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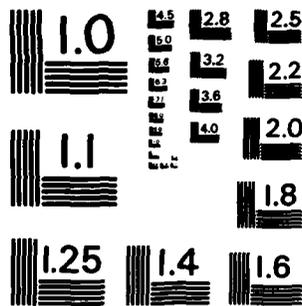
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# On the Rate of Energy Input in Thermal Solar Flares

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7 December 1983

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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For energy input rates that are below a certain critical value the temperature attained by the plasma is around  $20 \times 10^6$  K, but for values above the critical value, the gas is heated to much higher temperatures  $T_e \geq 10^8$  K, producing a certain class of hard X-ray events.



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## I. INTRODUCTION

Recent high resolution X-ray spectrometers flown on the DOD P78-1 spacecraft, the Solar Maximum Mission (SMM), and the Hinotori spacecraft have shed new light on physical conditions in solar flares and their evolution with time (e.g., Doschek, Kreplin, and Feldman 1979, Feldman, Cheng and Doschek 1982). This report 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.

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## II. P78-1 SPECTRA

The NRL P78-1 spectrometers cover four narrow wavelength ranges centered on the Fe II-Fe XXV lines near 1.85 Å, the Ca XX Lyman- $\alpha$  lines near 3.02 Å, the Ca XVIII-Ca XIX lines near 3.17 Å, and the Fe XXIII-Fe XXIV, and Mg XII lines near 8.4 Å. These wavelength ranges are covered by four different crystals mounted on a common shaft. For our purposes here, only the spectrometers covering the Ca XX lines and the Fe II-Fe XXV lines 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). 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 depends on where the line is located within the observed spectral window. For a line in the middle of a scan, the resolution is 56 s; but if the line occurs near the end of a scan, the time resolution alternates between about two minutes and a few seconds. In spectra that consist of several lines from the same ion (Fe XXV, Ca XIX) for which relative line intensities are known, the time resolution is significantly better. However, the continuum is observed continuously. Data are read out every 64 ms, and since the total wavelength range that each spectrometer scans is very narrow, the continuum is effectively observed over a restricted energy range with very high time resolution.

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The source of the continuum is twofold. First, there is radiation diffracted by the crystal. This radiation has an average energy of  $4.1 \text{ keV} \pm 0.06 \text{ keV}$ , where the plus-minus values are determined by the wavelength limits of a scan. Second, there is radiation 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.,  $\geq 11.1 \text{ keV}$ . The relative contributions of these two radiation sources to the total emission are not known precisely, but they are expected to be comparable in magnitude. 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  $11.1 \text{ keV}$ . This means that the dominant sources of the continuum observed by the spectrometer are part of the so-called "thermal" or "gradual" X-ray flare, and produce the radiation from the  $20 \times 10^6 \text{ K}$  thermal plasma and not the radiation from the impulsive 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 superimposed on the thermal flare continuum; e.g., the seven impulsive bursts produced in the very intense 7 June 1980 flare were observed and reported in 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 two wavelength bands. Further examples of these types of plots and a complete discussion of them is given in Feldman, Doschek, and Kreplin (1982). 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 ( $w$ ) have quite similar slopes and that their peak intensities occur at about the same time. This is an indication that the  $3 \text{ \AA}$  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. An example of a flare with a short rise-time is shown in Figure 1a. A flare with a long rise-time is shown in Figure 1c, and a typical example of an intermediate case is shown in Figure 1b.

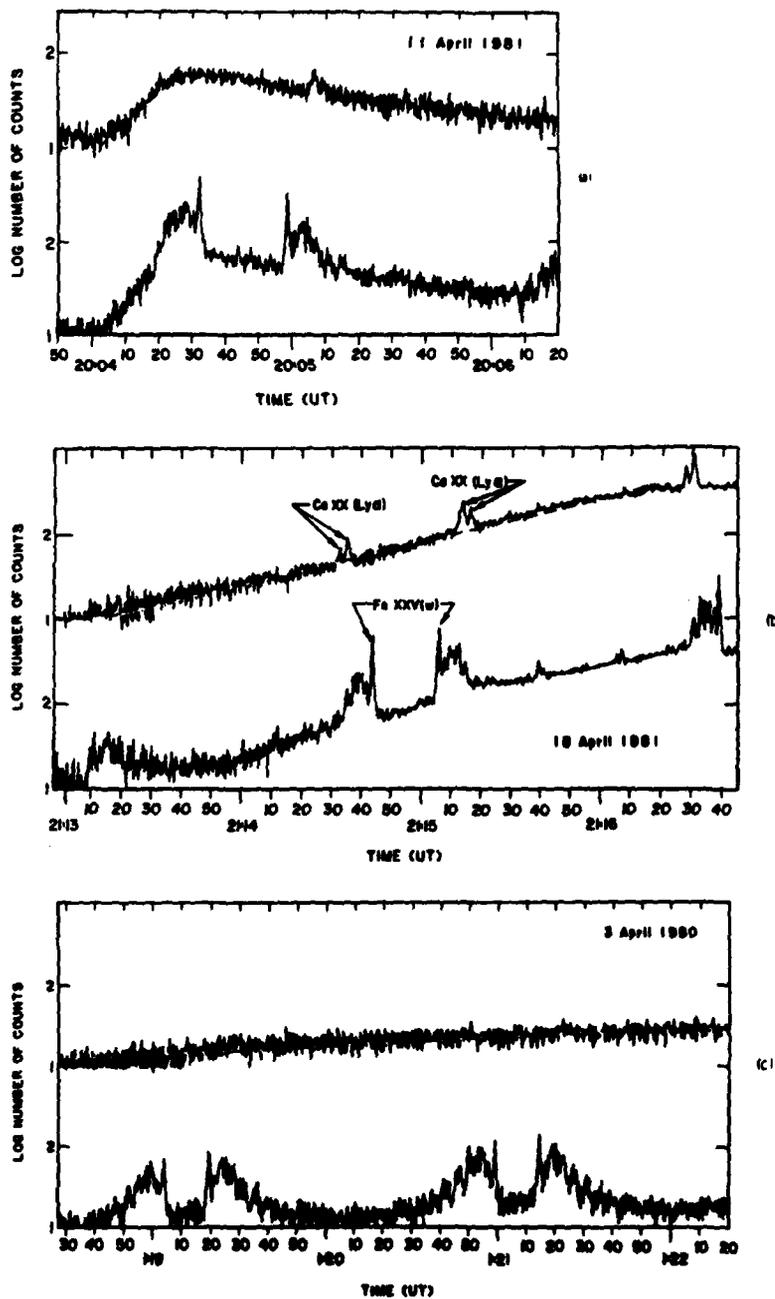


Figure 1. Three examples of typical flare spectra recorded by P78-1, with flux plotted logarithmically (base 10) and time plotted linearly: (a) flare with short rise-time  $\tau \approx 14$  s; (b) flare with intermediate rise-time  $\tau = 52$  s; and (c) flare with long rise-time  $\tau \approx 260$  s.

### 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 broadband detectors compared with our spectrometers. There are two ways of analyzing rise-times. 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 report.

We have decided to use the 3 Å continuum measured by the Ca XX spectrometer in order to have a good representation of the emission from the  $20 \times 10^6$  K plasma as a function of time for the rise phase of flares. The reasons are as follows: The Ca XX Ly- $\alpha$  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. Second, the presence of the more extended (in wavelength) emission line features in the Ca XIX and Fe XXV line spectrometers complicates the determination of continuum line intensities. Third, measurement of the lines alone does not provide adequate time resolution, since the rise phase may last only a few seconds.

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. 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 a factor of e.

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/64 ms. The most intense flares we have observed have peak emission measures of about  $10^{50} \text{ cm}^{-3}$ . The smallest value of the peak emission measure for which a slope can be reliably measured is about  $10^{48} \text{ cm}^{-3}$ . Thus, our sample of events concerns flares with peak emission measures larger than  $10^{48} \text{ cm}^{-3}$ . All of these flares have temperatures in the neighborhood of  $20 \pm 3 \times 10^6 \text{ K}$ , as determined from the ratio of the Fe spectral line j to the Fe XXV spectral line w (see Doschek, Kreplin, and Feldman 1979).

The number of events N that fall in different intervals of  $\tau$  is shown in Figure 2. Events with the same  $\tau$  are not necessarily similar. For example, an event with a particular  $\tau$  might have a long rise-time and a high peak flux level, or a short rise-time and a low peak flux level.

The shape of the histogram in Figure 2 is rather flat for  $\tau > 100 \text{ s}$  but 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 cut-off in  $\tau$  for  $\tau < 13 \text{ s}$ . 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  $\tau < 13 \text{ s}$  are not seen, it is known that events with much shorter time scale ( $< 1 \text{ s}$ ) 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.

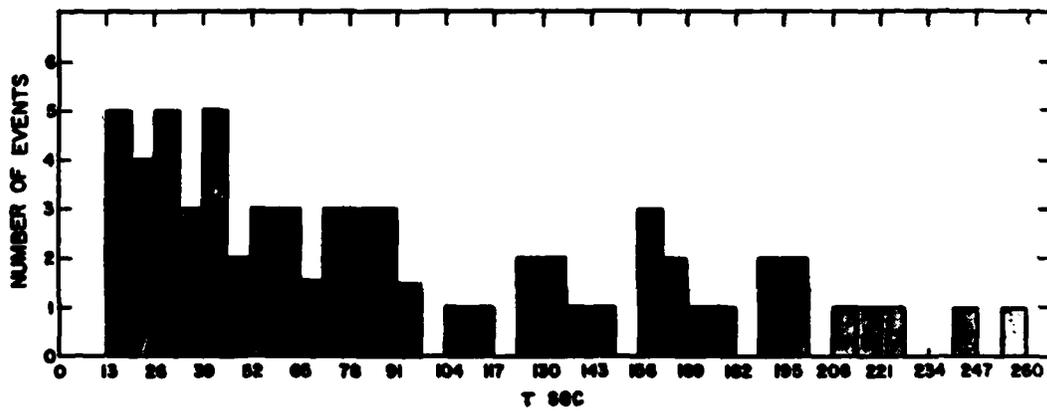


Figure 2. Number of events  $N$  as a function of  $\tau$ . Intervals of  $\tau$  are 6.5 s in width.

Because flare energy can be injected into plasma over short e-folding times,  $\tau \ll 13$  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 particular 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. We know that the slopes can be very large, because rise-times on the order of milliseconds have been measured, e.g., Kiplinger et al., 1983. However, it is difficult to determine just how small the slopes can be. We have examined hard X-ray events in the 20 keV channel of The Aerospace Corporation MONEX experiment on P78-1. 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 more impulsive bursts. Furthermore, even if the contribution of the thermal component is ignored, the rise may be an envelope of a series of rapid hard X-ray bursts. Examination of these data suggests that most hard X-ray bursts, for which an overall slope can be determined, are composites of several bursts with values of  $\tau < 13$  s.

#### IV. CONCLUSIONS

In conclusion we may state that 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 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 at  $\tau = 13$  sec. If such a cutoff exists, the implication is that soft and hard X-ray events are totally unrelated phenomena produced by entirely different energy channels.

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