ON THE RATE OF ENERGY INPUT IN THERMAL SOLAR FLARES

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ABSTRACT

The rise phases of solar soft X-ray flares observed by X-ray crystal spectrometers on P78-1 are discussed in terms of the rate of change of X-ray flux as a function of time. It is shown that the flux increases exponentially over most of the rise time. The e-folding time, $\tau$, has a cutoff at approximately 13 s. Soft X-ray flares with smaller values of $\tau$ are not observed. It is suggested that this phenomenon is due to the ability of the solar atmosphere to absorb the input energy and convert it into a typical soft X-ray flare, when the value of $\tau$ is $\geq 13$ s. For energy input rates with $\tau \geq 13$ s, the temperature attained by the plasma is typically around $20 \times 10^6$ K, but for values of $\tau < 13$ s, the gas is heated to much higher temperatures ($T_e \approx 10^8$ K), producing a certain class of hard X-ray flares.

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

I. INTRODUCTION

This Letter presents new results on the rate of energy input into the $20 \times 10^6$ K thermal component of solar flares. The results were obtained from an analysis of about 70 M and X-type X-ray flares observed from the P78-1 spacecraft. We suggest that a subset of hard X-ray events may be produced by the same energy source that produces soft X-ray flares, as opposed to the idea that the energy contained in the hard X-ray event is ultimately the energy source of the soft X-ray flare.

II. P78-1 SPECTRA

The Naval Research Laboratory (NRL) P78-1 spectrometers cover four narrow wavelength ranges. For our purposes here, only the spectrometers covering the Ca xx (Lya) lines near 3.02 Å and the Fe xx-Fe xxv lines near 1.85 Å need be considered further. These spectrometers consist of flat Ge crystals ($2d = 4.00$ Å) that scan in 56 s the wavelength ranges from 2.98 Å to 3.07 Å and 1.83 Å to 1.95 Å, in 20″ steps (or steps of $2.5 \times 10^{-4}$ Å for the 3 Å range and $3.5 \times 10^{-4}$ Å for the 1.9 Å range). Data are read out every 64 ms. A scan from short to long wavelength is immediately followed by a scan from long to short wavelength; so a steady stream of data is produced during a flare. The time resolution of a particular line varies from a few seconds to about 2 minutes, depending on where the line is located within the observed spectral window. However, the continuum is observed continuously over a restricted energy range with 64 ms time resolution.

The source of the continuum is twofold. First, there is radiation diffracted by the crystal. This radiation has an average energy of $4.1$ keV ± 0.06 keV. Second, there is radiation of comparable intensity caused by fluorescence of the Ge crystal. This radiation is primarily the L-K transition in Ge, but it is caused by solar X-rays with energies greater than the K-shell threshold ionization energy of Ge, i.e., $\geq 11.1$ keV. Furthermore, since the photoionization cross section decreases rapidly and monotonically with energy above the Ge ionization threshold, and since the solar X-ray flux behaves similarly in this wavelength region, most of the solar X-rays responsible for the fluorescent contribution probably have energies in the neighborhood of 11.1 keV. This means that the dominant source of the continuum observed by the spectrometer is the so-called "thermal," or "gradual," X-ray flare ($\approx 20 \times 10^6$ K) and not the impulsive flare ($\approx 10^8$ K) that produces hard X-ray bursts. So far this is consistent with most of the P78-1 observations. In several unusual cases, the signature of an impulsive event is observed superposed on the thermal flare continuum, e.g., the seven impulsive bursts produced in the very intense 1980 June 7 flare were observed and reported by Feldman, Doschek, and Kreplin (1982). However, in those few cases it is possible to separate the contributions from the two different components.

Figure 1 shows examples of typical X-ray flare spectra recorded by P78-1 during the rise phase of three flares. These spectra are back-and-forth scans over the two wavelength bands. Note that the logarithm of the continuum emission in the Ca xx spectrometer band and the logarithm of the emission from the Fe xxv resonance line ($\omega$) have quite similar slopes and that their peak intensities occur at about the same time. This is an indication that the 3 Å continuum is indeed a good representation of the thermal component of the flare for the rise phase. It was shown previously (e.g., Doschek et al. 1980) that the temperature during this phase remains constant or increases only slightly. Flares with short, intermediate, and long rise times are shown in Figures 1a–1c respectively.
Fig. 1.—Three examples of typical flare spectra recorded by P78-1: (a) flare with a short rise time, $\tau = 14$ s; (b) flare with an intermediate rise time, $\tau = 52$ s; (c) flare with a long rise time, $\tau = 260$ s. The flux is plotted logarithmically (base 10), and the time is plotted linearly. The strong resonance line of Fe xxv ($1s^23p^61s2p^61s^23p^53d^1$) is indicated, as well as the Ly$\alpha$ lines of Ca xx. The Fe xxv line is commonly referred to as line w. Identifications and wavelengths for the other iron lines are given by Doschek, Feldman, and Cowan (1981). A straight line has been fitted to the data in Figs. 1b and 1c in order to show how well the X-ray flux increase resembles an exponential.
III. FLARE RISE TIMES AND DISCUSSION

Previous studies of soft X-ray flare rise times have been carried out by Drake (1971), Thomas and Teske (1971), and Datlowe (1975). These studies were based on relatively broad band detectors compared with our spectrometers. Drake (1971) and Datlowe (1975) determined the number of events with rise times in different time intervals. Thomas and Teske (1971) determined the number of events as a function of "mean rate of flux enhancement." We follow a different procedure in this Letter.

We have decided to use the 3 Å continuum measured by the Ca xx spectrometer to represent the emission from the 20 × 10^6 K plasma for the rise phase of flares. The Ca xx Lyα lines, the only significant lines in the 3 Å region, are rather faint and can be accurately subtracted from the continuum intensity. Therefore, the time resolution is 64 ms, essentially without an interruption due to the presence of spectral lines.

We have found from the analysis of the 70 events that, for most of the flare rise times, the logarithm of the flux, log F(t), in the 3 Å continuum can be fitted quite accurately with a straight line, over most of the rise time. (The exponential rise breaks down near the peak intensity of the event.) Therefore, the flux can be written in the exponential form as $F(t) = F(t_1) \exp[(t - t_1)/\tau]$, where $\tau$ is the time required for the flux to increase by an e-folding time.

The parameter $\tau$ is determined from measurements of the slope of the plot of log (flux) versus time. The slope is measured from the minimum count rate for which we feel a reliable measurement can be made. This count rate is about 10 counts per 64 ms. The most intense flares we have observed have peak emission measures of about 10^{50} cm^{-3}. The smallest value of the peak emission measure for which a slope could be reliably measured is about 10^{48} cm^{-3}. All of these flares have temperatures in the range of 20 ± 3 × 10^6 K, as determined from the ratio of the Fe xxiv spectral line j to the Fe xxv spectral line w (see Doschek et al. 1980).

The number of events N that fall in different intervals of $\tau$ is shown in Figure 2. The shape of the histogram in Figure 2 is rather flat for $\tau > 100$ s and shows a tendency for events to cluster around values of $\tau$ less than 50 s. However, the most striking aspect of Figure 2 is that there is an apparent cutoff in $\tau$ for $\tau < 13$ s. It is not an instrumental effect since events with shorter values of $\tau$ could be detected by our spectrometers. These events may occur, but they cannot be very numerous. However, although large thermal events with $\tau < 13$ s are not seen, it is known that events with much shorter time scales (< 1 s) are produced frequently during flares and sometimes without an apparent flare. The obvious examples are the impulsive hard X-ray events with very short total durations.

Because flare energy can be injected into plasma over short e-folding times, $\tau < 13$ s, i.e., the hard X-ray flares, and because no soft X-rays with such short e-folding times are observed, we would like to suggest that this is an indication of the existence of a local property of the plasma that produces a bifurcation of rise times. We suggest that the 2 keV solar plasmas (perhaps plasma confined by magnetic loops) can respond to the flare energy input by conducting it away, radiating it away, or both, as long as the energy input rate does not exceed a critical value. However, once the energy input rate exceeds a critical value, the solar plasma reacts in a different way. The gas heats up to equivalent temperatures of 10^8 K and above, and produces a hard X-ray event.
In this connection, it is interesting to ask what is the smallest slope that can be measured for a pure hard X-ray event observed by the P78-1 hard X-ray spectrometer called MONEX. We know that the actual slopes can be very large because rise times on the order of milliseconds have been measured from the hard X-ray data obtained from the Solar Maximum Mission (SMM) (see, e.g., Kiplinger et al. 1983). We have examined hard X-ray events in the 20 keV channel of the Aerospace Corporation MONEX experiment. The time resolution for this channel is 1 s. The rise cannot be simply expressed by the parameter $\tau$ since the channel in question can be expected to have contributions from the $20 \times 10^6$ K plasma as well as from the high-energy bursts. Examination of these data suggests that most hard X-ray bursts, for which an overall slope can be determined, are composed of several bursts with values of $\tau < 13$ s.

In conclusion, the e-folding time cutoff suggests a possible link between soft X-ray events and a subset of hard X-ray bursts. We say a subset of hard X-ray events because we do not wish to imply that all hard X-ray events are necessarily produced in this manner. This subset of hard X-ray bursts may represent cases where the energy input rate was so large that the more common soft X-ray event could not be produced, but instead the plasma was forced to attain temperatures of about $10^8$ K. The same energy source may produce either a soft X-ray burst or a hard X-ray event of this subset, depending on the rate of energy input.

Finally, we note that the connection we have suggested between soft X-ray events and certain hard X-ray bursts contains the implicit assumption that the energy release rate into the plasma that produces the soft X-ray flare does not have an intrinsic cutoff that produces a corresponding cutoff at $\tau \approx 13$ s in the rate of X-ray flux increase. If such a cutoff exists, the implication is that soft and hard X-ray events are produced by entirely different heating mechanisms.

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