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Solar radio observations have provided the primary evidence for this hypothesis. In this Note we present x-ray evidence that supports the two stage acceleration hypothesis in its general characteristics and further provides detailed information on the accelerated electron spectra, time characteristics and intensity in each stage.

OBSERVATION

On March 30, 1969, an intense hard x-ray burst was observed in the 15 to 250 keV range with instrumentation on OSO-5. Details of the experiment are presented elsewhere in the literature (Frost 1969; Frost, Dennis and Lencho 1970). The burst began at 0247 U.T. in coincidence with a flare on the west limb of the Sun and evolved through two apparently non-thermal phases over a period of 45 minutes.

The observation was made with 9 channels of energy analysis subdividing the 15 to 250 keV range. A plot of the x-ray intensity-time profile observed in selected energy channels is presented in Figure 1. The first non-thermal phase of the burst consists of an impulsive peak beginning at 0246:59 U.T. and reaching maximum at 0247:48 U.T. In the 28 to 55 keV channel the decay of the impulsive peak stops at 0250 U.T. with the intensity remaining nearly constant until 0255 U.T. with a slight indication of a broad maximum between 0250 to 0255 U.T. During the subsequent slow decay the observation is terminated by sunset at 0331.5 U.T.

In the higher energy channels in Figure 1 a pronounced valley in the intensity profiles is observed at 0250 U.T. Thereafter a second increase in intensity begins and represents the second non-thermal phase of the burst. During the increase, at 0250.5 U.T. a type II radio burst appears in the metric band (Solar-Geophysical Data, May 1969). The intensity maximum reached in the 200 to 225 and 225 to 254 keV channels after the second increase exceeds that recorded in these channels at the peak of the impulsive burst, thus implying a markedly harder spectrum for the second phase of the x-ray burst.

The spectra observed for the first and second phases are plotted in Figures 2a and 2b, respectively. At the peak of the impulsive burst the spectrum is an $E^{-2.3}$ power law up to 100 keV and a much steeper $E^{-4.5}$ power law thereafter. The spectrum just prior to the rise of the second phase and the type II burst is an $E^{-2.8}$ power law to 100 keV where there is again a break in slope to a steeper $E^{-4.7}$ law. The spectrum found at the beginning of the impulsive burst agrees with that found prior to the rise of the second phase. The harder spectrum up to 100 keV at the peak is probably an $E^{-2.8}$ law distorted to an $E^{-2.3}$ law by pulse pile-up effects due to the high count rate. Thus we suspect that the spectrum does not change shape during the impulsive burst but remains constant with the shape obtained during the rise and decay.

Spectra with a break in slope at 100 keV were first observed by Frost (1969) in a quasi-periodic x-ray burst observed on March 1, 1969. The spectrum we consider here as well as that of the March 1, and other similar events from OSO-5 indicate that this type of spectrum appears to be characteristic of extremely impulsive x-ray bursts.

At 0250 U.T. the second rise in intensity begins, with the shape of the spectrum at the second maximum being E^{-2} up to 250 keV, the highest energy observed. The spectrum remains constant at E^{-2} from maximum until sunset, a duration of 40 minutes.

DISCUSSION

In discussing this event we assume that the observed x-radiation is produced by bremsstrahlung of electrons on protons in the appropriately dense regions of the solar atmosphere. Consequently, the x-ray spectrum is indicative of the spectrum of the accelerated electrons.

This observation lends support to the two stage acceleration hypothesis based on the following interpretation. There is surely an acceleration of electrons required to produce the bremsstrahlung of the impulsive peak in Figure 1. The break at 100 keV in the photon spectrum suggests that efficient acceleration for electrons, and perhaps protons, was limited to an energy of 100 keV. If this acceleration occurred by an induced electric field, then the time averaged induced field rose to a value such that the potential drop across the accelerating region was not much greater than 100 kV. Thus the impulsive peak can be interpreted as bremsstrahlung from electrons accelerated to an energy and in a fashion similar to that described by De Jager for the first phase.

The second rise in intensity starting at 0250.2 U.T. and 18 seconds prior to the appearance of a type II radio burst in the metric band (Solar-Geophysical Data, May 1969) suggests that a second acceleration of electrons has taken place. Moreover the slower rise of the second phase of the x-ray burst, its harder spectrum than that found in the first phase, the greater number of photons at higher energy and its close association in time with the appearance of a shock front as evidenced by the type II burst, suggests that the second acceleration proceeds by a different mechanism than the first. In this case the second acceleration begins no longer than 3 minutes after the first and not 10 to 30 minutes later as proposed by De Jager (1969). This agrees with Svestka's (1970) conclusion that, "If the acceleration is accomplished in two or more steps, these must immediately follow one after the other."

De Jager proposed that a Fermi mechanism is responsible for the second phase of the acceleration. One would expect this mechanism to be associated with a shock front and to accelerate electrons and protons to a power law in energy. The E^{-2} photon spectrum of the second phase implies a power law distribution for the electrons producing it.

A long standing problem in the Fermi mechanism has been that acceleration from thermal energies is difficult because the energy losses are usually greater than the imparted gains at low energy. An injection mechanism providing a source of preexisting energetic particles is needed for the Fermi mechanism to be effective. Such an injection mechanism is available in the two-stage acceleration hypothesis. In Figure 1 at 0250 U.T. just before the appearance of the shock front, the large x-ray flux indicates that there are large numbers of electrons (probably accompanied by protons) with energies up to 100 keV in the flare region. The photon spectrum at this time is plotted in Figure 2a. The electrons producing this spectrum are probably swept up along with the protons by the shock front and accelerated to relativisitic energies.

The intensity of the first acceleration and the delay until the appearance of the shock front determines the number of energetic particles available for injection into the second stage. The spectrum from the first stage and the velocity and configuration of the shock front appears to determine the spectrum resulting from the second stage acceleration. In this case the shock front appears in the metric band as a type II burst at 0250.5 U.T. (Solar-Geophysical Data, May 1969). The first definite evidence of second stage acceleration, the second increase in flux in the 225 to 254 keV channel, begins no later than 0250.2 U.T. The 18 second time difference could be the time taken by the shock front to travel from the point lower in the solar atmosphere, where it began accelerating particles, to the 80 MHz plasma level.

The event we have discussed here is not unique in its general characteristics. The event of March 1 (Frost 1969) has the same characteristics except that the impulsive component was quasi-periodic. The second phase of the March 1 event, which had an E^{-5} photon spectrum, also began in conjunction with a type II radio burst and probably should be reinterpreted in the light of our current findings as due to bremsstrahlung from electrons accelerated in a shock front.

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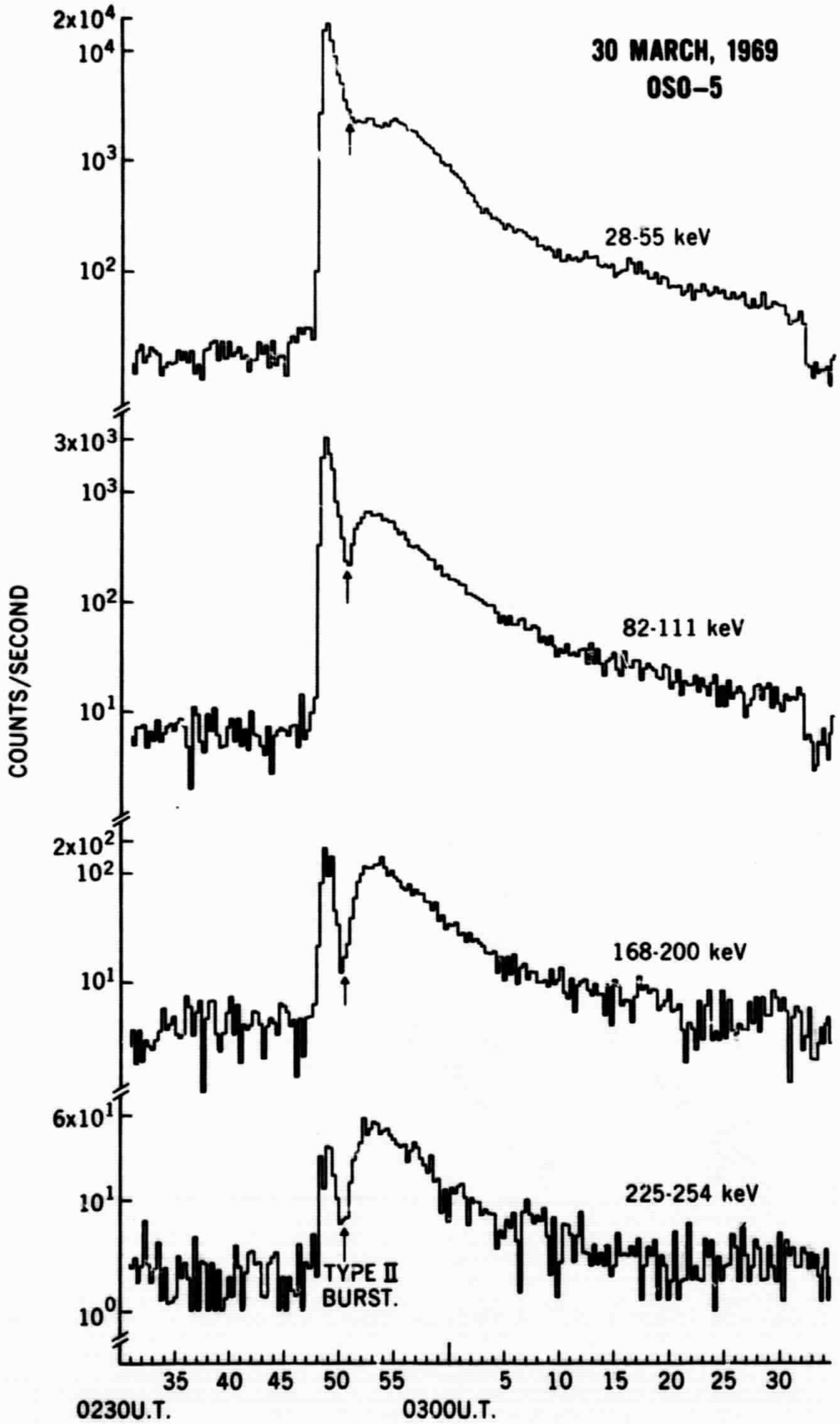
FIGURE CAPTIONS

Fig. 1. Intensity-time profiles which cover the energy intervals indicated to the right of each profile. Each point in the profiles is computed from 10 consecutive and evenly spaced measurements of approximately 0.18 seconds duration taken over 18 seconds. The verticle arrow indicates the time of appearance of a type II burst in the metric band, the abrupt drop in count rate after 0331.5 U.T. is due to sunset.

Fig. 2.(a) The circles represent the spectrum at the peak of the impulsive burst between 0247.5 and 0248.5 U.T. The squares; the spectrum between 0249.5 and 0249.8 U.T. just prior to the second increase and the type II burst. The dashed lines on each spectrum emphasize the break in slope that occurs at 100 keV. The spectrum at the peak is fitted with $E^{-2.3}$ power law up to 100 keV and $E^{-4.5}$ power law beyond 100 keV. The later spectrum; with $E^{-2.8}$ power law to 100 keV and $E^{-4.7}$ power law above 100 keV. The spectrum at the peak may be of the same shape as found later but distorted by the effects of pulse pile-up.

(b) The spectrum at the peak of the second phase between 0251.1 to 0242.5 U.T. (circles) is plotted above the spectrum observed later between 0306.5 and 0308.5.

Both spectra can be fitted with E^{-2} power law between 15 and 250 keV. The dashed curve represents the lower spectrum in Fig. 2a.



30 MARCH, 1969
OSO-5
COUNTS/SECOND
2x10⁴
10⁴
10³
10²
28-55 keV
3x10³
10³
10²
10¹
82-111 keV
2x10²
10²
10¹
168-200 keV
6x10¹
10¹
10⁰
225-254 keV
TYPE II
BURST.
35 40 45 50 55 5 10 15 20 25 30
0230U.T.
0300U.T.

Figure 1.

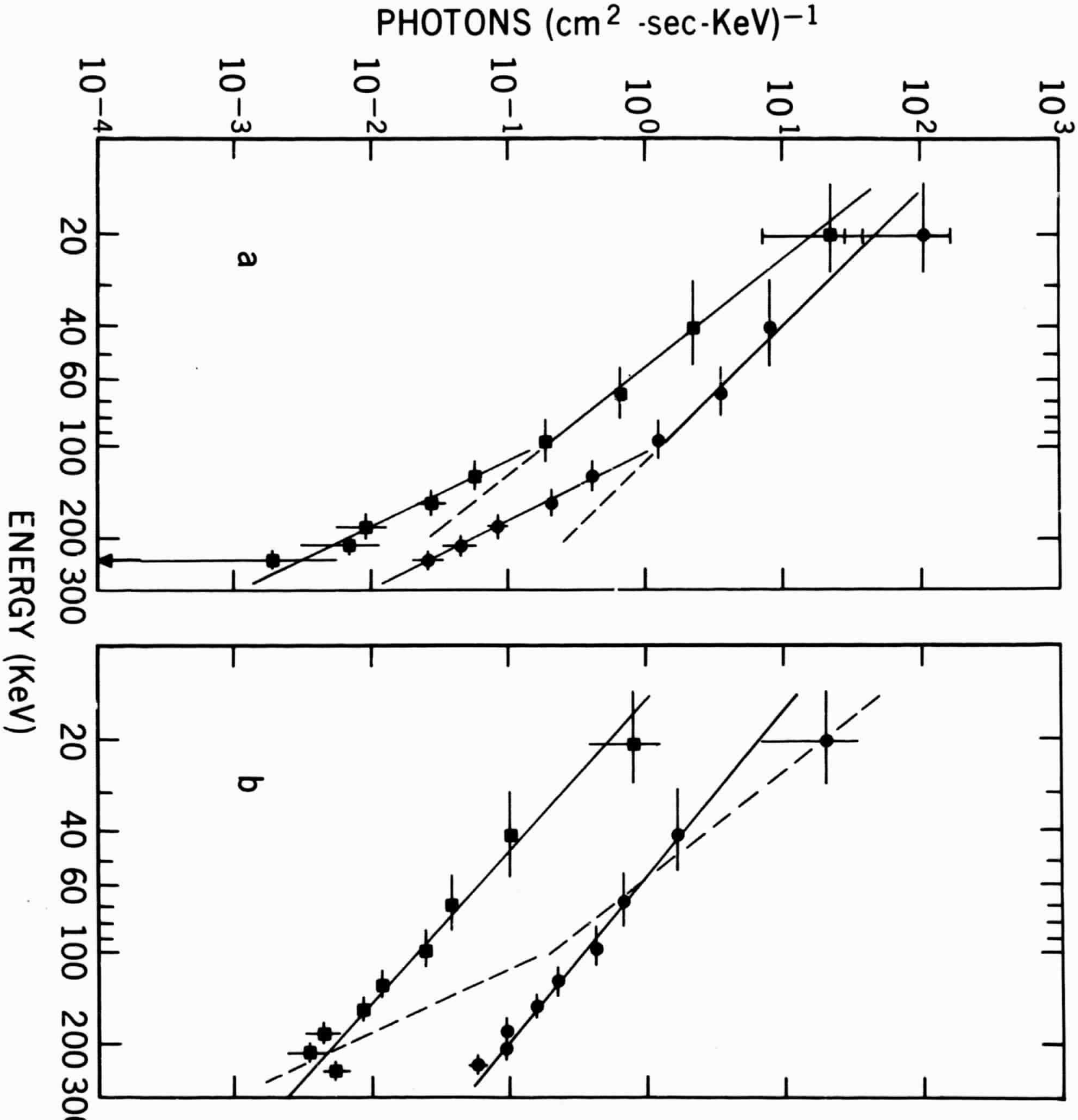

PHOTONS (cm² -sec-KeV)⁻¹
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
a
b
20
40 60 100
200 300
ENERGY (KeV)

Figure 2.