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OBSERVATION OF AN IMPULSIVE SOLAR X-RAY BURST FROM A CORONAL SOURCE

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ABSTRACT

New observations of the spatial, spectral, and temporal structure of an impulsive hard X-ray source in a behind-the-limb solar flare have been made with high time resolution, hard X-ray detectors aboard two spacecraft, the *International Sun Earth Explorer 3* (*ISEE 3*) and the *Pioneer Venus Orbiter* (*PVO*), which were separated in heliographic longitude by ~12°5. The principal findings are that (1) the coronal part of the X-ray source is ~600 times less intense than the lower-altitude part of the source; and (2) the coronal X-ray observations are consistent with a power-law electron spectrum which extends down to ~5 keV.

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

I. INTRODUCTION

One of the important solar flare parameters, unknown at present, is the spatial distribution of the impulsive hard X-ray emission. The other parameters, also not well known, are the low-energy cutoff of the impulsive X-ray spectrum and the basic time constant for spectral variations. Measurements of these parameters are essential for deducing the spectrum and total kinetic energy of the energetic electrons that produce the impulsive X-rays through the bremsstrahlung process. In the case of flares located on the solar disk, all parts of the impulsive hard X-ray source are visible to a near-Earth detector. For one such flare, one-dimensional measurement of the horizontal extent of an impulsive hard X-ray source has been reported by Takakura *et al.* (1971). An observation of the gradual hard X-ray emission of purely coronal origin has also been reported by Frost and Dennis (1971) and Hudson (1978). However, very little, if any, observational information about the vertical (radial) structure of the impulsive or gradual hard X-ray source is currently available. In flares that occur behind the solar limb, the occultation of the chromospheric/transition-region part of the source by the photosphere enables one to observe the coronal source alone. However, if such an observation is made with only one spacecraft, no information is available about the chromospheric/transition-region source, and hence the interpretation of the observation is ambiguous.

We report what we believe to be the first observation of the vertical structure of an impulsive hard X-ray source made by differential occultation from two spacecraft for a flare located behind the solar limb. The flare phenomenon reported here is different from that discussed before, for example, by Hudson (1978). The results presented briefly in this *Letter* include the spatial, spectral, and temporal characteristics of the impulsive hard X-ray source as well as the deduced characteristics of the energetic electron population inside the source.

II. INSTRUMENTATION

The solar X-ray measurements discussed here were made with experiments aboard two spacecraft, the *International Sun Earth Explorer 3* (*ISEE 3*) and the *Pioneer Venus Orbiter* (*PVO*). The X-ray spectrometer aboard *ISEE 3* has been described elsewhere (Anderson *et al.* 1978). Here we will mention only that it consists of two detectors: (1) a xenon-filled proportional counter, 1.2 cm^2 in area and covering a 4.8–14 keV energy range in six channels; and (2) a NaI (Tl) scintillator, 22 cm^2 in area and covering a 12–1250 keV energy range in 12 channels. The X-ray entrance window is 94 mg cm^{-2} Be + 6.9 mg cm^{-2} Al for the proportional counter and 185 mg cm^{-2} Be + 133 mg cm^{-2} Mg for the scintillator. The gain of the two detectors can be monitored through calibration with two on-board radioactive sources (Cd^{109} and Am^{241}). No change in the scintillator gain has been detected so far. The gain of the proportional counter did change somewhat with time and has been corrected by ground command. For the measurements under discussion, the deviation from the nominal X-ray energy channels was $<5\%$, and appropriate corrections have been applied wherever necessary. The time resolution is $\lesssim 0.5$ s for 5–168 keV X-rays and somewhat poorer at higher energies.

The γ-ray burst detector system aboard the *PVO* is designed primarily to detect cosmic γ-ray bursts. It consists of two cylindrical CsI (Na) scintillators, each

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3.8 cm in diameter and 3.2 cm in height, mounted diametrically opposite one another inside the *PVO* spacecraft. The X-ray entrance window is 288 mg cm^{-2} Pb. The outputs of the two scintillators are summed together and pulse-height analyzed in four energy channels: 50–100 keV, 100–250 keV, 250–500 keV, and 500–1000 keV. As the spacecraft spins, the total effective area of the two detectors for solar radiation is $\sim$20 cm^2, except for a short time when it is $\sim$10 cm^2 due to the attenuation of the solar radiation by parts of the spacecraft. This uncertainty of a factor of $\lesssim 2$ in the deduced X-ray flux caused by the spin modulation does not, however, affect significantly the basic results reported in this *Letter.* Only the "burst" mode data from the *PVO* experiment are currently available. Thus the data for a given event have a high time resolution (0.0117 s), but the total duration is small ($\lesssim$20 s). We will use the *PVO* data primarily for obtaining an estimate of the X-ray flux $\gtrsim$50 keV at the peak of the X-ray burst.

III. OBSERVATIONS

Figure 1*a* shows an X-ray burst recorded by the *ISEE 3* experiment on 1978 October 5 ($\sim$0632 UT).[2] Figure 1*b* shows the differential X-ray spectra recorded by *ISEE 3* and *PVO* instruments near the maximum of the burst. The good time correlation with an impulsive microwave burst and metric type III burst recorded by ground-based radio observatories indicates that the burst recorded by *ISEE 3* is an impulsive X-ray burst associated with a solar flare (Kane 1974). However, no optical flare has so far been reported at that time (*Solar Geophysical Data* 1979), implying that the relevant flare was either too small to be observed optically or was located behind the solar limb. Simultaneous observation of a large, hard X-ray burst by the *PVO* instrument (Fig. 1*b*) makes it extremely unlikely that the optical flare was too small to be observed. We are therefore led to conclude that the flare was located behind the solar limb. An examination of the flare-producing active regions present on the solar disk just prior to or after 1978 October 5 indicates that the relevant flare probably occurred in McMath region 15587, which was located $\sim$15° behind the east limb of the Sun at the time of the flare. This is consistent with observations by *PVO,* which was located at $\sim$12°5 to the east of the Sun-Earth line, as compared to

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[2] The times and photon fluxes given in this report refer to those which an observer located at 1 AU from the Sun would observe for the relevant solar radiation. In other words, all the times are normalized to the Universal Time (GMT) and all the photon fluxes are normalized to a distance of 1 AU from the Sun.

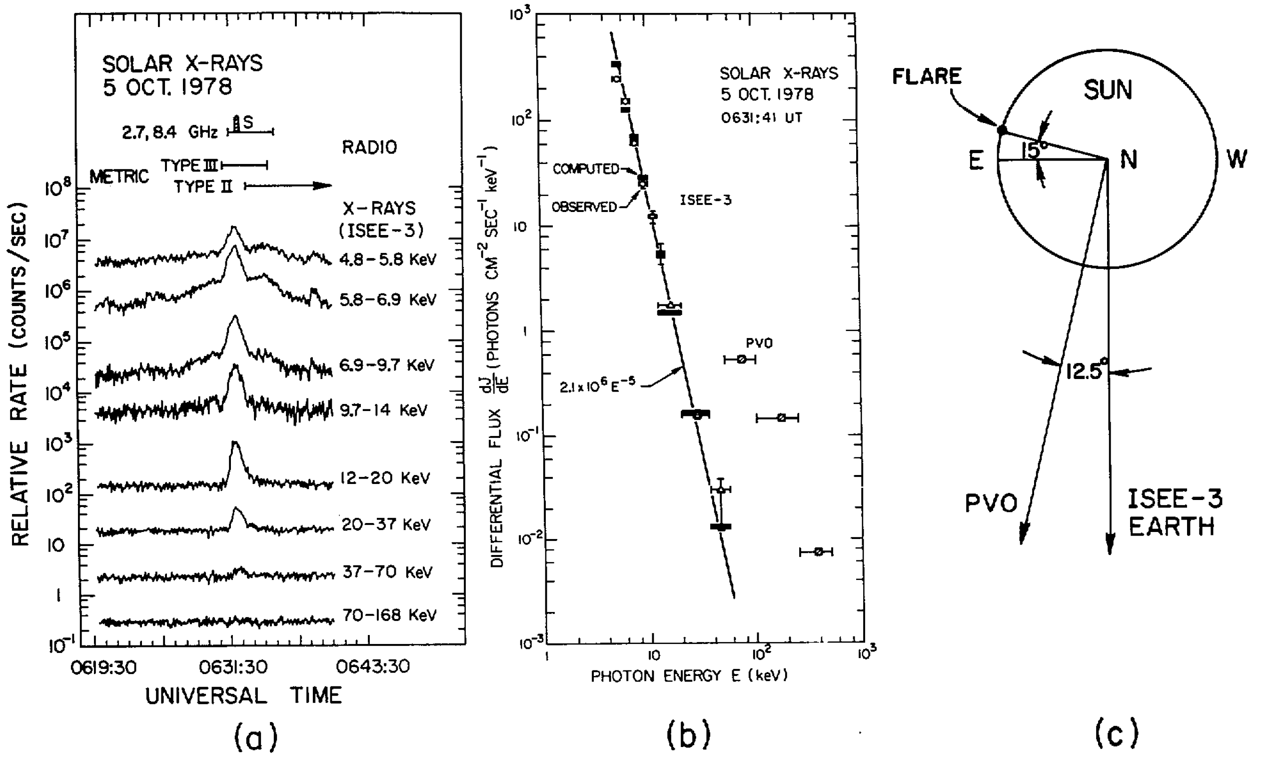

FIG. 1.—Observations of an impulsive X-ray burst on 1978 October 5 attributed to a relatively large solar flare located $\sim$15° behind the east limb of the Sun. (*a*) Time-intensity profile. The impulsive emission can be clearly identified down to the lowest X-ray energy ($\sim$5 keV) observable with the *ISEE 3* spectrometer. (*b*) Spectral plot at the time of maximum. Note that the X-ray flux observed by *ISEE 3* is much smaller than that observed by the *PVO* detectors. Also note that the impulsive X-ray spectrum observed by *ISEE 3* is consistent with a power law down to $\sim$5 keV energy. (*c*) Estimated locations of the solar flare and the *ISEE 3* and *PVO* spacecraft.

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ISEE 3, which was located essentially on the Sun-Earth line at the time of the burst (Fig. 1*c*). Therefore, it seems fairly certain that the burst shown in Figure 1 is an impulsive X-ray burst associated with a solar flare located at ~15° behind the east limb of the Sun. Thus the regions of the flare visible to the *PVO* and *ISEE 3* instruments had altitudes $\gtrsim 700$ km and $\gtrsim 25{,}000$ km, respectively. This is consistent with the fact that above 50 keV, the X-ray flux recorded by *PVO* was about 600 times larger than that recorded by *ISEE 3*.

There are several distinguishing features of the October 5 X-ray burst recorded by *ISEE 3*. While the rise time, which is ~10 s for ~25 keV X-rays, increases with decreasing X-ray energy, the decay time (~30 s) is essentially independent of X-ray energy in the 5–35 keV range. For most disk flares, the rise and decay times are often ~3 s and ~5 s, respectively, both increasing with the decrease in the X-ray energy (Kane and Anderson 1970). The rise and decay characteristics of the October 5 event observed by *ISEE 3* are therefore substantially different from those for the impulsive bursts associated with the disk flares.

Another distinguishing characteristic of the event in Figure 1 is that the X-ray spectrum at the maximum is consistent with a power law of the form $\sim E^{-5}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ down to ~5 keV. This, we believe, is the first observation of an impulsive solar X-ray burst where the impulsive emission could be clearly observed down to ~5 keV and a spectral fit consistent with a single power law could also be obtained. In the attempts made in the past, either the spectral information was marginal (Kahler 1973) or no impulsive component could be clearly identified at X-ray energies <10 keV (Peterson, Datlowe, and McKenzie 1973). Although we have shown in Figure 1*b* a "power-law fit" with a single exponent, we would like to emphasize that this does not rule out a "thermal spectral fit" with multiple temperatures.

In order to make a reliable interpretation of the present behind-the-limb flare observations it is important that the response of the *ISEE 3* and *PVO* instruments be known for an on-the-disk flare which was fully in view of both the instruments. Such an opportunity was provided by the 1978 October 16 (~2145 UT) flare which occurred in McMath region 15598 and was located at N33, E48. The *ISEE 3* and *PVO* observations of that flare are shown in Figure 2. Unlike Figure 1*a*, where the hard and soft X-rays rise and decay essentially simultaneously, Figure 2*a* shows that the impulsive emission is detectable only at hard X-ray ($\gtrsim 12$ keV) energies. Further, Figure 2*b* shows that the differential X-ray spectra as measured by *ISEE 3* and *PVO* are consistent in spite of the

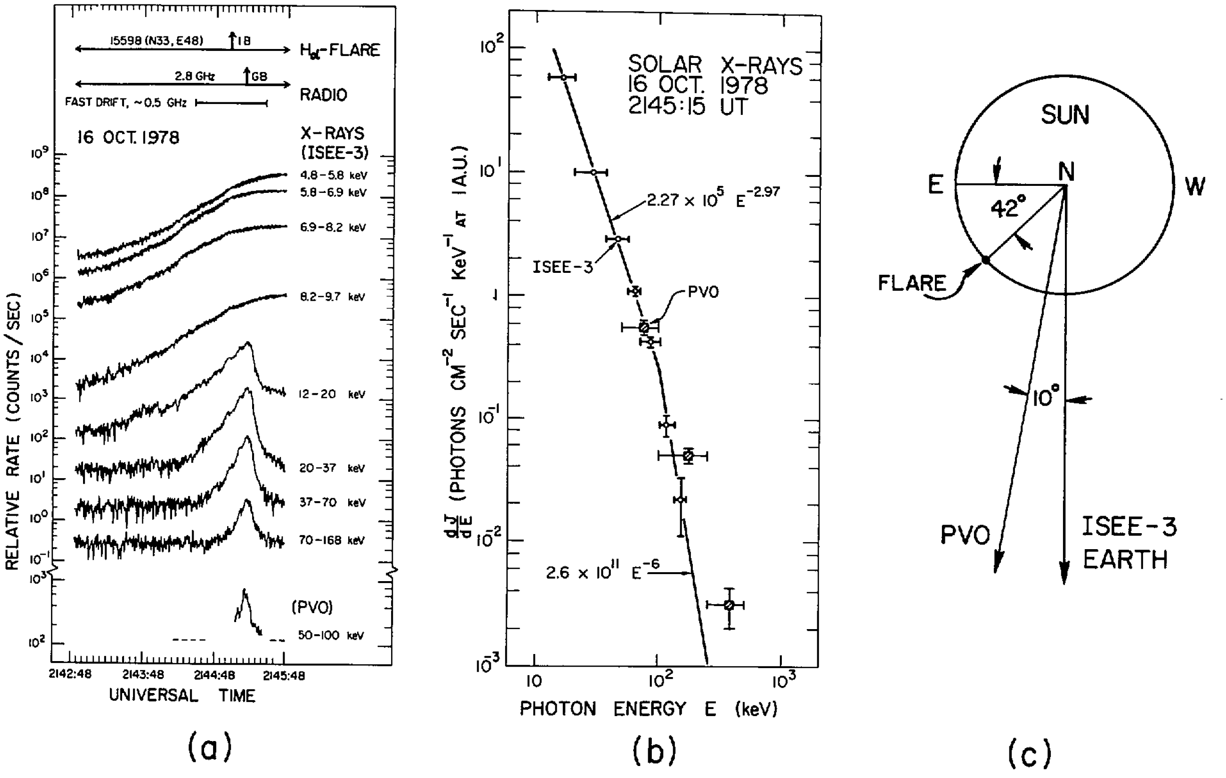

FIG. 2.—Observations of an impulsive X-ray burst on 1978 October 16 associated with an on-the-disk flare. (*a*) Time-intensity profile. Note the absence of detectable impulsive emission at X-ray energies $\lesssim 10$ keV. (*b*) Spectral plot at the time of maximum. Note the good agreement between the differential X-ray spectra measured with the *ISEE 3* and the *PVO* instruments. (*c*) Locations of the solar flare and the *ISEE 3* and *PVO* spacecraft.

differences in the detectors, width of energy windows, data sampling system, etc.

Table 1 summarizes the *ISEE 3* and *PVO* observations of the 1978 October 5 and 16 flares. In the October 16 event the flux of X-rays $\gtrsim 50$ keV observed by *ISEE 3* agrees very well with the flux observed by *PVO*. However, in the behind-the-limb flare the flux of X-rays $\gtrsim 50$ keV near the Earth, deduced from an extrapolation of the spectrum by *ISEE 3* in the 5–60 keV range, is smaller than the flux detected by *PVO* by at least a factor of 600. The magnitude of this factor is well beyond any spurious effects which might be caused by instrumental differences.

IV. INTERPRETATION

In absence of adequate spatial resolution, interpretation of the hard X-ray emission from a behind-the-limb flare is subject to several assumptions. For example, it is often assumed that the source of the hard X-ray emission detected near the Earth is located in the corona above the flare site and not in the chromosphere/transition region somewhere on the visible disk. It is conceivable, however, that some of the electrons accelerated near the flare propagate along a large magnetic loop across the solar limb and precipitate into the chromosphere on the front side of the Sun, thus producing a secondary hard X-ray source on the disk. In the rest of the discussion we will assume that the source of the X-rays observed by *ISEE 3* on October 5 was located in the corona above the flare.

We consider two relatively simple explanations of the *ISEE 3* and *PVO* observations:

1. The impulsive hard X-ray source is located primarily in the corona at altitudes $\gtrsim 25{,}000$ km above the photosphere. The difference in the X-ray fluxes measured by *PVO* and *ISEE 3* is caused by the directivity of the X-ray emission.
2. The impulsive hard X-ray source extends from altitudes much below 25,000 km (upper chromosphere/transition region) to altitudes well above 25,000 km (corona). The "coronal" source is ~ 600 times less intense than the "transition region" source. The occultation of the low-altitude source by the photosphere caused the X-ray flux at *ISEE 3* to be much smaller than that at *PVO.*

Since the difference in heliocentric longitudes of the *ISEE 3* and *PVO* spacecraft was only $\sim 12^\circ.5$, explanation (1) would require extremely high directivity in the X-ray emission. Moreover, such a high directivity would be inconsistent with the observed absence of significant center-to-limb variation in the occurrence frequency of impulsive X-ray bursts (Kane 1974; Datlowe *et al.* 1977). Therefore, we favor explanation (2), where the impulsive X-ray source is extended and has both chromospheric/transition region and coronal components.

In disk flares where all of the impulsive and gradual X-ray sources are visible, the gradual soft X-ray ($\lesssim 10$ keV) emission usually dominates over the impulsive component even at the maximum of the impulsive phase. The impulsive X-ray spectrum below 10 keV is therefore extremely difficult, if not impossible, to measure in these flares since currently available instruments do not have a high spatial resolution. However, in the behind-the-limb flare of October 5 the impulsive component was the dominant component at coronal altitudes even down to the lowest X-ray energy (~ 5 keV) observable with the *ISEE 3* instrument. Moreover, the soft X-ray flux at the peak of the gradual soft X-ray emission (~ 0635 UT) was smaller than the peak impulsive soft X-ray flux by at least a factor of 2. This is in contrast to the disk flares (cf. Fig. 2), where the soft X-ray flux is much larger at the peak of the gradual soft X-ray emission than during the impulsive phase. Hence we conclude that in the October 5 flare the major part of the gradual soft X-ray source was located at altitudes well below 25,000 km above the photosphere.

The spectrum of the energetic electrons inside the X-ray source can be deduced to a first approximation from the observed X-ray spectrum (Kane and Anderson 1970; Hudson, Canfield, and Kane 1978). Although measurements of the X-ray spectrum alone cannot completely distinguish between a thermal and a nonthermal electron spectrum (cf. Brown 1975), the fact that the spectrum of the impulsive coronal X-rays is consistent with a power law down to ~ 5 keV suggests a nonthermal emission process. In the following discussion, the electron spectrum above 5 keV will be assumed to be a power law.

If we assume that the X-ray emission from the coronal part of the impulsive X-ray source is thin-target bremsstrahlung, we can deduce the characteristics of the energetic electrons inside the coronal source using standard bremsstrahlung formulae (cf. Hudson, Canfield, and Kane 1978), provided the

TABLE 1

ISEE 3 AND *PVO* OBSERVATIONS OF SOLAR FLARES

Date (1978)	Oct 5	Oct 16
Location of flare	$\sim 15^\circ$ behind east limb (deduced)	N33, E48
Time of hard X-ray max (UT)	$\sim 0631{:}41$	$\sim 2145{:}15$
X-ray spectrum (*ISEE 3*) (photons $\mathrm{cm^{-2}\,s^{-1}\,keV^{-1}}$ at 1 AU)	$\sim 2.1 \times 10^6 E^{-5}$ (5–60 keV)	$\sim 2.3 \times 10^5 E^{-3}$ (12–100 keV); $\sim 2.6 \times 10^{11} E^{-6}$ (100–160 keV)
Flux of X-rays $\gtrsim 50$ keV (photons $\mathrm{cm^{-2}\,s^{-1}}$ at 1 AU):		
J(*ISEE 3*)	$\lesssim 0.084$ (deduced)	~ 39
J(*PVO*)	50.3 ± 1.7	36.3 ± 3.6
Ratio J(*ISEE 3*)/J(*PVO*)	$\lesssim 1.7 \times 10^{-3}$	~ 1

average ion density n_i inside the coronal source is known. If τ is the characteristic lifetime of electrons inside the coronal source, the rate of electron injection/acceleration is $(10^{49}/n_i\tau)E_e^{-4.5}$ electrons s^{-1} keV^{-1}. If electrons are injected at the same rate into the low-altitude part where they produce X-rays by thick-target bremsstrahlung, we obtain $(9.1 \times 10^9)/n_i\tau$ photons cm^{-2} s^{-1} as the flux of X-rays $\gtrsim$50 keV at 1 AU expected from the low-altitude impulsive source. Comparing this with the flux of 50 photons cm^{-2} s^{-1} observed by the *PVO* detector we find that $n_i\tau \approx 2 \times 10^8$ s cm^{-3}. We note that this value of $n_i\tau$ is consistent with (1) the altitude of the coronal source, where the ambient coronal density is expected to be $\lesssim 10^8$ cm^{-3}; and (2) the decay time ($\tau \sim 30$ s) of the coronal X-ray emission, which if determined by the electron-ion (coulomb) collisions alone, would give $n_i \sim 10^8$ cm^{-3}. However, since τ is essentially independent of electron energy, it is very likely that $n_i \lesssim 10^8$ and τ is determined not by collisions but by other loss processes, such as electron escape from the source.

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