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THE SOLAR FLARE OF 1980 MARCH 29 AT 0918 UT AS OBSERVED WITH THE HARD X-RAY BURST SPECTROMETER ON THE *SOLAR MAXIMUM MISSION*

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ABSTRACT

High-energy X-ray observations in the energy range from 26 to 386 keV are reported for the solar flare on 1980 March 29 starting at $09^h17^m10^s$ UT. With the 1–2 s time resolution previously available, this flare would have appeared as the largest single hard X-ray spike ever reported with *e*-folding rise and fall times of ~2 s, a FWHM of ~10 s, and a peak flux of 6 photons cm^{-2} s^{-1} keV^{-1} at 50 keV. With the 10 ms time resolution available from the Hard X-Ray Burst Spectrometer on *SMM*, significant deviations from a smooth time profile can be resolved on the leading edge and at the peak of the burst. These deviations are in the form of at least five steps or eight separate peaks ~1 s wide with separation times of 1–2 s. They are interpreted as resulting from multiple driven tearing-mode instabilities in a single magnetic loop or by a cascade effect in an arcade of loops. The photon-number spectrum on the leading edge and at the peak of the burst can be represented by a thermal bremsstrahlung function with the temperature and emission measure increasing to maximum values of $\sim 5 \times 10^8$ K and $\sim 5 \times 10^{45}$ cm^{-3}, respectively, at the time of peak intensity. On the trailing edge of the burst, the data show a significant excess at high energies (>100 keV) above the fitted thermal bremsstrahlung function. Such a high-energy tail may be the result of second-stage acceleration, or it may reflect the evolution of a single thermal electron distribution in some form of magnetic trap.

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

I. INTRODUCTION

Hard X-ray spike bursts have attracted considerable attention in the past, since it is possible that they are the simplest form of a high-energy solar flare. The more complex impulsive phase of most other flares may be made up of the superposition of many such "elementary bursts" (van Beek, de Feiter, and de Jager 1974, 1976; Crannell *et al.* 1978; de Jager and de Jonge 1978; Karpen, Crannell, and Frost 1979). The intense hard X-ray burst on 1980 March 29 at 0918 UT would have appeared (except for a small precursor) as the largest single spike burst ever reported if it had been observed with the relatively coarse 1–2 s time resolution previously available on the *OSO 5*, *OGO 5*, and *TD 1A* satellites. The high statistical significance of the data obtained for this event by the Hard X-Ray Burst Spectrometer (HXRBS—Orwig, Frost, and Dennis 1980), combined with the broad spectral coverage (26–380 keV) and the 10 ms time resolution, make this observation a unique opportunity to study such a spike burst in more detail than has previously been possible. The hard X-ray observations of this event are presented here, and results from observations of the same event at different frequencies are presented by Culhane *et al.* (1981), Rust *et al.* (1981), and Ryan *et al.* (1981).

II. X-RAY OBSERVATIONS

The time-intensity profile of the flare is shown in Figure 1 for three energy intervals. Apart from the small precursor, the event consists of a main burst with a peak flux of 6 photons cm^{-2} s^{-1} keV^{-1} at 50 keV and a width of ~10 s at half this peak flux. The leading and trailing edges of this main peak both show decreasing time constants with increasing energy, and this is reflected in the spectral changes discussed below. The detailed time profile of the main burst is shown in Figure 2, where the rates are plotted with the finest time resolution available. Significant deviations from a smooth profile can be seen on the leading edge and at the peak of the burst, but the decay after $09^h18^m15^s$ does appear smooth. The deviations, seen most clearly at 26 to 52 keV, are in the form of at least five steps and may be interpreted as resulting from up to eight separate peaks with separation times ranging from 1 to 2 s. The most distinct of the peaks, most clearly resolved in the higher-energy data, is at $09^h18^m10^s$ UT.

The spectral information is shown in Figure 3 for different stages of the flare. In this preliminary analysis, the count rate data have been converted to incident X-ray photon fluxes using only the diagonal elements of the instrument response function. No attempt has been made at this stage in the analysis to include the detector resolution or the K-escape process in the deconvolution calculations. Consequently, the quoted spectral parameters derived from least-squares fits may be in error by as much as a factor of 2. Nevertheless, the relative changes of the parameters with time are more accurate, and it is the changes in the parameters and in the spectral form that we wish to emphasize. Based on prelaunch tests (Orwig, Frost, and Dennis 1980), the effects of pulse pileup are believed to be negligible compared to the other uncertainties in the current state of the data analysis.

During the early part of the event, up to and including the time of maximum count rate, the photon number spectrum can be well represented by a thermal bremsstrahlung function (Tucker 1975; Crannell *et al.* 1978). These spectral fits are shown in Figure 3. A simple exponential or a double power-law function would also fit the data equally well, and, consequently, temperatures derived from the spectral fits do not necessarily indicate that the electron distribution is thermal. After $09^h18^m15^s$, on the falling edge of the main burst, the spectrum can no longer be well represented by a single-temperature thermal bremsstrahlung function over the full energy range as can be seen in Figure 3. Nevertheless, the temperature and emission measure obtained from least-squares fits to all the data are plotted in Figure 1, even though the fits are not acceptable at higher energies later in the event. These fits are acceptable over a restricted energy range mainly below 100 keV. As shown in Figure 1, both the temperature and the emission measure increased after the time of the precursor to maximum values at the time of the peak count rate and then decreased proportionately until at least $09^h18^m45^s$.

The excess flux above the fitted bremsstrahlung function at energies greater than 100 keV may be interpreted as thermal bremsstrahlung from an additional, higher-temperature electron distribution or as a second component with a power-law spectrum. If we interpret this tail as resulting from a higher-temperature thermal distribution, we find that the temperature reached a peak of 6×10^8 K between $09^h18^m21^s.3$ and $09^h18^m29^s.5$, approximately 10 s after the start of the decay. If we interpret the high-energy tail as a power law, then the spectral index is approximately 3. Actually, in the time interval when the temperature derived from the high-energy data is at its maximum, the spectrum over the full energy range can be fitted with a power-law function with a spectral index of 4.5. This may be fortuitous if the spectrum has two components that are changing independently.

III. DISCUSSION

The detailed hard X-ray observations presented in this *Letter* show that the solar flare on 1980 March 29 at 0918 UT (and probably others like it) cannot be regarded as a single spike burst. While the main burst has approximately equal rise and fall times consistent with a single adiabatic compression and expansion (Mätzler *et al.* 1978), the data suggest that it is made up of at least eight separate peaks. The observed step-wise increase in flux on the leading edge of the burst is similar to the time profile of the quasi-periodic bursts first reported by Frost (1969) and seen in many hard X-ray and microwave bursts. This similarity

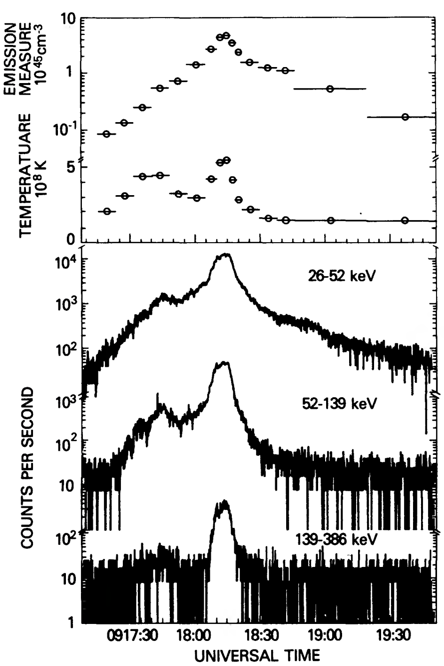

FIG. 1.—Time profile of the detector count rate in three energy bands for the X-ray event of 1980 March 29. Note the logarithmic scale and the time resolution of 0.128 s. Also shown on the same time scale are the temperature and the emission measure determined from least-squares fits of a thermal bremsstrahlung function to the spectral data. The uncertainties resulting from statistics alone are smaller than the size of the circles but the temperature may be high by as much as a factor of 2 because of systematic effects (see text).

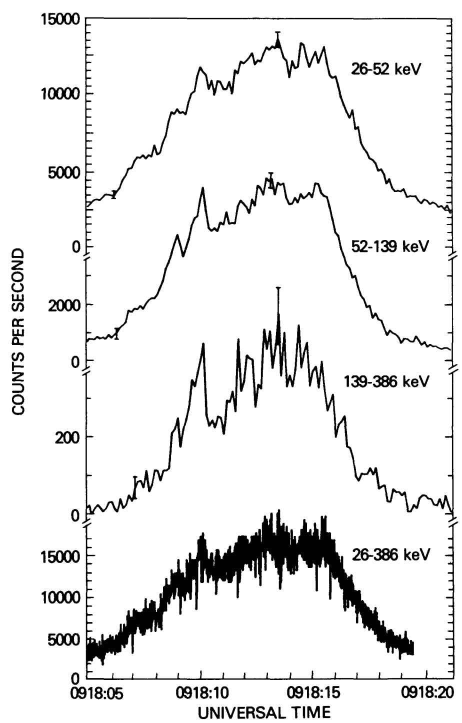

FIG. 2.—Expanded count-rate profile of the peak of the event in four different energy bands. The time resolution is 10 ms for the integral energy band from 26 to 386 keV, and 0.128 s for the other energy bands.

suggests that this event is a typical solar flare, but compressed in time as a result of the parameters of the source region. Wiehl and Mätzler (1980) have attributed similar structure to a disturbance traveling through the plasma at the Alfvén speed during the adiabatic compression. A more detailed explanation has been presented by Spicer (Spicer 1977; Kahler *et al.* 1980) in terms of multiple driven tearing-mode instabilities. If a spectrum of tearing modes exists, then reconnection via one level of tearing mode can take place after reconnection via a lower level becomes saturated. This is possible provided that the driving source is strong enough to keep the magnetic field gradients increasing. In this model the sharp and relatively smooth decrease in flux after the peak would result if the driving source were no longer able to maintain increasing magnetic field gradients in the face of the relaxations produced by the tearing-mode instabilities. Another possible explanation of the detailed time structure is that the individual steps and spikes are produced at different locations, possibly from different magnetic loops. This hypothesis is supported by the Nancay radioheliograph observations at 169 MHz which show at least two different locations for the type III radio bursts occurring in the same time interval (Rust *et al.* 1981).

The observed hardening of the X-ray spectrum up to the peak of the flare and the subsequent softening was first reported by Kane and Anderson (1970) and

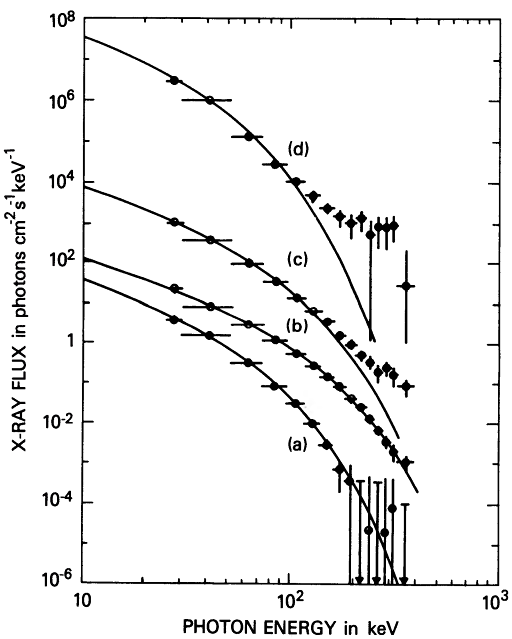

FIG. 3.—The photon number spectrum obtained at different stages throughout the main peak of the flare: (*a*) leading edge, $09^h17^m57^s$ to $09^h18^m05^s$ ($\times$ 1), (*b*) peak, $09^h18^m09^s$ to $09^h18^m15^s$ ($\times$ 1), (*c*) trailing edge, $09^h18^m15^s$ to $09^h18^m21^s$ ($\times 10^2$), (*d*) later on trailing edge, $09^h18^m21^s$ to $09^h18^m29^s$ ($\times 10^6$). The smooth curves are the least-squares fits of a thermal bremsstrahlung function to the data in all 15 channels. Note that the data and the fitted function for each time interval have been multiplied by a factor, indicated above, to clearly separate the plots.

has been confirmed by Crannell *et al.* (1978) and Elcan (1978) for most of the events reported. The appearance of a high-energy tail during impulsive events of the type reported here has not previously been established, however, perhaps because of limited sensitivity above 100 keV. Crannell *et al.* (1978) did report a hardening of the spectrum at the peak of one event and during the fall of several others.

Possible explanations of the spectral changes observed after the peak of the 1980 March 29 burst include (i) a second stage of acceleration in which a small fraction of the electrons, initially energized in the first stage of the burst, are further accelerated, and (ii) the evolution of a single distribution of energetic electrons after the initial energization.

The evidence for second-stage acceleration has been reviewed by Ramaty *et al.* (1980). Some fraction of the electrons energized in the impulsive phase of the flare may be further accelerated by an expanding shock wave manifested by a radio type II burst. A type II–like burst was reported after the 1980 March 29 flare (A. O. Benz, private communication), but for some reason a large flux of high-energy electrons similar in magnitude to that inferred for the 1969 March 30 event (Frost and Dennis 1971) was not produced. Enough electrons may have been accelerated, however, to produce the high-energy tail observed on the X-ray spectrum.

In the trap model introduced by Takakura and Kai (1966), a single distribution of electrons evolves after the initial acceleration. This model would produce a hardening of the spectrum during the decay phase of a burst as a result of the increase in the collisional electron energy loss time in a magnetic trap with increasing energy. Such a model was discounted by Kane *et al.* (1980), however, because of the apparent disagreement of the observations with this prediction. It now appears that the early observations may not have been sufficiently sensitive to detect the spectral hardening, particularly in the smaller events. Bai and Ramaty (1979) used a trap model with continuous electron acceleration throughout the event to interpret the impulsive bursts in the 1972 August flares. No delay in the peak times with increasing energy comparable to the 4–9 s delay at 150 keV reported for those flares is found in the 1980 March 29 flare. Nevertheless, it is possible that the appearance of the observed high-energy tail could result from the evolution of the electron spectrum in such a model. Mätzler *et al.* (1978) have offered an alternative explanation of the X-ray spectral hardening in which a small fraction of the energetic electrons escape from a magnetic trap and are not subject to deceleration during the adiabatic compression in their model. The problem with this idea is that these electrons would escape into a region of much lower temperature producing a more rapid energy loss by collisions.

IV. CONCLUSIONS

The fine time resolution observations of the solar flare on 1980 March 29 at 0918 UT show that this event is not a single hard X-ray spike, as would have been concluded from previous observations with 1–2 s time resolution. Rather it is made up of eight or more individual spikes approximately 1 s wide and spaced 1–2 s apart, resulting in the observed irregular stepwise increase on the leading edge of the burst. These features may well represent the time profile of the electron acceleration mechanism itself and could be produced by successive driven tearing-mode instabilities or by a cascade effect in an arcade of magnetic loops.

The X-ray spectral information is interpreted as indicating the energization of electrons to a maximum equivalent temperature of 5×10^8 K reached at the peak of the event. On the relatively smooth trailing edge of the event, most of the electrons rapidly lose their energy, but an excess flux appears above the fitted thermal bremsstrahlung function at X-ray energies in excess of 100 keV. This high-energy tail suggests either second-stage acceleration or the evolution of the distribution of energized electrons in a magnetic trap.

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