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A PURELY CORONAL HARD X-RAY EVENT

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ABSTRACT

The solar flare responsible for the coronal transient of 1971 December 14 generated a remarkable hard X-ray event observed by *OSO 7*. Like the 1969 March 30 event, it had a flat energy spectrum $j(h\nu) = 0.15\,(h\nu/20\text{ keV})^{-2.09}$ photons (cm^2 s keV)$^{-1}$ over the 10–200 keV energy range at maximum and a duration exceeding 40 minutes. Although it produced type II and type IV radio emission, and an interplanetary shock wave detected at Earth, it had no observable impulsive phase and no observable soft X-ray burst. The parent flare occurred more than 20° beyond the solar east limb, and so we conclude that these X-ray phenomena normally observed in a large flare occurred below the occultation altitude of $\sim 7 \times 10^4$ km. The hard X-ray event did not represent the escape of the majority of impulsive-phase electrons: The total number of electrons greater than 10 keV, N_{10}, fell in the range 2×10^{33}–3×10^{36}. The event probably coincided with the stationary type IV emission, but the present data cannot rule out either an origin $\sim 0.9\ R_\odot$ above the photosphere in the moving type IV sources or a very diffuse emission produced by the shock wave (type II burst).

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

I. INTRODUCTION

Hard (≥ 20 keV) X-radiation during a solar flare should show the existence of coronal nonthermal processes as clearly as do the meter-wave radio bursts (e.g., Wild and Smerd 1972). Observations of the nonthermal bremsstrahlung of energetic electrons would give us a great deal of information about the interesting phenomena of the solar corona: propagating electron beams, as in type III bursts; local acceleration to high energies, as in type IV bursts; and the coronal effects of shock waves, as in type II bursts. Nevertheless, the abundant observations of hard X-radiation during the impulsive phase of a flare (e.g., Datlowe, Elcan, and Hudson 1974) tend instead to show a closer relationship to the chromospheric parts of a flare (Kane and Donnelly 1971; Hudson 1973; Lin and Hudson 1976).

A very few observations have suggested a truly coronal origin for hard X-ray emission: Frost and Dennis (1971) observed (with *OSO 5*) a flare with an impulsive burst followed by a second, slow, hard X-ray event that had a good association with type II bursts; the slow, hard X-ray burst had an unusually smooth time profile and a markedly different energy spectrum. Subsequently, the ESRO *TD-1A* satellite observed two complex bursts during the major 1972 August flares (Hoyng, Brown, and van Beek 1976). These events had the full range of coronal radio manifestations and also displayed long time duration in hard X-ray emission. Brown and Hoyng (1975) presented a theory of oscillations in an electron-trapping configuration (Takakura and Kai 1966) of the coronal magnetic field ("coronal trap") to explain the interesting spectral behavior during the gradual phase of the hard X-ray event. S. F. Smerd (Frost 1974) suggested an association of the gradual hard X-ray emission with stationary type IV or flare continuum sources rather than with the type II or moving type IV bursts. S. Énomé (personal communication) has found that other events probably of this type have microwave spectra with characteristically low peak frequencies.

This paper describes *OSO 7* observations of a related event, 0240 UT 1971 December 14. For a description of the instrument that made the observations, see Harrington *et al.* (1972). Datlowe, Elcan, and Hudson (1974) and Datlowe, Hudson, and Peterson (1974) have studied the *OSO 7* data systematically in order to define the morphology of impulsive-burst occurrence patterns and to draw physical conclusions from these statistics. Roy and Datlowe (1975) and McKenzie (1975) have also surveyed the *OSO 7* data for over-the-limb events, but they did not discuss events as extreme as the one reported here.

II. X-RAY AND OTHER OBSERVATIONS

Figure 1 shows the X-ray observations. In the 20–30 keV channel of the *OSO 7* spectrometer, the counting rate exceeded background from ~0240 UT to the interruption by satellite night at ~0322 UT. At the same time, the 5.1–6.6 keV channel (soft X-rays) showed no obviously related burst, at least in the typical pattern of occurrence following a hard X-ray burst. Such a related soft X-ray burst should have a time profile resembling the time integral of the hard X-ray variation (Neupert 1968). The duration of the hard X-ray burst, greater than ~42 minutes, makes it as long as the longest yet reported (1969 March 30 [Frost and Dennis 1971]). A further point of

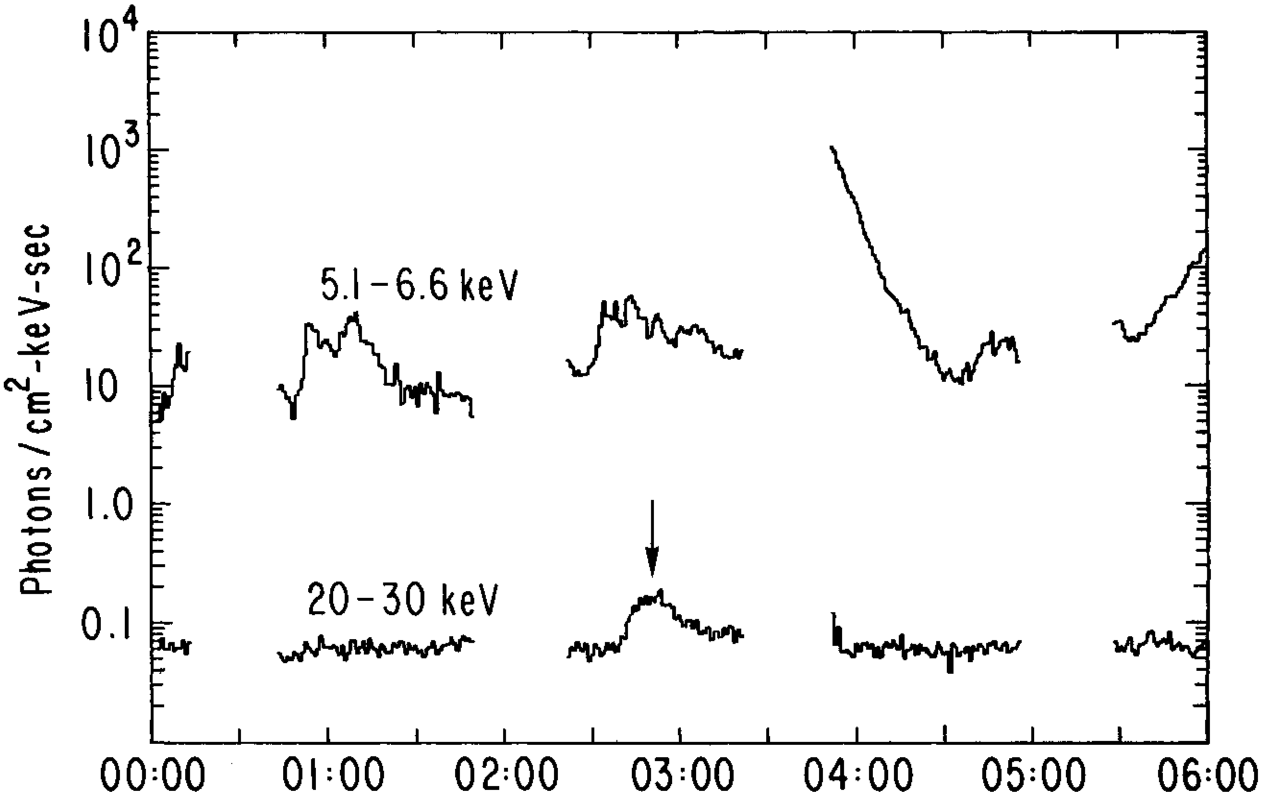

FIG. 1.—Long-duration hard X-ray burst, beginning 1971 December 14 at ~0240 UT in the 20–30 keV channel. The event had a striking absence of the soft X-ray emission normally expected from a major solar flare. According to Kosugi (1976), the parent flare occurred ~25° beyond the east limb, corresponding to an occultation height of ~66,000 km. The burst remained detectable from ~0240 UT until the end of data at ~0324 UT.

peculiarity is the abnormally large hard/soft ratio; a good correlation normally exists between the peak hard X-ray flux of a flare and its peak soft X-ray flux, as measured by *OSO 7* (Datlowe *et al.* 1978). The upper limit on soft X-ray flux for this event places it at least two orders of magnitude from the usual hard/soft ratio. Thus on two counts this event appears, from the X-ray data alone, to have highly unusual properties.

The correlated information from radio and optical observations provides an immediate explanation for the X-ray peculiarity. Kosugi (1976) has estimated that the flare producing the observed effects occurred ~25° beyond the east limb of the Sun. He has described 160 MHz interferometer observations that locate both stationary and moving type IV bursts at the correct position on the limb for this interpretation. In addition, a spray appeared in Hα at 0252 UT (but not in similar observations at 0242 or 0302 UT). Finally, and most dramatically, the *OSO 7* white-light coronagraph observed a white-light transient (Brueckner 1974; see also Maran and Thomas 1973), starting with the frame at 0407 UT. In addition to the moving clouds observed in this phase, the coronagraph also showed the disappearance of a bright coronal streamer prior to the event. The soft X-ray event visible after ~0348 UT (Fig. 1), as well as the slow event starting at ~0600 UT, occurred in close time coincidence with Hα flares on the disk and did not appear unusual in any way. An interesting anomaly in this complex of phenomena did occur with the observation of an interplanetary shock wave via a geomagnetic sudden commencement at 1905 UT on December 16 (R. E. McGuire, personal communication). Flares near the solar limb rarely produce shocks detectable at Earth (e.g., Svestka 1975), but observations of type II bursts (Smerd 1970) show that around-the-limb refraction does occur.

The X-ray data therefore confirm Kosugi's identification of a large behind-the-limb flare beginning at about 0236.5 UT: The unusual hard X-ray event coincides exactly with the coronal phenomena.

III. SIGNIFICANCE OF EVENT LOCATION

The originating flare occurred either in McMath active region 11,656, 25° beyond the limb (Kosugi 1976), or still further around, in region 11,657. From the formula of McKenzie (1975) this gives a minimum occultation height of 66,000 km; of course, the detailed geometry of magnetic field structures in the active region may introduce some error here. In angular measure this height equals 88" at the distance of the Sun; assuming equal horizontal and vertical extent at this magnitude, we estimate a solid angle of ~2 × 10^{-7} sr subtended by the source. With a peak 20 keV flux of ~0.15 photons (cm^2 s keV)$^{-1}$, its surface brightness exceeded that of the diffuse X-ray background (e.g., Peterson 1975) by a factor of ~2×10^6. This implies that the solar corona could dominate the hard X-ray sky brightness relatively far from the Sun (> 10′) after a major flare. Coronal brightenings would also occur nearer the Sun more frequently, because of the greater frequency of occurrence of small flares.

A limb occultation sharply isolates soft (Catalano and Van Allen 1973) as well as hard X-ray sources. A flare of the magnitude of the event described here, capable of producing an interplanetary shock wave and the associated radio phenomena, should also typically have left a long-lasting loop prominence system high in the corona. The absence of a large soft X-ray burst in Figure 1, at a level about two orders of magnitude below that normally expected for impulsive-phase hard X-ray bursts, establishes clearly that the gradual hard X-ray emission occurred above the coronal loops responsible for the soft X-ray burst. We tentatively associate the gradual hard X-ray burst with open field lines that extend well above the closed loop structures participating in the flare itself, and we note that, in any case, the occurrence of the observed hard X-ray emission was geometrically distinct from that of the gradual soft X-ray source, and was also distinct from the impulsive hard X-ray source normally found in such a flare.

In contrast, the 1969 March 30 event occurred at 15°–20° behind the limb, corresponding to an occultation height of 2.5–4.5 × 10^4 km. It produced, even at this great height, both an impulsive-phase hard X-ray burst and a very large soft X-ray burst. Let us assume that the 1969 March 30 and 1971 December 14 events had comparable physical properties, except for the difference (about a factor of 2) in occultation heights. We compare the effects of occultation on three physically different X-ray components: hard X-ray impulsive phase, hard X-ray gradual phase, and soft X-ray gradual phase. Table 1 summarizes the comparisons, using *Solrad* data for the soft component. The data show the greater coronal extent of the gradual hard X-ray component. However, under the assumption that the two flares also had comparable magnitudes, the data suggest that the coronal component also has a strong concentration toward lower altitudes, as expected from the rapid decrease of coronal density with height.

A gradual variation of the hard X-ray spectral distribution occurred during the burst. As shown in Figure 2, the spectrum at onset appeared slightly steeper than at maximum or later in the event; furthermore, this softer spectrum corresponded to an initial maximum at 1000 MHz not present at the highest microwave frequencies. If we assume that this signifies the existence of two spatially separate sources, we might identify the softer spectrum with the early stages of the moving type IV burst (Kosugi 1976). Although this burst only became visible a few minutes later at meter wavelengths, the association would make sense in view of the expected decrease in X-ray luminosity as the source moves outward into less dense regions. On such an assumption, the hard spectrum would represent the stationary source. According to the calculations of Melrose and Brown (1976), this does not necessarily suggest that the stationary source represents the top of a coronal trap.

TABLE 1

Comparison with 1969 March 30 Event

Component	1969 March 30/ 1971 December 14	Source of Data
Impulsive hard X-rays....	$>1.5 \times 10^3$	*OSO 5*/*OSO 7*
Gradual hard X-rays.....	110	*OSO 5*/*OSO 7*
Gradual soft X-rays......	$>3 \times 10^2$	*Solrad* 1–8 Å

IV. PHYSICAL CONDITIONS IN THE SOURCE

The X-ray spectrum in Figure 3 shows a striking similarity to those described by Frost and Dennis (1971): a good fit to a flat ($\gamma \approx 2$) power law. In thin-target bremsstrahlung this corresponds to an electron spectral index $\delta \approx 1.5$, and the X-ray data indicate that this flat spectrum extends to energies above ~200 keV. Using the nonrelativistic Bethe-Heitler cross section, with a factor 1.8 to allow for heavy elements, we find that

$$n_i N_{10} = 1.2 \times 10^{44} \Phi_{20} , \tag{1}$$

where n_i represents the ion density (cm^{-3}) in the source, N_{10} the integral number of electrons above 10 keV, and Φ_{20} the 20 keV number flux in photons (cm^2 s keV)$^{-1}$. At the event maximum, $\Phi_{20} \approx 0.15$, which gives $n_i N_{10} = 1.8 \times 10^{43}$ cm^{-3}. We now compute N_{10} from several possible assumptions about the source density, as summarized in Table 2. These numbers represent the instantaneous electron population. If acceleration continues (i.e., if trapping does not keep the electron cloud together, implying that the electron lifetime exceeds the event duration), the newly accelerated electrons must disappear either behind the limb or outward into interplanetary space. In this case the values for the instantaneous electron population given in Table 2 represent *lower limits* on the total number accelerated.

We first ask whether these numbers resemble those computed for the impulsive-phase population of nonthermal electrons. The first entry in Table 2 permits us this trial identification of impulsive-phase and gradual-phase populations. We obtain an *upper limit* on the total number of accelerated electrons by assuming free escape either upward or downward. For an event duration ~950 s (FWHM) and an assumed scale-height crossing time of 0.4 s, we then calculate $N_{10} < 9 \times 10^{37}$ electrons. This conservative upper limit falls well below the total thick-target number, greater than 10^{39} (Hoyng *et al.*), in comparable events.

We conclude on this basis that the gradual-phase particles could represent a part of the impulsive-phase electron population, but less than 1%–10%. Therefore, the impulsive-phase electrons for the most part did not

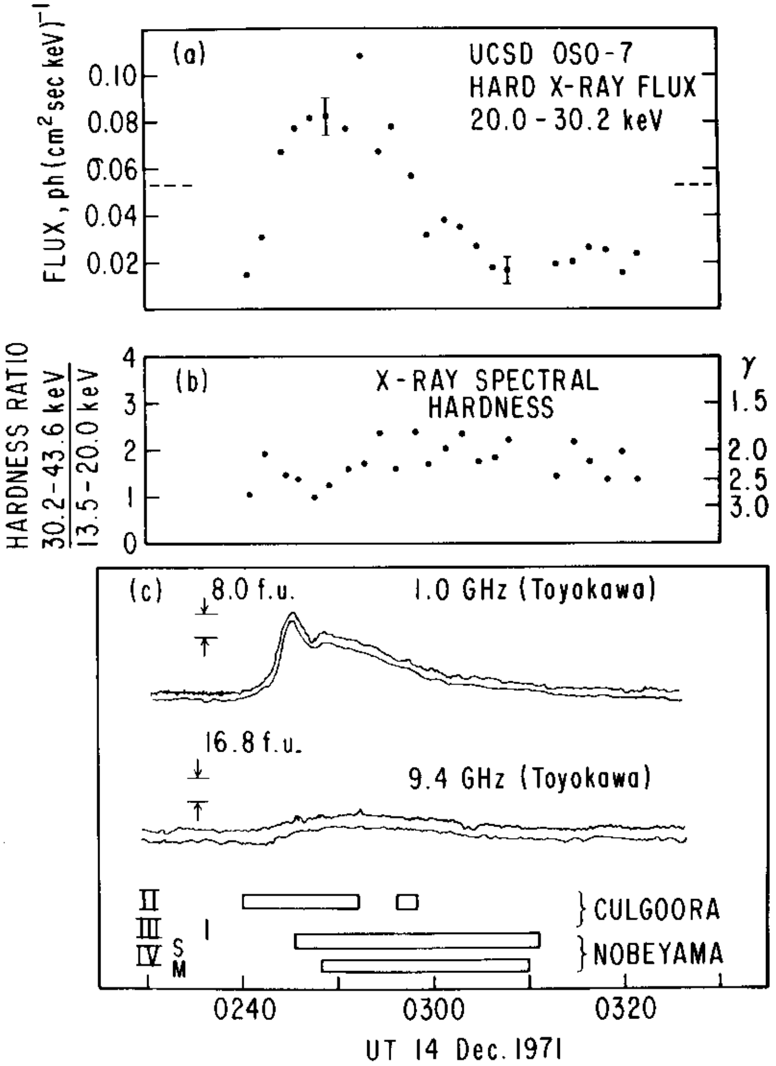

FIG. 2.—Comparison of X-ray flux and spectral variations with microwave and meter-wave radio data. (*a*) The 20–30 keV flux excess appears; the dashed line indicates the background level. (*b*) The spectral hardness of the X-ray emission. (*c*) Summary of the radio data. The weak microwave flux did not have a spectrum characteristic of typical impulsive microwave bursts and probably represents an occulted fraction of microwave type IV continuum. The Nobeyama data refer to 160 MHz.

escape as far as 1.1 $R_\odot$, in accordance with their absence at 1 AU in similar events (Lin and Hudson 1971, 1976).

Other hypotheses in Table 2—namely, the association of the X-radiation with either the type II or the moving type IV bursts, or the white-light transients—imply local acceleration in a second stage. Frost and Dennis (1971) suggested this explanation to account for the difference in the spectral distributions they found in the two hard X-ray phases of the 1969 March 30 event. Assuming the source of X-rays to coincide with the moving type IV burst at a great enough distance to prevent propagation effects from influencing the radio spectrum, we can use the results of Takakura (1972) to estimate the number of electrons from the radio observations. For $B < 10$ gauss, these calculations give $N_{10} > 10^{32}$ (Takakura, personal communication). The X-ray observations imply larger numbers of electrons, by as much as a factor of 10 for even the 20 × Newkirk (1961) density; but the results do not seem inconsistent. We do not have sufficient data to narrow the range of acceptable models. We cannot directly rule out a traveling source of hard X-radiation high in the corona, especially in view of the extremely high densities found in the compact blobs of the white-light coronal transient. Also, we may consider an identification of the gradual hard X-ray emission with the shock front of the type II burst. In this case the enormous spatial extent of the phenomenon makes it impossible to give representative parameters in Table 2. Two alternatives for the hard X-radiation exist if the type II identification holds: The nonthermal electrons may radiate (thin-target bremsstrahlung) at the site of acceleration in the shock

TABLE 2

NUMBER OF NONTHERMAL ELECTRONS

Source Location	Height ($R_\odot$)	Ambient Density n_i (cm^{-3})	N_{10} Instantaneous
Stationary type IV burst............	1.1	5×10^8–10^{10}*	2×10^{33}–4×10^{34}
Moving type IV burst..............	1.9	7×10^6–1.4×10^8*	1.3×10^{35}–2.6×10^{36}
White-light transient...............	...	$>2 \times 10^7$†	8×10^{35}
Type II burst......................	?	?	?

* 1–20 × Newkirk 1961.

† Brueckner 1974. This density refers to the compact transients observed by *OSO 7* above $\sim 6\ R_\odot$, moving outward without apparent expansion.

front, or they may precipitate into the chromosphere (thick-target bremsstrahlung) over a wide area including the visible hemisphere.

V. CONCLUSION

The 1971 December 14 gradual hard X-ray event observed by *OSO 7* fits into a sequence with observations of other large (type II and type IV) flares that have reported hard X-ray observations: the August flares, on the solar disk; the 1969 March 30 flare, partially occulted; and the 1971 December 14 flare, fully occulted except for the gradual hard X-ray component. The August flares and the 1969 March 30 flare also display the trend in this sequence in that the time profiles of the August events did not permit a clean separation of the two hard X-ray components. The coronal hard X-ray emission lies above even the high loops responsible for soft X-ray production and postflare loop systems. In the 1971 December 14 event, these loops did not grow gradually into view above the limb afterward. The X-ray data confirm the direct interplanetary measurements that indicate the lack of easy escape by impulsive-phase electrons into the interplanetary medium (Lin and Hudson 1971, 1976). A coronal trap for these electrons could not have extended higher than 0.1 $R_\odot$ above the photosphere. We cannot at the present time determine whether the gradual hard X-rays came from low-lying sources, perhaps in magnetic structures lying above the soft X-ray source, or whether they arose in higher regions, perhaps connected with the moving type IV burst or low-temperature ejecta. The former case seems more plausible. It would mean an association with a meter-wave flare continuum and a microwave type IV burst, if viewed on the disk.

We need further exploration of the coronal hard X-ray emission to resolve these questions and to permit meaningful analysis of physical parameters and processes. In addition to direct imaging observations, a further search for occulted hard X-ray events will prove helpful: A band of longitude 20° wide on either limb should include ~10% of all type II–type IV sources. Finally, we need additional quantitative analyses of radio sources to provide a meaningful basis for comparison.

I have benefited from discussions with D. W. Datlowe, M. J. Elcan, and L. E. Peterson; Datlowe and Elcan made this analysis possible by organizing the *OSO 7* data into a very convenient format. S. Énomé, R. Stewart, and T. Takakura provided radio data and helpful advice. Support came from NASA (NSG-7161) and the NSF (AST 76-01280). In carrying out this research, I have benefited from participation in the Skylab Solar Workshop Series on Solar Flares. The workshops are sponsored by NASA and NSF and managed by the High Altitude Observatory.

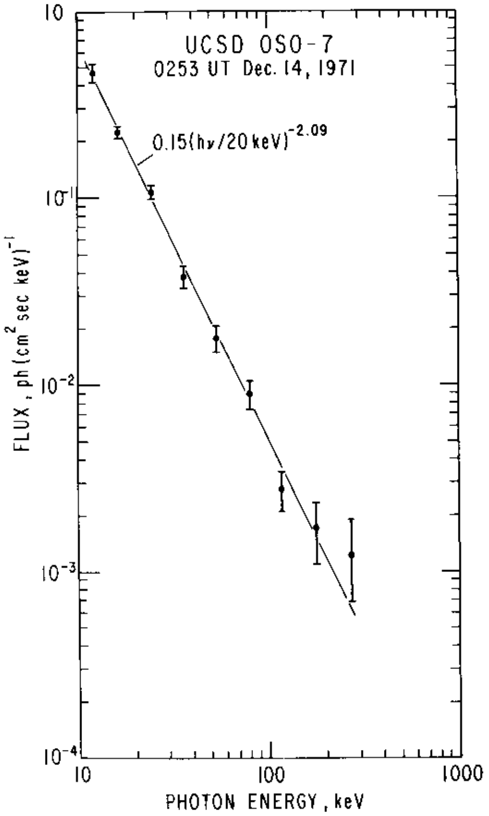

FIG. 3.—X-ray energy spectrum for the 100 s integration interval 0251:51–0253:33 UT. The extremely flat spectrum extending to high energies resembles that of the 1969 March 30 event (Frost and Dennis 1971). No evidence for a downward break appears in this spectrum or other spectra derived from this event.

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