THE ASTROPHYSICAL JOURNAL, 165:655–659, 1971 May 1

EVIDENCE FROM HARD X-RAYS FOR TWO-STAGE PARTICLE ACCELERATION IN A SOLAR FLARE

K. J. FROST AND B. R. DENNIS
Solar Plasmas Branch, Laboratory for Solar Physics, NASA-Goddard
Space Flight Center, Greenbelt, Maryland 20771

Received 1970 November 30

ABSTRACT

A solar X-ray burst which evolves in time through two nonthermal phases is presented The burst is considered to be bremsstrahlung from electrons accelerated in two stages in the solar atmosphere In the first stage, acceleration effectively to 100 keV occurs, perhaps by an induced electric field; in the second stage, the acceleration to higher energies could occur by a Fermi mechanism operating in a shock front

I. INTRODUCTION

Wild, Smerd, and Weiss (1963) and De Jager (1969) have suggested that the acceleration of particles in a solar flare occurs in two stages or phases. The description of the two phases is as follows. In the first phase, particles are accelerated to energies of the order of 100 keV. This occurs in coincidence with the flash phase of the flare, and some 10^{37} particles are accelerated depending on the magnitude of the flare. The accelerating mechanism in this stage is thought to be due to an induced electric field which may perhaps arise in a pinch-type instability. The second acceleration, occurring some 10–30 minutes after the first, is ascribed to a Fermi mechanism operating in a shock front. In the second acceleration 10^{-3} of the particles involved in the first stage are accelerated to energies 10^3 greater than in the first stage.

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

II. OBSERVATION

On 1969 March 30 an intense burst of hard X-rays was observed in the 15–250-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 UT in coincidence with a flare behind the west limb of the Sun and evolved through two apparently nonthermal phases over a period of 45 minutes.

The observation was made with nine channels of energy analysis subdividing the 15–250-keV range. A plot of the X-ray intensity–time profile observed in selected energy channels is presented in Figure 1. The first nonthermal phase of the burst consists of an impulsive peak beginning at 0246:59 UT and reaching maximum at 0247:48 UT. In the 28–55-keV channel the decay of the impulsive peak stops at 0250 UT; the intensity then remains nearly constant until 0255 UT with a slight indication of a broad maximum between 0250 and 0255 UT. During the subsequent slow decay the observation is terminated by sunset at 0331.5 UT. In the higher energy channels in Figure 1 a pronounced valley in the intensity profiles is observed at 0250 UT. Thereafter a second increase in intensity begins which represents the second nonthermal phase of the burst. During the increase, at 0250.5 UT a Type II radio burst appears in the metric band (*Solar-Geophysi-*

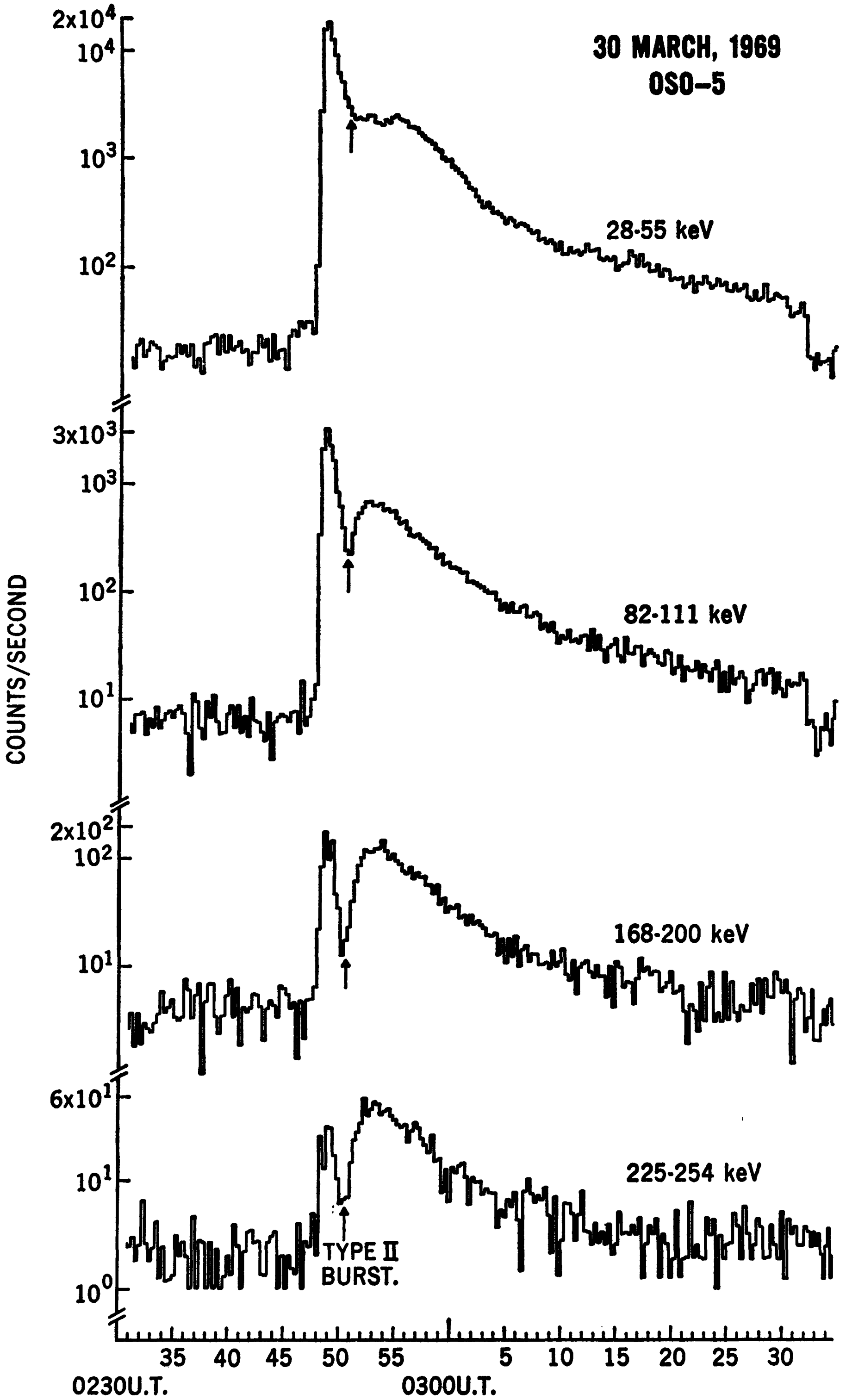

FIG 1 —Intensity-time profiles which cover the energy intervals indicated to the right of each profile Each point in the profiles is computed from 10 consecutive and evenly spaced measurements of approximately 0 18 seconds duration taken over 18 seconds Vertical arrow indicates the time of appearance of a Type II burst in the metric band; the abrupt drop in counting rate after 0331 5 UT is due to sunset.

cal Data, 1969 May). The intensity maximum reached in the 200–225- and 225–254-keV channels after the second increase exceeds that recorded in these channels at the peak of the impulsive burst, an observation which implies 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 2*a* and 2*b*, 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-pileup effects due to the high counting 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 1969 March 1. The spectrum we consider here, as well as that of the March 1 and other similar events from OSO-5, indicates that this type of spectrum appears to be characteristic of extremely impulsive X-ray bursts.

At 0250 UT 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.

III. DISCUSSION

In discussing this event we assume that the observed X-radiation is produced by bremsstrahlung from electrons on protons in the appropriately dense regions of the solar

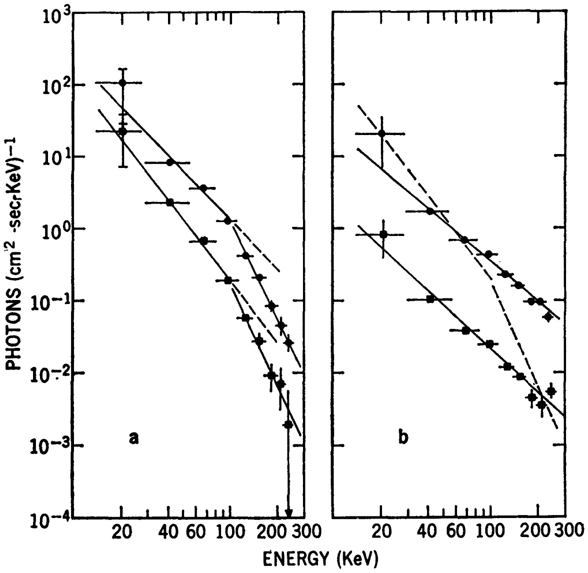

FIG 2 —(*a*) *Circles*, spectrum at the peak of the impulsive burst between 0247.5 and 0248.5 UT; *squares*, spectrum between 0249 5 and 0249 8 UT just prior to the second increase and the Type II burst. The dashed lines on each spectrum emphasize the break in slope that occurs at 100 keV The spectrum at the peak is fitted with an $E^{-2\ 3}$ power law up to 100 keV and an $E^{-4\ 5}$ power law beyond 100 keV. The later spectrum is fitted with an $E^{-2\ 8}$ power law to 100 keV and an $E^{-4\ 7}$ 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 pileup (*b*) Spectrum at the peak of the second phase between 0251 1 and 0242 5 UT (*circles*) plotted above the spectrum observed later between 0306.5 and 0398 5 Both spectra can be fitted with an E^{-2} power law between 15 and 250 keV Dashed curve represents the lower spectrum in Fig 2*a*.

atmosphere. Consequently, the X-ray spectrum is indicative of the spectrum of the accelerated electrons.

This observation lends support to the hypothesis of two-stage acceleration 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 keV. 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 UT and 18 seconds prior to the appearance of a Type II radio burst in the metric band (*Solar-Geophysical Data*, 1969 May) 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, 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 suggest that the second acceleration proceeds by a different mechanism than the first. In this case the second acceleration begins no more than 3 minutes after the first acceleration—not 10–30 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 hypothesis of two-stage acceleration. In Figure 1 the large X-ray flux at 0250 UT, just before the appearance of the shock front, 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 2*a*. The electrons producing this spectrum are probably swept up along with the protons by the shock front and accelerated to relativistic energies.

The intensity of the first acceleration and the delay until the appearance of the shock front determine 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 appear 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 UT (*Solar-Geophysical Data*, 1969 May). The first definite evidence of second-stage acceleration—the second increase in flux in the 225–254-keV channel—begins no later than 0250.2 UT. 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.

REFERENCES

De Jager, C 1969, in *Cospar Symposium on Solar Flares and Space Research,* ed C. De Jager and Z Svestka (Amsterdam: North-Holland Publishing Co), pp 1–15

Frost, K J 1969, *Ap J* (*Letters*), **158,** L159

Frost, K J , Dennis, B R., and Lencho, R J 1970, preprint Goddard Space Flight Center (submitted to *Proc I A U Symp 41*)

Svestka, Z 1970, *Solar Phys* , **13,** 471

Wild, J P , Smerd, S F , and Weiss, A A 1963, *Ann Rev Astr and Ap* , **1,** 291