated the temporal relation between HXR and O v line emission for several flares and found that individual emission peaks occurred simultaneously to within ±0.5 s in all events studied. These results imply a strong physical coupling between the processes that yield both types of emission.

In this paper we examine the relation between energy emitted (ergs s^{-1}) in HXR (between 25 and 100 keV) and energy emitted (ergs s^{-1}) in the 1371 Â line of O v (25 eV = 250,000 K) during the impulsive phase of several solar flares. We show that there is a very well-defined relationship between the two types of emission throughout any given flare, but this relationship varies markedly from one flare to the next. We argue that these results indicate that there is a very definite physical relationship between the processes yielding these two types of emission, and this relationship is determined for each flare by the initial density distribution in the loop before the start of energy release.

II. OBSERVATIONS

The observations used in this investigation were obtained simultaneously by the Hard X-Ray Burst Spectrometer (HXRBS) and the Ultraviolet Spectrometer Polarimeter (UVSP) on the Solar Maximum Mission (SMM) satellite. The HXRBS has been described by Orwig, Frost, and Dennis (1980). It produces 15 channel photon energy loss spectrum measurements over the spectral range 25-350 keV with a temporal resolution of 128 ms, but with no spatial resolution. These data can be used to obtain estimates of the total energy emitted in HXR from the entire flare area with very high temporal resolution. Assuming an electron beam thick target model for the impulsive phase X-ray production (Brown 1976), for example, these data can be used to infer the electron energy flux spectrum which produced the HXR and the amount of energy available to heat the chromosphere and transition region (see, for example, Emslie, Brown, and Donnelly 1978).

Calculations of the energy emitted in HXR throughout the flare using the measured photon energy loss spectra were made as follows. Each flare was divided into equally spaced time
intervals. In each interval a calculated photon flux spectrum incident on the detector was obtained from the measured photon energy-loss spectrum. For the flares studied here the incident differential photon flux spectra were best fit by a power-law shape of the form

$$\frac{dN(E)}{dE} = AE^{-\gamma} \text{photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}, \quad (1)$$

where \(dN(E)/dE\) is the photon number flux at photon energy \(E\). For each interval, best fit values were obtained for \(A\) and \(\gamma\) using an iterative fitting procedure which utilizes the detailed instrument response versus photon energy. Assuming isotropic HXR emission, the energy flux emitted in each interval at the flare site was then calculated from the equation

$$P(E_0) = 4\pi R^2 \int_{E_0}^{\infty} E \frac{dN(E)}{dE} dE \text{ergs s}^{-1}, \quad (2)$$

where \(R\) is the Sun to Earth distance, and \(E_0\) is the low-energy cutoff to the power-law fit to the photon flux spectrum, taken to be 25 keV.

The UVSP has been described by Woodgate et al. (1980). It is capable of observing in a variety of modes allowing choices in spectral lines, spatial resolution, and temporal resolution. The observations used for this study were restricted to the O v line at 1371 Å formed at a temperature of approximately 250,000 K. This line was chosen because it has been shown to correspond in temporal and spatial nature with the HXR (see, for example, Poland et al. 1982 and Woodgate et al. 1983), and there were more flares observed in this line than any other.

Examination of the HXRBS and UVSP data for those flares that occurred during the SMM observing period showed that there were 17 flares observed simultaneously in O v and HXR. Of these, six were on the disk and well within the UVSP field of view (i.e., little or none of the flare emission was estimated to be outside the UVSP field of view); four were on or near the limb; and seven were on the limb or disk but could have had significant emission outside the UVSP field of view.

Figure 1 shows a simple plot of the time history of one of the flares used in this study. The quantities plotted are ergs s\(^{-1}\) from the entire flare area. The O v emission is calculated from detector counts using the UVSP instrument calibration assuming that all of the O v emission is occurring within the bandpass of the slits used (0.3 Å), and within the observed field of view. The HXR emission was determined as discussed above. Error bars are shown at two brightness levels to indicate noise levels due to counting statistics. This figure demonstrates the simultaneity of individual impulsive peaks as discussed by Woodgate et al. (1983). The striking similarity of the two curves strongly suggests a physically causal relationship between the two types of emission despite their widely disparate energy ranges.

In order to investigate the energy relationship between the two types of emission we have plotted logarithmically in Figure 2 the rate of energy emitted in HXR versus the rate of energy emitted in O v for the flare shown in Figure 1. In this figure the squares are for times before flare maximum, the diamonds are within 5 s of maximum, and the plus signs are postmaximum. The HXR emission is from the entire Sun, while the O v emission is from the pixels showing flare enhancement in that line. This figure clearly shows that there is a well-defined relation between the two types of emission during both the rising and falling parts of the impulsive phase. It should be noted, however, that while the HXR emission changes by over two orders of magnitude, the O v changes by only a factor of 2. Although the relatively small change in O v is partially due to the relatively large background in this line, the observations do show that the fractional change in HXR is greater than the fractional change in O v after background is removed.

In Figure 3 we have plotted HXR emission versus O v emission for each flare that we believe to be contained completely in the UVSP field of view. The curve labeled 7 is for the flare presented in Figures 1 and 2. It can be seen from

![Figure 1](https://example.com/fig1.png)

**Fig. 1.**—The upper curve shows emission in O v for the entire flare as a function of time (actual values are \(10^{23}\) times larger than shown). The lower curve shows emission in HXR above 25 keV for the entire flare as a function of time (actual values are \(3.84 \times 10^{20}\) times larger than shown). Noise errors for a single measurement are shown at two different times for each plot.
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Fig. 2.—HXR emission as a function of O v emission in ergs s⁻¹ for the flare shown in Fig. 1. Squares are before flare maximum, diamonds are within 5 s of maximum, and plus signs are after flare maximum. Only every third point has been plotted for clarity of the figure.

Fig. 3.—HXR emission as a function of O v emission: (1) June 29, 18:23; (2) November 6, 17:27; (3) November 11, 20:53; (4) November 11, 23:40; (5) November 5, 23:46; (6) June 28, 02:46; (7) November 2, 02:11; (8) November 2, 02:08; (9) November 1, 19:19; (10) November 8, 14:52, all in 1980. Curves labeled with a solid line are disk flares; — — — are limb flares; and — — — are on the disk but near the limb. Arrows on the split curves show the direction in time. Number 7 is the same flare shown in Figs. 1 and 2.

this figure that the variation in O v emission from one flare to the next is much greater than the variation during a given flare. The slope of the curves also varies from one flare to the next. For most of the flares in Figure 3, the relation is almost a straight line (in log-log), with the premaximum points and the postmaximum points on almost the same line (i.e., there is little hysteresis for most of the flares observed). This point is important since it shows that the physical processes relating the two types of emission are the same on the rise and fall of the impulsive phase. Several flares do show a split behavior or hysteresis, such as the ones designated 1, 2, and 3 in Figure 3, but even these do not show nearly the spread that one gets from flare to flare. Finally, the data in Figure 3 show that the disk flares observed show more O v for a given HXR emission than do limb flares. These same characteristics are present in seven more flares observed by the SMM instruments but were not included in this analysis since the main flare points are near the edge of the O v field of view and some emission may have been missed.

Each flare was examined for spectral hardness of the HXR emission to determine if this might be a discriminating aspect for each flare. The spectral hardness was random with respect to O v emission; thus, there is no consistency between O v emission and HXR spectral hardness.

III. MODEL CALCULATIONS

In an attempt to understand the observations in the context of a one-dimensional loop heated by a high-energy electron beam (Syrovatskii and Shmeleva 1972), we have made some exploratory calculations aimed at predicting the behavior of the O v emission from such a model. The basic physical process we consider is the acceleration of an electron beam down a loop (by magnetic field annihilation, for example). The beam collides with the ambient protons yielding HXR through bremsstrahlung and heats the gas via Coulomb collisions with the ambient electrons. The gas heated to transition region temperatures emits increased O v. The primary goal of these calculations has been to predict the effect of the initial density distribution on the energy transport characteristics and radiative emission of gases in a loop subjected to beam heating. We have restricted our calculations to a short time interval (~2 s) to simulate one of the small bursts seen in Figure 1. We have also performed some calculations aimed at studying the effects of the plasma not being in ionization equilibrium due to the rapid heating.

The energy transport and hydrodynamic calculations were made with the computer program discussed in Smith and Auer (1980). The numerical technique is essentially that described in Boris and Book (1976); the time-dependent equations of conservation of mass, momentum, and energy are solved...
simultaneously using flux-corrected transport techniques for convective terms, while the conduction and radiative loss terms are solved implicitly. For this study the calculations were done with crude parameters and coarse spatial gridding in order to determine the effects of changes in the parameters, not to match the observations with a detailed model flare. The aim is to examine the possibility that the varying relation between X-ray and O v emission for different flares is due to variations in the initial density distribution.

Two density distribution models were calculated to examine various effects on the computed O v emission. In order to produce the density gradients we assumed two temperature gradients and calculated the density based on hydrostatic equilibrium and a base electron density of $10^{13}$ cm$^{-3}$. Model 1 had a steep temperature gradient, while model 2 had a more gradual temperature gradient. These temperature distributions were intended only for the purpose of setting initial density distributions, as shown in Figure 4, and were not intended as a reproduction of solar conditions.

For all of the calculations the heating was assumed to have a spatial functional form similar to that calculated by Syrovatskii and Shmeleva (1972) but simplified for our purposes. The amount of energy deposited in cell $i$ is given by

$$E_i = E_{	ext{rem}}(1 - e^{-m_i/s}),$$

where $E_{	ext{rem}}$ is the energy remaining in the beam after higher cells have removed some of its energy, $m_i$ is the mass in cell $i$, and $s$ is the scale height of beam absorption. The energy flux of the beam was increased linearly with time from 0 at $t = 0$ s to $10^{11}$ ergs cm$^{-2}$ s$^{-1}$ at $t = 2$ s. Two different spatial distributions of energy deposition from the beam were examined for each model. Thus, two calculations were made for each model for a total of four cases. In cases 1 and 2 $s$ was large ($10^{-4}$), so less energy was absorbed higher in the atmosphere and more heating occurred deeper in the atmosphere. In cases 3 and 4, $s$ was smaller ($10^{-5}$), so most of the energy was absorbed higher in the atmosphere and had to be conducted to the transition region and chromosphere.

The effects of heating each initial model are shown in Figures 5a, 5b, 5c, and 5d, where Figure 5a corresponds to case 1, Figure 5b to case 2, and so forth. In these figures we have plotted the temperature as a function of the column mass density for a number of times in the simulation. Regions between $1.5 \times 10^5$ K and $3.5 \times 10^5$ K have been marked on each figure to indicate the temperature range over which virtually all of the O v is emitted in equilibrium. The models were run for only 2 s since after this time mass motions become important and a finer computational grid in the transition region would be needed to realistically model these effects. Furthermore, in our observed flares individual bursts last on the order of a few seconds, and it is not known whether we are observing one loop or several separate flaring loops. Thus one must question the applicability of any of the current numerical models to this problem after the first few seconds. It can be seen from the figures that the density and mass in the region expected to produce O v is a function of the initial density distribution (compare Figs. 5a vs 5b and Figs. 5c vs. 5d) and where the energy is deposited (Figs. 5a vs. 5c and Figs. 5b vs. 5d).

**Table 1**

<table>
<thead>
<tr>
<th>t(s)</th>
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<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
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<tr>
<td></td>
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<td>$N_e^2 dx$</td>
<td>$N_e$</td>
<td>$N_e^2 dx$</td>
</tr>
<tr>
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<td>4.4 + 29</td>
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<td>3.6 + 29</td>
<td>9.8 + 10</td>
<td>9.0 + 29</td>
</tr>
<tr>
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<td>5.0 + 30</td>
<td>2.8 + 11</td>
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</tr>
<tr>
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<td>8.0 + 11</td>
<td>7.8 + 30</td>
<td>5.0 + 11</td>
<td>5.4 + 30</td>
</tr>
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<td>9.0 + 11</td>
<td>8.4 + 30</td>
<td>8.0 + 11</td>
<td>8.4 + 30</td>
</tr>
</tbody>
</table>
Fig. 5.—Temperature as a function of column mass for the four cases calculated. Figs. 5a and 5c are for model 1, and Figs. 5b and 5d are for model 2. Figs. 5a and 5b are for beam heating lower in the atmosphere, while Figs. 5c and 5d are for beam heating higher in the atmosphere. Horizontal arrows show the regions where most of the energy is deposited. The numbers adjacent to the curves indicate the time in seconds from the start of the model calculations, and the two horizontal lines denote the temperature band of primary emission in O v. The arrows at the top of some of the curves indicate that the next position point in the model occurs at a much higher temperature.

5d). This is also demonstrated in Figure 4 where we have indicated the location of the 250,000 K point in each case at several times in the calculation.

The important quantity from these calculations is the emission measure, $N_e^2dx$, which is proportional to O v emission and can be compared with the observations. In Table 1 we list the values of the emission measure $N_e^2dx$ (150,000 K < $T$ < 350,000 K) obtained at various times for the four cases. It can be seen from this table and the figures that both initial density distribution and location of heating cause differences in the observed O v emission as a function of time. The exception to this is that both cases 1 and 2 had the same emission at 2 s, but this is most likely a result of the choice of density distributions. The important point to be noted is that differences in initial density distribution can cause differences in observed emission as a function of time.

The reason for the difference in effects between direct heating dominating in the transition zone (cases 1 and 2) and conduction dominating (cases 3 and 4) can be seen from the energy equation. Assuming the velocity is zero, we can write the energy equation as

$$\frac{3}{2} k \frac{\partial N_e T}{\partial t} + \frac{\partial}{\partial x} \left( -K_e \frac{\partial T}{\partial x} \right) = SN_e - N_e^2 \Phi(T), \quad (4)$$
where \( N_e, T, t, \) and \( x \) have their usual meanings, \( K_e \) is the electron conductivity, \( S \) is the beam heating per unit mass, and \( \Phi(T) \) is the Cox and Tucker (1969) radiative cooling function. If we further assume that on the time scale we are considering, the density does not change (this is proven by calculations), we have

\[
\frac{3}{2} \frac{\partial T}{\partial t} = S + \frac{1}{N_e} \frac{\partial}{\partial x} \left( K_e \frac{\partial T}{\partial x} \right) - N_e \Phi(T). \tag{5}
\]

We see from this that if the heating, \( S \), dominates conduction, then the temperature change at a given point is less dependent upon the density than if conduction dominates. This effect is verified in the model calculations (i.e., compare the \( \theta \)'s in Fig. 4—the cases for which direct heating dominates; then compare the \( \phi \)'s—the cases for which conduction dominates).

Another, less obvious, but important aspect of \( \text{O} \, \text{v} \) emission can be seen from this equation. The \( \text{O} \, \text{v} \) line is a transition into a transition zone line formed in the region where conduction and radiative cooling are approximately equal. As this region is driven deeper layers with higher density, one might expect radiation to become dominant and the \( \text{O} \, \text{v} \) emission to increase. However, the temperature gradient for points beyond the transition-regions and conduction-dominated regions would also become greater, thus narrowing the region of \( \text{O} \, \text{v} \) formation. We thus see that detailed calculations must be done very carefully in order to meaningfully compare the computed and observed emission values for \( \text{O} \, \text{v} \).

Throughout the discussion of the \( \text{O} \, \text{v} \) emission, we have assumed that the oxygen ions are in ionization equilibrium. This is generally a good assumption for quiet-Sun phenomena, but it is questionable for the faster time scales encountered in flares. To examine the importance of this effect, we have carried out a number of calculations of the departures from equilibrium in a flare plasma. The calculations were performed using the ionization balance portion of the Naval Research Laboratory solar flux tube model (Mariska et al. 1982). Since hydrodynamics will be of little importance in the first few seconds of a flare, these calculations considered only the response of a plasma to heating with no mass motions allowed. Plasmas with initial temperatures from \( 5 \times 10^4 \) to \( 2.5 \times 10^5 \) K and electron densities from \( 5.0 \times 10^{10} \) to \( 5.0 \times 10^{11} \) cm\(^{-3} \) were considered. To simulate a flare, the temperature of the plasma was instantaneously raised by a factor of 10 and a factor of 100, and the departure from ionization balance in oxygen as a function of time was examined. For the \( \text{O} \, \text{v} \) ion, we found that the return to equilibrium was very rapid. The longest time noted was about 0.2 s. Thus, for the time periods considered in this paper, ionization equilibrium is a good approximation, and nonequilibrium effects cannot provide an explanation of the changes seen in the \( \text{O} \, \text{v} \) emission in the UVSP data.

We can see from the above discussion that \( \text{O} \, \text{v} \) emission for a given energy input is dependent upon the initial conditions in the model. While the penetration qualities of the beam seem to have an effect in the models, penetration is related to spectral hardness which is observationally seen to be unrelated to UV and \( \text{O} \, \text{v} \) emission. Our calculations do show, however, that the initial density distribution in the loop does dictate the \( \text{O} \, \text{v} \) emission as a function of time and energy input. We must emphasize that our model calculations have shown general trends and relationships between important physical processes (conduction and direct heating, for example), but more detailed calculations will be needed to predict the observations.

IV. DISCUSSION

There are two aspects of the results presented above that yield insight into the energy transport processes during the impulsive phase of solar flares.

1. The present observations, together with those of Kane and Donnelly (1971), show the strong physical link between non-thermal HXR emission (10-100 keV) and apparently thermal UV emission.

2. The model calculations show that the general characteristics of the observations can be explained in the context of a loop model with an electron beam producing hard X-rays at the feet of the loop and heating the chromosphere to yield enhanced UV, but more detailed calculations are needed to prove that this mechanism is the correct physical link. These concepts will be discussed below.

Previous studies have shown a good temporal correlation between HXR and UV emission during the impulsive phase of solar flares. Our observations have added to this by showing that there is a well-defined relation between \( \text{O} \, \text{v} \) and HXR emission for a given flare, but the slope and zero point of this relation vary markedly from one flare to the next. While these results may at first appear in conflict with those of Kane and Donnelly (1971), they actually may be consistent. Their result showed a consistency between the 10-1000 Å UV emission and HXR but the distribution within the 10-1000 Å region was not investigated. Thus, their UV data included the entire corona, transition region, and chromosphere, whereas \( \text{O} \, \text{v} \) is formed near the top of the transition region. The variation in \( \text{O} \, \text{v} \) observations may well result from differences in the initial conditions of the loop before the start of the flare. While differences in the initial density structure may not affect the total HXR emission nor the total corona–transition region–chromosphere emission, they would most likely have a large impact on the relative emission from different temperature regimes. This may be particularly relevant for transition region lines, where the density and temperature gradients are much steeper. Thus, the variation seen in \( \text{O} \, \text{v} \) emission may be consistent with the observations of Kane and Donnelly (1971).

Another apparent inconsistency is in the center-to-limb variation. Kane and Donnelly found a center-to-limb decrease of the UV emission relative to HXR, whereas we find that only flares directly on the limb show less \( \text{O} \, \text{v} \) emission than disk flares. However, our sample is too small to do an adequate study of this aspect of the problem. Even if there is no center-to-limb effect in \( \text{O} \, \text{v} \), this can be reconciled with the Kane and Donnelly result in that \( \text{O} \, \text{v} \) is formed longward of the Lyman continuum and higher in the atmosphere than most of the other UV emission. Thus, one would not expect \( \text{O} \, \text{v} \) to be reduced by the solar atmosphere until the flare region was either on or just past the limb. HXR presumably do not show a center-to-limb effect because significant absorption occurs only lower in the atmosphere than the height at which they are formed.

The observations presented above are thus consistent with earlier work and show that throughout the impulsive phase there is a direct physical link and relationship between the HXR and UV emitting processes. We have seen that there is a
variation in this relationship from one flare to the next and have shown that differences in the initial density distribution in the flare loop can be a contributing factor. McClymont, Canfield, and Fisher (1983) show that beam intensity may also be a contributing factor in the observed variations from flare to flare. These observations and analysis support the concept of a direct link between the processes that yield both types of emission.

In order to understand this link from a physical viewpoint, one must examine the details of the relationships between various physical processes (i.e., one must do model calculations). Our preliminary model calculations have shown that differences in the initial density distribution can cause the types of differences observed in the relation between HXR and O \textsuperscript{v} from one flare to the next. However, most of our model calculations show an increase in O \textsuperscript{v} emission during a given flare of at least one order of magnitude while the observations show only a factor of 2–3 increase. Thus, while the general characteristics of the behavior of O \textsuperscript{v} with respect to HXR can be predicted with our model calculations, reproducing the magnitude and detailed behavior has not yet been achieved.

We are currently improving our model calculations in order to examine the implications of various energy transport characteristics. It is expected that we can place limits on the nature of the assumed electron beam and density of the initial atmosphere in order to reproduce the observed nature of the O \textsuperscript{v} emission and its relation to HXR. The results from these calculations will be presented in a future paper.

The authors acknowledge the helpful discussions with R. Canfield, G. Emslie, G. Fisher, and H. Mason, and the helpful comments of R. Donnelly. J. T. M. acknowledges support from the NASA Solar Terrestrial Theory program and ONR.

REFERENCES


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