THE ASTROPHYSICAL JOURNAL, 217:549–564, 1977 October 15

HARD X-RAY SPECTRA OF COSMIC GAMMA-RAY BURSTS

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Received 1977 March 14; accepted 1977 April 15

ABSTRACT

Hard X-ray measurements of six γ-ray bursts observed during the period 1969 October–1971 April are presented. The measurements were made with the University of California (Berkeley) detector on the OGO-5 satellite and the NRL detector on the OSO-6 satellite. Spectra for five of the six bursts have been determined using measurements from both satellites in order to reduce ambiguities due to uncertain source locations. A significant fraction, ~20–60%, of the energy of the bursts falls in the hard X-ray range (20–130 keV). The time-integrated spectra have been fitted by power-law, exponential, and thermal bremsstrahlung functions. They are consistent with power laws which steepen at energies $\gtrsim 150$ keV, as reported earlier for two other bursts. Evidence for spectral variability from event to event in the hard X-ray region is presented. For a power-law representation, $dN/dE \sim E^{-\alpha}$, α has values ranging from ~1 to ~2.5. The hard X-ray spectra of the γ-ray bursts differ significantly from those of the recently discovered 1–15 keV X-ray bursts.

Subject headings: gamma-rays: bursts — X-rays: bursts — X-rays: spectra

I. INTRODUCTION

With the discovery of cosmic γ-ray bursts (Klebesadel, Strong, and Olson 1973; Strong, Klebesadel, and Olson 1974), the investigation of high-energy astrophysics has a new and exciting dimension. The bursts were first observed at energies $\gtrsim 150$ keV by detectors on at least two of the *Vela* series of satellites. Since their discovery, over 50 bursts of a similar nature have been identified by instruments flown on a variety of spacecraft. For a summary as of 1975, see Klebesadel and Strong (1976*a*) and Cline and Desai (1976). These bursts are typically characterized by rise times $\lesssim 1$ s, durations from $\lesssim 1$ s to ~100 s, structure on time scales as short as ~20 ms (Imhof *et al.* 1975), individual photon energies extending to $\gtrsim 1$ MeV (Cline and Desai 1975), and integrated energies ranging from $\sim 3 \times 10^{-6}$ to $\gtrsim 10^{-3}$ ergs cm^{-2}.

Various theories have been suggested to explain the origin of the bursts. A review of many of them can be found in Ruderman's article (1975) or in the general article by Prilutskii, Rozental, and Usov (1976). Suggested sources for the bursts include shocks from supernovae, cooling of the surfaces of newly formed neutron stars, flares from common stars or magnetic white dwarfs, starquakes or magnetic instabilities of neutron stars, accretion disk formed about compact objects such as black holes, matter-antimatter collisions, and the breakup of relativistic dust grains, among others. Unfortunately, the data obtained to date do not as yet place significant restrictions on those theories for which details of the bursts have been worked out. But, based on limited directional information and on energy considerations, it is likely that most of the sources lie within a few hundred parsecs of the Earth.

Spectral measurements of the bursts are necessary for understanding the mechanisms by which they are produced. The IMP-6 and IMP-7 satellites have provided spectral information for 15 bursts at energies above 100 keV. From these measurements Cline and Desai (1975) show that the time-integrated spectra of these events are similar; they can be fitted by an exponential ($dN/dE \propto \exp[-E_\gamma/150(\mathrm{keV})]$) for $E_\gamma <$ 400 keV and by a power law ($dN/dE \propto E_\gamma^{-\alpha}$) at higher energies. (There is, however, some uncertainty in the incident γ-ray spectra because of absorption and scattering in the material of the spinning spacecraft.) These spectral measurements have led various authors to characterize the bursts only by their high-energy emission ($E_\gamma > 150$ keV). The purpose of this paper is to demonstrate that hard X-radiation (10–150 keV) represents a significant fraction of the energy emitted during the bursts.

Several observations of γ-ray bursts at hard X-ray energies have been reported earlier (Wheaton *et al.* 1973; Kane, Mahoney, and Anderson 1974; Metzger *et al.* 1974; Palumbo, Pizzichini, and Vespignani 1974; Imhof *et al.* 1974; Share, Meekins, and Kreplin 1974; Mazets *et al.* 1974; Share 1976; Kane and Anderson 1976). Spectral variability during the bursts appears to be an important characteristic at these energies. To date, the hard X-ray spectra of only four of the bursts have been determined. Metzger *et al.* (1974) found that the time-integrated spectrum between 2 and 200 keV of the 1972 April 27 burst can be fitted by a power law, $dN/dE \propto E_\gamma^{-\alpha}$, with $\alpha = 1.4$. The burst of 1972 May 14, observed by Wheaton *et al.* (1973) had a time-averaged spectrum with exponent, α, of approximately the same value over the 10–200 keV range. The other two spectra (Imhof *et al.* 1974; Palumbo, Pizzichini, and Vespignani 1974) were constructed from measurements made on only portions of the bursts. Imhof's data for the burst of 1972 December 18 also yield $\alpha \approx 1$. However, the spectrum measured by Palumbo, Pizzichini, and Vespignani *et al.* (1974) for the 1969 October 7, burst appears to be somewhat steeper than the others, with $\alpha \approx 2.7$. Spectral measurements of this same burst, which we present here, yield a value of $\alpha \approx 1.2$.

In this paper we discuss the temporal and spectral measurements made at hard X-ray energies for five bursts observed by instruments on both the OGO-5 and OSO-6 satellites, and for one burst detected only by OSO-6. In our earlier, separately prepared reports, referenced above, no attempt was made to determine the spectrum of the incident radiation. This was due in part to difficulties in interpreting spectra for bursts in which the source directions are poorly known at best. The use of two independent detectors substantially reduces the ambiguities in the deduced spectra. In the next section we briefly review the operational characteristics of the two instruments. The details of the observations of the six bursts follow in the third section. In the same section we outline the procedures used to derive the spectra of the incident radiation. The discussion of these results and our conclusions are presented in §§ IV and V, respectively.

II. INSTRUMENTATION

Both the OGO-5 and OSO-6 X-ray detectors were designed to study solar flares in the energy range between about 10 and 150 keV. The OGO-5 detector was operational from 1968 March until 1971 June, and was in a highly eccentric orbit with the apogee at about 1.5×10^5 km. The OSO-6 detector was operational from 1969 August until 1972 January and was in a $\sim$500 km orbit at an inclination of $\sim$33°. Both instruments were pointed at the Sun. The design and operation of the instruments have been described previously (Kane and Anderson 1976; Share 1976); here we shall discuss those aspects of the instrumentation which directly affect the interpretation of the observed pulse-height spectra.

Drawings of the two detectors are shown in Figure 1. They both consisted of unshielded NaI(Tl) scintillation crystals, but their geometries were distinctly different. The OGO-5 detector had a frontal area of 9.5 cm^2 and was 0.5 cm thick, while the OSO-6 instrument had a frontal area of 1.3 cm^2 and was 2.54 cm thick. This difference in geometry is reflected in the effective detecting areas of the two instruments, plotted in Figure 2 as a function of incident photon energy and angle. The curves represent a numerical average of the product of projected surface area, interaction probabilities (photoelectric and Compton), and absorption in the housings around the crystals. In this approximation of the instruments' responses we have assumed that photons undergoing Compton interactions are totally absorbed.

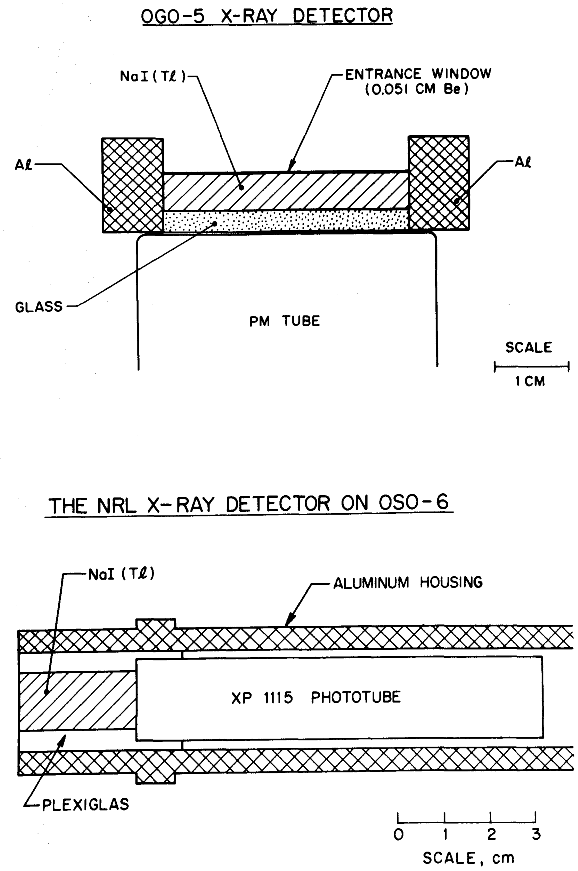

FIG. 1.—Schematics of the X-ray detectors on the OGO-5 and OSO-6 satellites.

In practice, some of the incident photons with energies $\geqslant$300 keV will Compton scatter inside the detector and escape, producing pulses equivalent to $\leqslant$80 keV photons absorbed in the detector. In order to determine experimentally the magnitude of this effect, a detector similar to one on OGO-5 (see Fig. 1) was exposed in the laboratory to 511 keV photons from a ^{22}Na source. In addition to the photon peak at $\sim$511 keV, a broad peak was also found at $\sim$130 keV (due to Compton scattered photons) in the pulse-height spectrum. The total counts in 1–80 keV, 81–400 keV, and 401–600 keV energy ranges were measured as a function of the angle of incidence ψ of the 511 keV photons. The ratio of 1–80 keV pulses to 1–600 keV pulses was found to be $\sim$0.17, independent of ψ. Thus, for all angles $\psi \leqslant 90°$, about 17% of the 511 keV photons interacting in the OGO-5 detector produced pulses $\leqslant$80 keV. This value of $\sim$17% should represent an upper limit for the OSO-6 detector because its smallest dimension is about 3 times larger than the thickness of the OGO-5 detector.

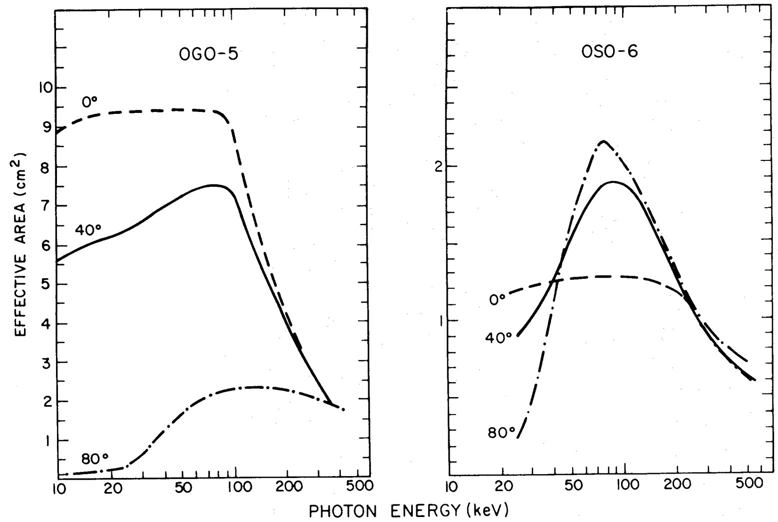

FIG. 2.—Effective area of the OGO-5 and OSO-6 detectors as a function of the photon energy E and the angle of incidence ψ. The three curves correspond to $\psi = 0°$, 40°, and 80°, respectively.

Hence we believe that Figure 2 adequately represents the response of the OGO-5 and OSO-6 detectors for incident X-rays having relatively steep energy spectra, such as those observed for the four γ-ray bursts discussed in § I. For a hard spectrum such as a 150 keV exponential, without an additional low-energy component, we estimate that Compton scattering will, at worst, contribute only an increase of $\lesssim 15\%$ to the number of low-energy (< 80 keV) X-rays detected by the OGO-5 and OSO-6 detectors.

It is clear from Figure 2 that the OGO-5 detector's response is a sensitive function of incident angle ψ over its full range in energy. In comparison, for energies > 35 keV the OSO-6 detector's response varies little for incident angles ψ between 40° and 90°. These calculated curves do not take into account absorption and scattering in other sections of the satellites; this would be too difficult to model at present. However, the fields of view of both detectors are free of all external obstructions for angles up to at least 70° and are only partially obstructed for $70° < \psi < 90°$. The effect of such obstructions is demonstrated in Figure 3, where we reproduce the OGO-5 detector's measured response to 16 and 60 keV X-rays from an ^{241}Am source (Kane and Anderson 1976). The measured response can differ significantly from the calculations at large angles of incidence due to scattering and absorption in adjacent particle detectors in the same instrument housing.

The OGO-5 detector operated about 75% of each orbit, while it was in interplanetary space. It spectrally analyzed X-rays from 9.6 to 128 keV into seven differential channels and had an integral channel for energies > 128 keV. A complete spectrum was read out in either 2.304, 0.288, or 0.036 s, depending on the telemetry rate. The OSO-6 detector operated during daylight periods only, or about 70% of each orbit. It used six channels covering the range from 23 to 82 keV and had an integral channel > 82 keV. A complete spectrum was read out in 2.56 s. Both instruments accumulated data in only half of their energy channels during each half of the telemetry cycle; during that same time the other channels were being read out. In OSO-6 alternate energy channels were grouped together (i.e., 1, 3, 5, 7 and 2, 4, 6) for data accumulation and readout; in OGO-5 the four lowest and four highest energy channels were grouped together. This difference in the data accumulation of the two instruments is helpful in distinguishing true spectral features from apparent features that may be caused by 50% duty cycles of the instruments for bursts having a complicated time structure.

III. OBSERVATIONS

A total of 12 cosmic hard X-rays bursts were observed by the Berkeley and NRL experiments. Five of the 12 were detected by both instruments. These bursts occurred on 1969 October 7, 1970 January 25, 1970 October 1, 1970 December 1, and 1971 March 18. We shall discuss the observations of these bursts in detail along with the burst occurring on 1971 February 27, which was observed only by the NRL detector on OSO-6. The time histories of the events observed in different energy intervals in the detectors are shown in part (*a*) of Figures 4, 6, 7, 8, 9, and 10. The numbers of X-rays recorded in the various energy channels of the two instruments during the bursts are given in Table 1 after being corrected for background. Determination of the incident X-ray spectrum for each burst is dependent on knowing the angle, ψ, of the source relative to the detectors' axes (recall here that both instruments were pointed at the Sun). This angle is reasonably well known from measurements made from other satellites for only two of the events, 1969 October 7 and 1971 March 18. For the remaining four

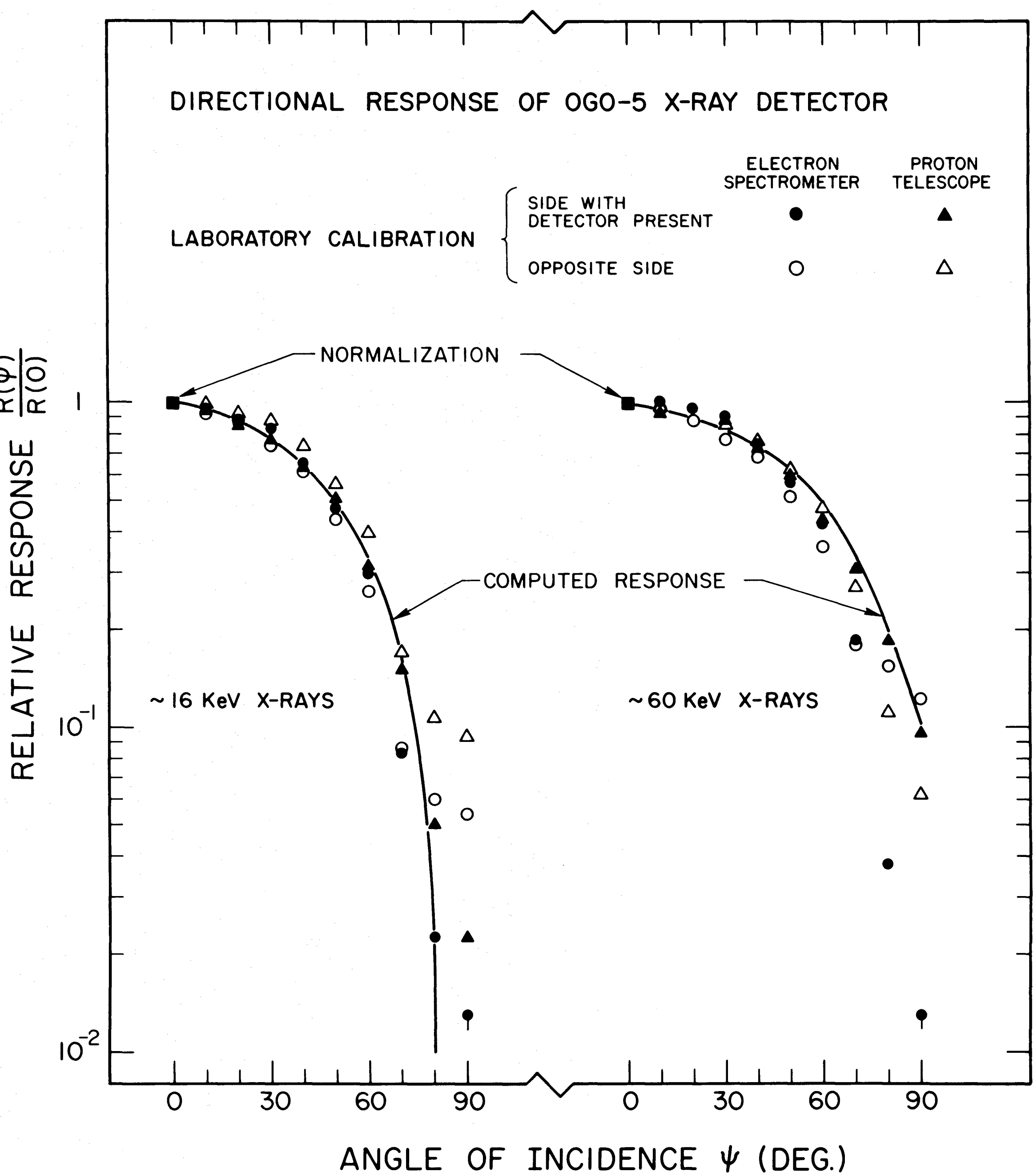

FIG. 3.—A comparison of the observed and computed directional response of the OGO-5 detector to ~16 keV and ~60 keV X-rays. The laboratory calibration was made with the angle of incidence in two mutually perpendicular planes: one containing the X-ray detector and electron spectrometer, and the other containing X-ray detector and proton-α telescope.

events we have derived the spectrum first by using the characteristics of the uncorrected data to estimate the incident angles, and then, where possible, by requiring that the corrected spectra from both instruments be consistent. Illustration of this approach is left to the discussion of the individual events.

a) *Event of 1969 October 7*

This event was reported in the initial *Vela* catalog (Strong, Klebesadel, and Olson 1974) and was subsequently found in the data of the Berkeley (Kane, Mahoney, and Anderson 1974), Bologna (Palumbo, Pizzichini, and Vespignani 1974), and NRL (Share, Meekins, and Kreplin 1974) detectors. The event lasted over 100 s and is displayed in Figure 4*a*. Kane and Anderson (1976) identified four separate bursts within this event, and have illustrated their spectral differences. Two small bursts were recorded before the time at which the *Vela* system triggered, and were visible in both the OSO-6 and OGO-5 data. The main

TABLE 1

UNCORRECTED SPECTRAL DATA

ENERGY (keV)	OBSERVED EXCESS (counts keV^{-1}) 1969 Oct 7	1970 Jan 25	1970 Oct 1	1970 Dec 1	1971 Feb 27	1971 Mar 18
A. OGO-5 (Berkeley)						
From..........	26725.9*	18081.1	56531.7	72058.1		55684.2
To.............	26829.6*	18092.6	56538.6	72059.2		55695.1
9.6–19.2	...	5.27 ± 3.79	...	...		7.03 ± 2.36
19.2–32	58.9 ± 3.26	7.58 ± 1.33	0.40 ± 0.62	0.56 ± 0.34		9.74 ± 1.13
32–48	44.5 ± 2.19	6.78 ± 0.89	1.08 ± 0.46	0.65 ± 0.25		15.6 ± 1.09
48–64	33.2 ± 1.80	4.63 ± 0.71	1.99 ± 0.45	0.61 ± 0.23		13.4 ± 0.99
64–80	23.6 ± 1.54	1.53 ± 0.50	2.66 ± 0.46	1.11 ± 0.28		10.0 ± 0.84
80–104	16.1 ± 0.96	1.83 ± 0.35	1.16 ± 0.25	0.39 ± 0.14		7.81 ± 0.60
104–128	7.80 ± 0.68	0.71 ± 0.25	0.67 ± 0.19	0.35 ± 0.13		4.08 ± 0.43
>80	918 ± 44.0†	97.9 ± 16.0†	53.5 ± 11.1†	32.0 ± 6.7†		473.9 ± 24.6†
>128	350 ± 33.9†	37.6 ± 12.4†	10.3 ± 8.24†	14.6 ± 5.0†		192 ± 17.3†
B. OSO-6 (NRL)						
From..........	26725.8*	18082.3	56530.5	72056.7	62853.2	55680.9
To.............	26828.3*	18092.8	56538.3	72059.3	62861.0	55693.3
23–30	...	...	...	...	...	...
30–38	...	...	7.0 ± 3.0	...	...	...
38–49	10.2 ± 4.6	2.4 ± 1.5	7.1 ± 1.0	0.27 ± 0.018	6.45 ± 0.91	2.3 ± 0.9
49–60	9.8 ± 3.5	1.8 ± 1.5	5.6 ± 0.9	0.64 ± 0.027	6.36 ± 0.91	4.6 ± 0.9
60–71	6.2 ± 1.4	1.5 ± 0.6	4.6 ± 0.7	0.73 ± 0.028	3.73 ± 0.64	6.1 ± 0.9
71–82	7.9 ± 1.5	1.3 ± 0.5	2.8 ± 0.6	0.64 ± 0.027	3.00 ± 0.55	5.5 ± 0.8
>82	686 ± 45†	45 ± 11†	75 ± 12†	55 ± 9†	76 ± 12†	439 ± 25†

* UT seconds.
† Counts.

burst begins at about 26790 sec UT and is resolved into two subpulses at high energies. These two pulses are also evident in the *Vela* data (these and future remarks concerning the *Vela* time profiles come from Strong, Klebesadel, and Olson 1974 and Klebesadel and Strong 1976). A fourth burst which occurred about 20 s later, and appears strongest at low energies, was also recorded by *Vela*.

The source for this event was located by Bologna's collimated hard X-ray experiment (Palumbo, Pizzichini, and Vespignani 1974) in the wheel of OSO-6 and by the *Vela* satellites. It was situated at an angle of $40° \pm 15°$ ($\alpha \approx 187°$, $\delta \approx 30°$) from the axes of the Berkeley and NRL detectors. Using this angle of incidence and the efficiency curves given in Figure 2, we constructed corrected spectra (taking into account the 50% duty cycle of the instruments) for both the main pulse and the entire event. Shown in Figure 5 is a comparison of the spectra of the main burst measured by the Bologna, Berkeley, and NRL detectors. The fact that the three experiments agree is of fundamental importance for our analyses of other events for which the incident angle is not well known. However, it is clear that the spectrum is not as steep as the power law $dN/dE \propto E_\gamma^{-(2.7\pm0.7)}$ which Palumbo, Pizzichini, and Vespignani (1974) reported. The exponent is closer to a value near -1.2.

Shown in Figure 4*b* is the spectrum integrated over the entire event as observed by the NRL and Berkeley detectors. For comparison we have drawn in an exponential spectrum $[dN/dE_\gamma \propto \exp(-E_\gamma/150)]$ fitted to the total energy observed by *Vela* (Strong, Klebesadel, and Olson 1974; Klebesadel and Strong 1976*a*). This is a valid comparison because the total energies given for the *Vela* observations were derived using this assumed spectral shape. The *Vela* measurement of total energy is expected to be good to within about a factor of 2 (Strong, Klebesadel, and Evans 1975). Spectral parameters derived from the OGO-5 and OSO-6 measurements of this and other events will be discussed in § IV and are summarized in Table 2.

b) *Event of 1971 March 18*

We discuss this event next because it is also one for which a unique source location has been determined. Timing data for this burst are given in Figure 6*a*. OGO-5 was fortunately in a high-data rate mode and provided details of the multipulse structure of the event. The event lasted ~11 s and consisted of two main pulses, the first of which appears to be harder than the second one (see Kane and Anderson 1976 for further discussion of the time variability). The second pulse was also observed by the *Vela* detectors, but at a significantly lower intensity than the main pulse. This is consistent with its softer nature as found by OGO-5. The onset of this event as observed by OSO-6 appears to have occurred ~2 s earlier than observed by either

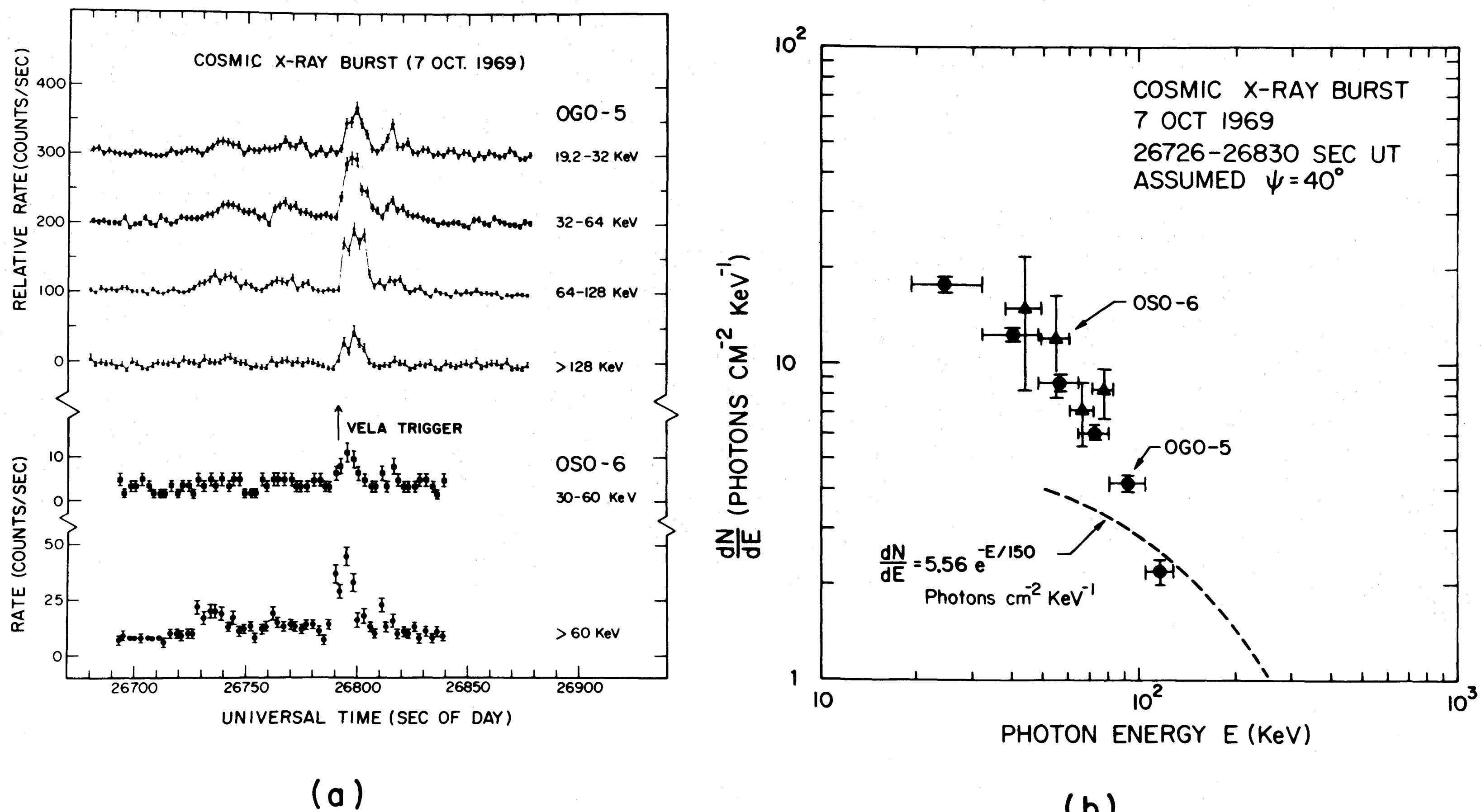

FIG. 4.—The OGO-5 and OSO-6 observations of the 1969 October 7 cosmic X-ray burst: (*a*) time-intensity profile (the arrow designates the time at which the *Vela* detectors were triggered); (*b*) spectrum deduced from OGO-5, OSO-6, and *Vela* measurements (see text for details).

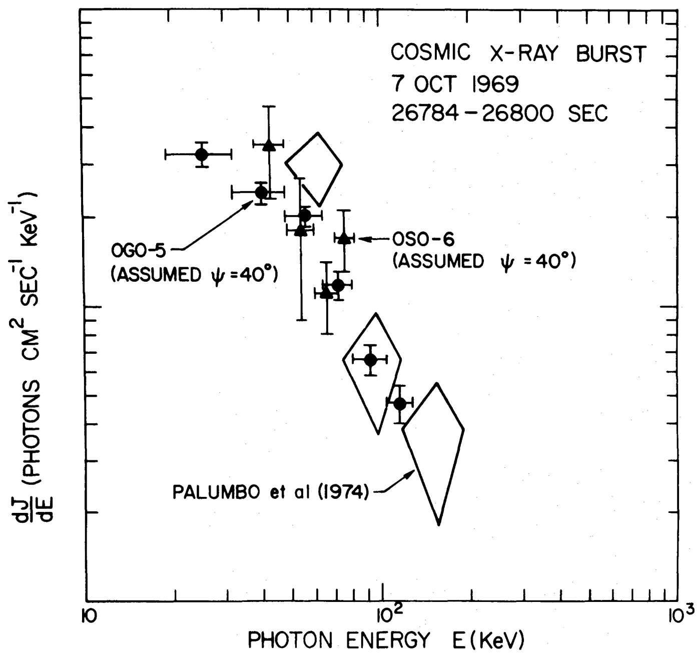

FIG. 5.—A composite spectrum for the main burst of the 1969 October 7 event deduced from OGO-5, OSO-6 (NRL), and OSO-6 (Palumbo *et al.* 1974) measurements.

Vela or OGO-5. At present we have no explanation for this difference.

The *Vela* satellites have determined two possible source locations for this event. One of them was within the field of view of the Bologna experiment (Pizzichini, Palumbo, and Spizzichino 1975). As the burst was not observed by this instrument, the source must have been located near the second position at a right ascension of 83° and declination of +14° (this is a revised position obtained from Klebesadel and Strong 1976*b*). The uncertainty in location is probably about ±10°. This places the source about 80° from the axes of both the Berkeley and NRL detectors, or near the edge of the fields of view of both instruments. This is evident in the uncorrected spectra given in Table 1, in which the low-energy data from OSO-6 exhibit strong attenuation, while those from OGO-5 exhibit moderate attenuation (compare this with the data from the October 7 event). From this we have concluded that the source was fortunately not occulted by any substantial part of the OGO-5 spacecraft, and that the incident X-ray spectrum can be obtained using the calculated efficiency for a source at $\psi = 80°$. The corrected OGO-5 spectrum for the entire event is shown in Figure 6*b* and appears to be fairly steep. The low-energy attenuation in the OSO-6 spectrum is consistent with a photon pathlength through 3–4 g cm^{-2} of Al.

TABLE 2

SUMMARY OF SPECTRAL DATA

Date	1969 Oct 7	1970 Jan 25	1970 Oct 1	1970 Dec 1	1971 Feb 27	1971 Mar 18
Time (s, UT)	26726–26830	18081–18092	56531–56538	72058–72059	62853–62861	55684–55695
A. Spectral Parameters						
Detector Used	Berkeley	Berkeley	NRL	Berkeley	NRL	Berkeley
Power-Law Index[1] (α)	1.2 ± 0.3	1.9 ± 0.3	2.3 ± 0.3	1.1 ± 0.4	2.1 ± 0.4	1.7 ± 0.3
Exponential[2] (E_0, keV)	45 ± 3	30 ± 4	23 ± 4	60 ± 20	27 ± 5	35 ± 5
Thermal[3] (E_0', keV)	200 ± 100	60 ± 20	40 ± 10	...[5]	50 ± 20	80 ± 20
B. Integral Counts > 80 keV						
Observed	1836	196	150	64	152	948
Power-Law Extrapolation	2093	220	201	100	232	1130
Exponential Extrapolation	1250	118	87	...	124	600
Thermal Extrapolation	1600	140	112	...	137	745
C. Energy in Burst[4] (ergs cm^{-2})						
20–130 keV	8×10^{-5}	2×10^{-5}	6×10^{-5}	8×10^{-6}	5×10^{-5}	1.2×10^{-4}
Vela (≥150 keV)[6]	1.5×10^{-4}	...	7.5×10^{-5}	3.0×10^{-5}	5.3×10^{-5}	7.5×10^{-5}

NOTES.—(1) $dN/dE \sim E^{-\alpha}$ photons cm^{-2} keV^{-1}; (2) $dN/dE \sim e^{-E/E_0}$ photons cm^{-2} keV^{-1}; (3) $dN/dE \sim 1/Ee^{-E/E_0'}$ photons cm^{-2} keV^{-1}; (4) See text for details; (5) Uncertain; (6) Assumed $E_0 \approx 150$ keV exponential spectrum.

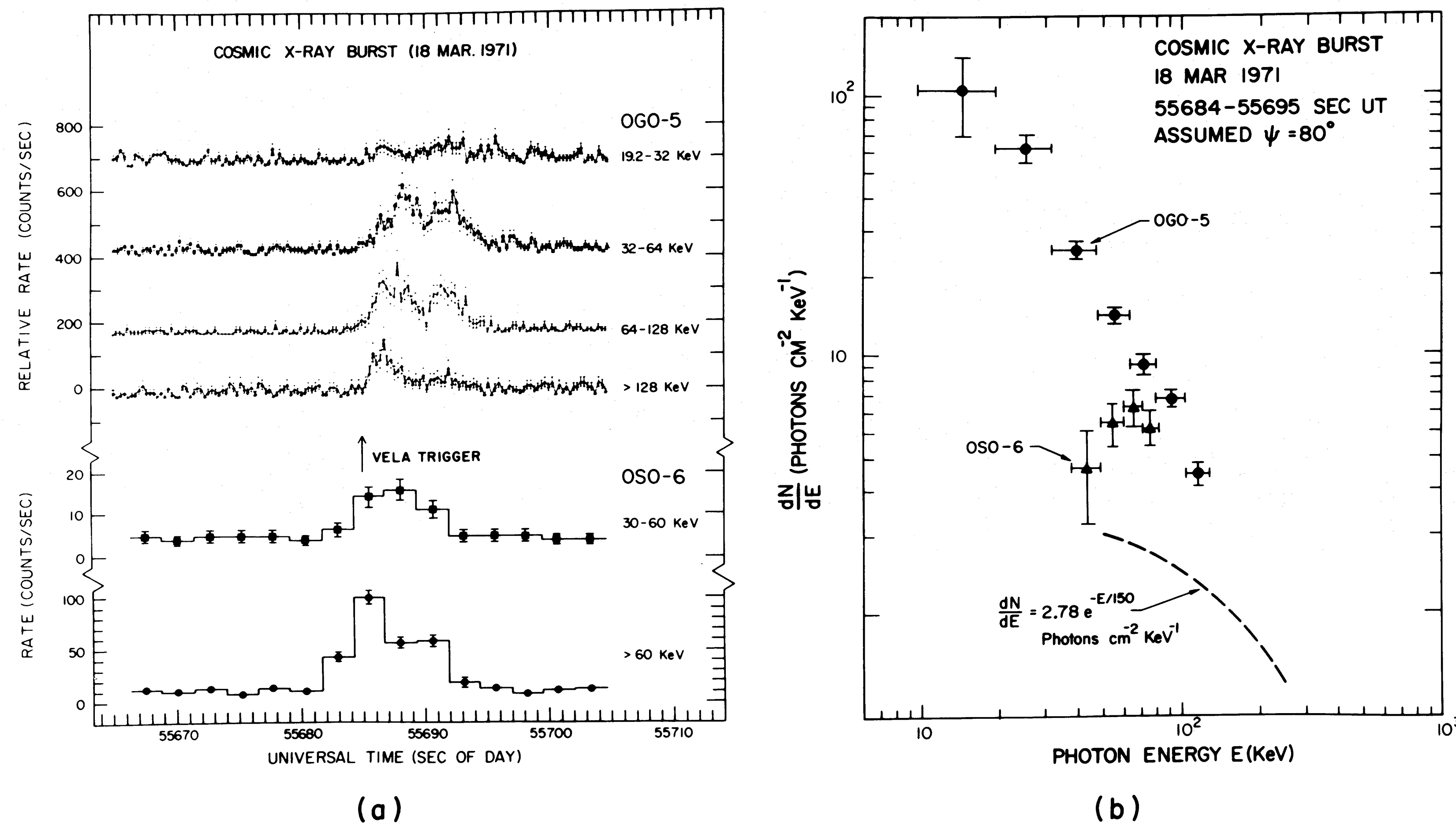

FIG. 6.—1971 March 18 cosmic X-ray burst: similar to Fig. 4

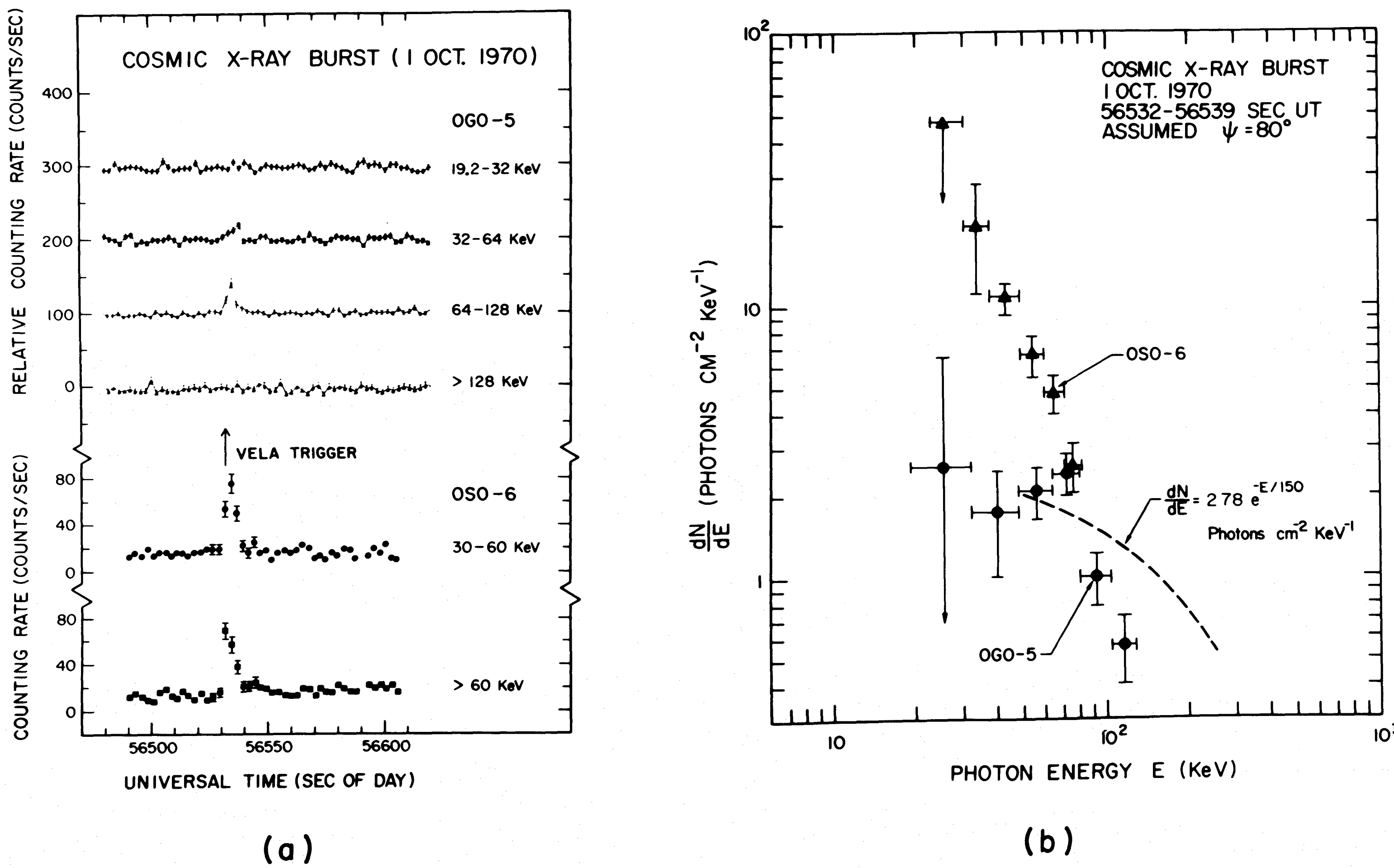

FIG. 7.—1970 October 1 cosmic X-ray burst: similar to Fig. 4

Shown for comparison is a 150 keV exponential spectrum fitted to the total energy observed by *Vela*. The fact that this spectrum lies significantly below an extrapolation of the OGO-5 spectrum is consistent with a relatively steep shape. The event was also detected by the IMP-6 detector (Cline *et al.* 1973) whose field of view passed through the source during the decay of the first pulse. The spectrum obtained is considerably steeper than is typical for other bursts detected by IMP-6; this is consistent with the findings above. The absolute intensity as measured by IMP-6 near 100 keV is about a factor of 10 below the OGO-5 data. This can be explained by the limited direct exposure of the IMP detector to the source and by significant attenuation at other times.

c) *Event of 1970 October 1*

This burst was first detected in the record of the NRL detector and was confirmed by OGO-5 (Share 1976). It was also observed by the *Vela 5A* satellite. Figure 7*a* shows the time profile of the burst as observed from OSO-6 and OGO-5; the onset times observed in all three instruments are in good agreement. As observed from OSO-6 the X-rays >60 keV have a rise time $\lesssim 2.6$ s whereas those at lower energy reach their maximum intensity ~ 2 s later. Following this maximum, the intensity falls off to near background level in ~ 7 s. About 5 s later there is evidence in all three detectors for a second weak burst of a few seconds' duration.

The directional information available for this event is insufficient to localize the source (Share 1976). The uncorrected data in Table 1, however, do provide some indication of the location of the source relative to the two detectors. Although the event was visible in the OSO-6 detector down to 30 keV without significant attenuation, the OGO-5 data below 60 keV are strongly attenuated. The situation is similar to that observed for the March 18 event, suggesting that the source was at an angle large enough to be obscured by part of the OGO-5 spacecraft but small enough to fall within the field of view of the NRL detector. We have therefore assumed an incident angle of 80° in obtaining the corrected X-ray spectrum shown in Figure 7*b*. It is important to note that the resulting spectrum from the NRL detector is not a sensitive function of the chosen angle near the periphery of its field of view (see Fig. 2). The corrected OGO-5 data exhibit attenuation consistent with traversal through about 3–4 g cm^{-2} of Al. (Another possible explanation for the appearance of the OGO-5 spectrum is that the burst was highly structured and that its intensity was weakest just at the times when the low-energy data were accumulated. This is ruled out by the *Vela* timing data and by the smooth appearance of the OSO-6 spectrum; recall that in OSO-6 alternate channels, e.g., 30–38 keV, 49–60 keV, etc., are accumulated and readout together.) Once again we show for comparison an exponential fit to the total energy in the burst observed by *Vela*.

d) *Event of 1970 January 25*

This burst was discovered by the OSO-6 and OGO-5 instruments, but was not detected by any of the *Vela* satellites (Share 1976). Its time profile as recorded at various energies is shown in Figure 8*a*. The OGO-5 data are plotted at a resolution of 0.58 s and show evidence of a fairly complex burst profile with a quasi-periodic appearance (especially in the 32–64 keV range). The burst lasted for about 11 s. Referring to Table 1, we note that the burst was observed by both detectors without substantial attenuation at low energies. This suggests that the source was located within the unobstructed fields of view of both instruments. We estimate the incident angle of the source by requiring that the corrected OGO-5 and OSO-6 spectral intensities agree with one another. Shown in Figure 8*b* are the corrected spectra obtained for an assumed angle of incidence of 70°.

e) *Event of 1970 December 1*

This was a relatively weak burst which had a duration of ~ 1 s as observed by *Vela* and displayed at 0.58 s resolution by the OGO-5 data shown in Figure 9*a*. The available information on the location of the source is insufficient to specify its angle relative to the instruments' axes. If one inspects the spectral data in Table 1, it is apparent that low-energy X-rays were significantly attenuated before reaching both instruments. It is unlikely that the effect in OGO-5 is due to the narrowness of the burst because the measurement was made at 0.29 s resolution. This suggests that the source was located near the edge of the fields of view of both instruments. In estimating the spectrum of the incident radiation we have once again assumed an angle of 80° for the direction of the source. The spectra corrected for this angle of incidence are shown in Figure 9*b*. The statistical uncertainties are large, and the absolute intensity derived from the NRL data is also uncertain due to the unknown duty cycle of the NRL experiment for this short burst (we assumed 50%). Its spectrum also suggests that the source was partially occulted by part of the OSO-6 spacecraft. The *Vela* data fitted to an exponential spectrum are shown again for comparison. With the many uncertainties involved, the agreement found between the intensities observed by the three detectors is reasonable.

f) *Event of 1971 February 27*

This event was discovered by the *Vela* satellites and was subsequently located in the data of both the NRL (Share, Meekins, and Kreplin 1974) and Bologna (Pizzichini, Palumbo, and Spizzichino 1975) experiments on OSO-6. It was not observed by OGO-5 because the experiment was not operating at that time. The time profile of the burst as observed by the NRL detector is shown in Figure 10*a*. The burst as viewed by OSO-6 occurred a few seconds before the trigger time of the *Vela* detectors and exhibited a gradual rise and relatively abrupt fall in intensity. The burst

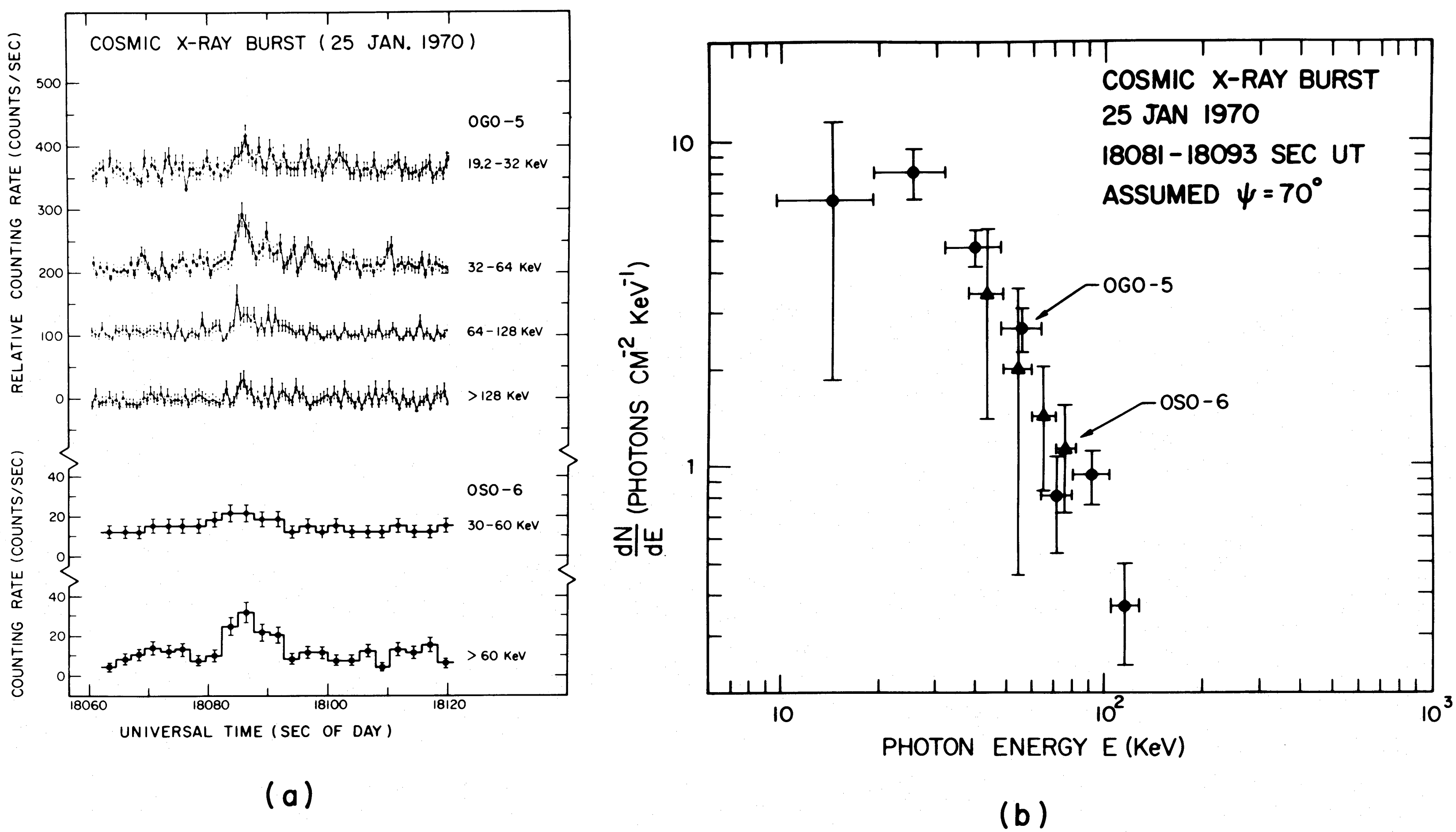

FIG. 8.—1970 January 25 cosmic X-ray burst: similar to Fig. 4. This event was not observed by the *Vela* spacecraft.

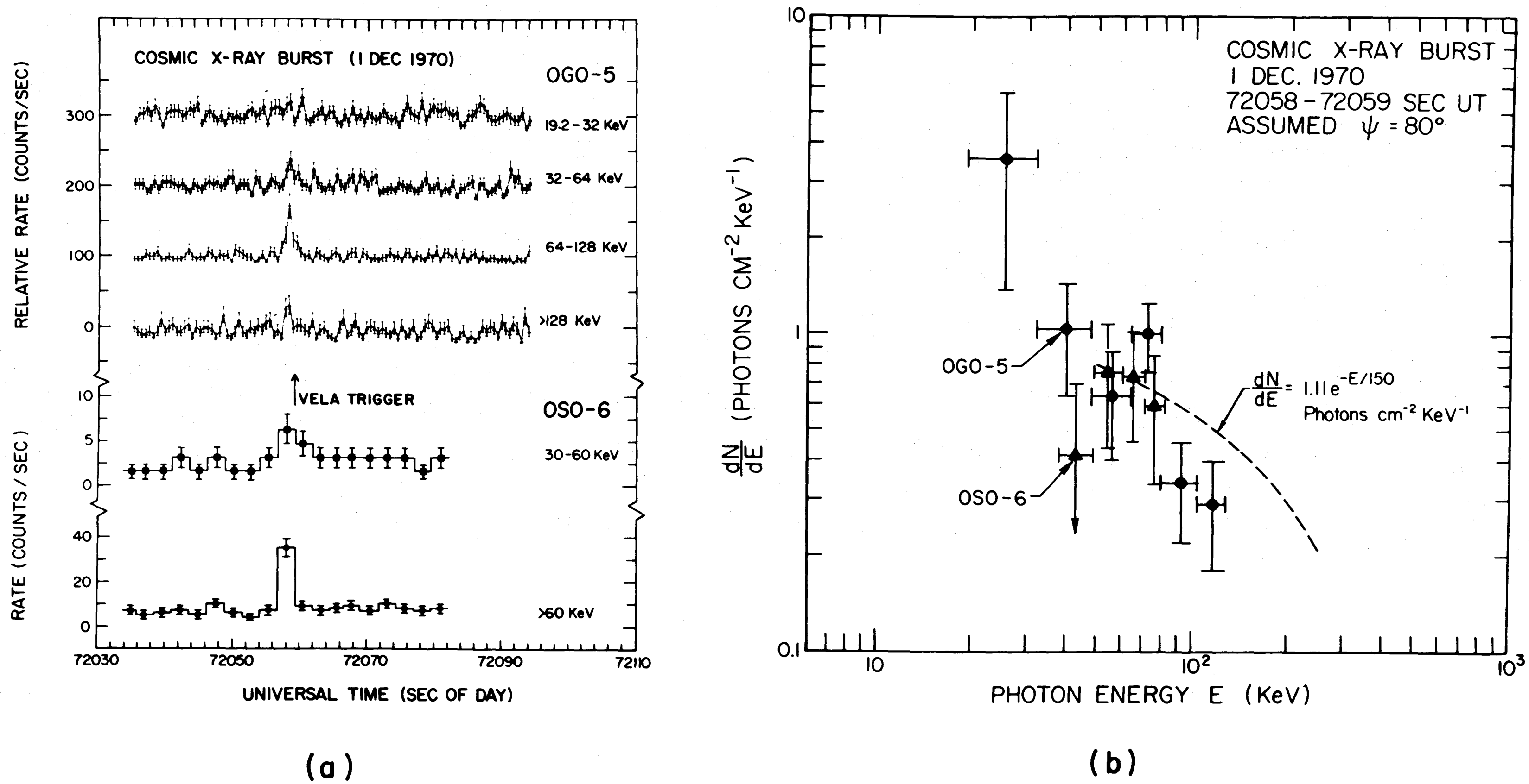

FIG. 9.—1970 December 1 cosmic X-ray burst: similar to Fig. 4

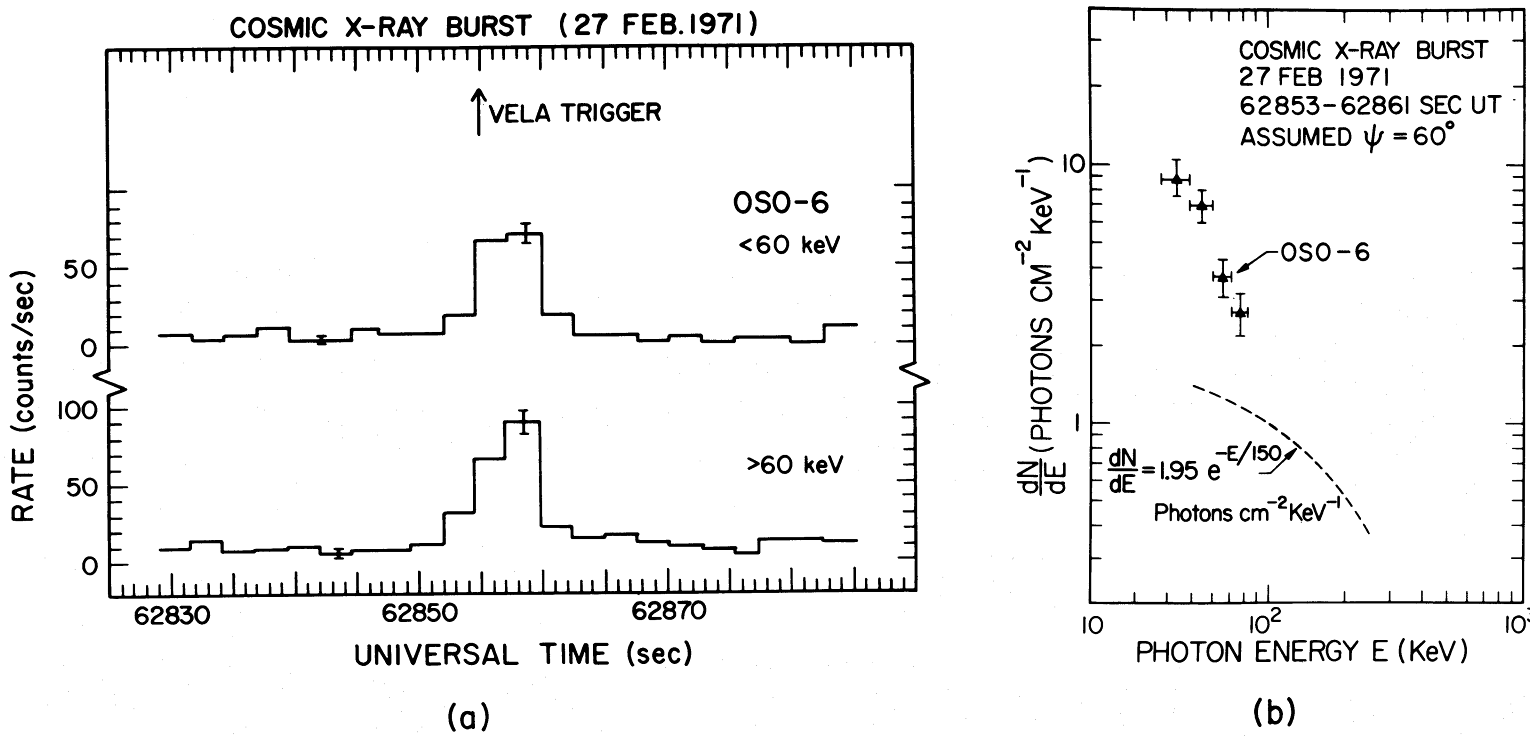

FIG. 10.—1971 February 27 cosmic X-ray burst: similar to Fig. 4. The OGO-5 experiment was not operating at the time of this event.

as observed by *Vela* had a structured appearance and total duration of ~ 5 s, which is consistent with the OSO-6 data.

Only crude directional information for this event is available (Share, Meekins, and Kreplin 1974; Pizzichini, Palumbo, and Spizzichino 1975). Nevertheless, it is likely that the source was well within the field of view of the NRL detector. This is evident from the uncorrected data in Table 1, which exhibit a fairly steep spectral response. Because the NRL detector's energy response is not a sensitive function of the incident angle, ψ, for angles $\gtrsim 40°$ (see Fig. 1), and because of solid angle considerations, we have assumed $\psi \approx 60°$. The corrected spectrum for this angle is shown in Figure 10*b*. The exponential fit to *Vela*'s reported total energy flux is also shown for comparison. An extrapolation of the OSO-6 data to high energy is consistent with the *Vela* intensity.

IV. DISCUSSION

Although more than 50 γ-ray bursts have been detected, measurements of only 16 have been made at energies $\lesssim 100$ keV (see references in § I). Spectral information for only four of these has been published. Using data from the NRL detector on OSO-6 and the Berkeley detector on OGO-5, we have derived hard X-ray spectra for six bursts, five of which have not been published earlier. The event which occurred on 1969 October 7 was the only one whose source location was both well known and well within the fields of view of both detectors. We have shown that the spectral intensities measured by the detectors during the main burst are in good agreement both with one another and with the published data obtained from Bologna's shielded detector on OSO-6 (see Fig. 5). This agreement indicates that there are no large systematic errors in the derived response functions of the instruments.

The time-integrated spectra derived for the six events are shown in part (*b*) of Figures 4, 6, 7, 8, 9, and 10. Due to the poorly known source directions and to absorption effects at large angles, the spectra obtained for the latter five events are more uncertain. We have detailed our method of analysis for each of these events in § III. It is clear from the shape of these spectra and comparison with the higher energy data from *Vela* that a large part of the emission of the "γ-ray" bursts is within the hard X-ray range.

The six time-integrated spectra have been fitted above 20 keV to three assumed functional forms: power-law ($\propto E_\gamma^{-\alpha}$), exponential [$\propto \exp(-E_\gamma/E_0)$], and "thermal" [$\propto 1/E_\gamma \exp(-E_\gamma/E_0')$]. The fits were made to the data from the detector providing the better statistics and/or exhibiting no evidence for substantial low-energy attenuation. Derived spectral characteristics are given in Table 2. The errors shown combine statistical uncertainties with our estimates of the systematic uncertainties resulting from the poorly defined source locations. Over the limited energy range of the measurements, it is not possible to choose among the three assumed spectral types. However, additional information is available from the integral rates $\gtrsim 80$ keV given in Table 1. Using the best-fit spectral parameters and the detection efficiencies in Figure 2, we have calculated the expected integral rates for the bursts assuming that they follow the spectral functions up to ~ 600 keV. A comparison of the calculated and observed integral rates is given in Table 2. The exponential function [$\propto \exp(-E/E_0)$] yields integral rates significantly below the observations; the thermal function is in better agreement but is still consistently lower than the observations. On the other hand, the power-law function yields rates consistently above the observations. This suggests that neither of the three simple functional forms can fit the observed spectra of the bursts over the full range from ~ 20 keV to ~ 600 keV. To fit the observations both the exponential and thermal spectral functions require additional high-energy components, while the power-law function must steepen at energies $\gtrsim 150$ keV.

These spectral measurements can be compared with previously published data. Metzger *et al.* (1974) attempted to represent the time-integrated spectrum of the 1972 April 27 burst by a single thermal bremsstrahlung function [$\propto 1/E_\gamma \exp(-E_\gamma/E_0)$], but found that it did not agree with the *Apollo 16* data at either low energies (2–8 keV) or high energies (>1 MeV). They found that a power-law function which steepened at $E_\gamma \gtrsim 200$ keV provided a good fit to the data. Wheaton *et al.* (1973) found that power-law functions fit the OSO-7 11–100 keV data taken at different times during the burst on 1972 May 14; a comparison with IMP-6 data taken during the same time intervals also reveals that the spectra steepen above a few hundred keV. Cline and Desai (1975) report that the time-integrated spectra of the bursts observed by IMP-6 and IMP-7 all appear to be similar. They choose to represent the spectra by an ~ 150 keV exponential and a power law above ~ 400 keV. However, the data may also be consistent with a power-law function which steepens above a few hundred keV (see Wheaton *et al.* 1973).

Referring to Table 2, we note that the time-integrated hard X-ray spectra of the bursts appear to vary from event to event. The power-law exponents (α) range in value from ~ 1 to ~ 2.5. This spectral "variability" at low energy contrasts with the spectral "constancy" found by Cline and Desai (1975) at high energies for the time-integrated data from several events. In this context, it is interesting to note that the hard X-ray spectra have also been found to vary significantly during bursts (e.g., Wheaton *et al.* 1973; Imhof *et al.* 1975; Kane and Anderson 1976). There is no consistent pattern to the spectral variability occurring during a given burst. Both spectral hardening and softening have been observed as the event progresses. In § III we have compared the temporal profiles of five of the bursts in the 10–130 keV region with those observed above 150 keV by *Vela*. Although spectral variation is evident, the durations of the bursts and the general pulse structures observed in these different energy ranges are quite similar. This suggests a common origin for the emissions. In contrast, it has been suggested that the high-energy bursts (>150 keV) ride on a more slowly varying, longer lasting, hard X-ray component (e.g., Prilutskii, Rozental, and Usov 1976; Piran and Shaham 1975). We do not believe that the present data warrant this conclusion. The fact that hard X-ray emission was observed significantly before the *Vela* trigger time for the 1969 October 7 event is more likely the result of threshold effects in the *Vela* system than that of spectral differences.

The energies contained within the 20–130 keV range for the six bursts discussed in this paper were determined using the best-fit power-law spectra. The results are given in Table 2, where they are compared with energy contained in photons $\geqslant 150$ keV deduced from *Vela* measurements. These estimates are based on values of the "total energy flux" in these bursts as reported by Strong, Klebesadel, and Olson (1974) and Klebesadel and Strong (1976*a*), where they have assumed an ~ 150 keV exponential photon spectrum over all photon energies. In such a spectrum $\sim 75\%$ of the total energy is contained in photons above 150 keV, the threshold of the *Vela* detectors. Therefore, the *Vela* energy fluxes $\geqslant 150$ keV presented in Table 2 represent the published total energy flux values multiplied by a factor 0.75. Of interest is the general tendency for events with flatter spectra in the 20–130 keV range to contain a smaller fraction of the total energy in this range; this is as we would expect. It is clear that a significant fraction of the total energy ($\geqslant 20$ keV) within the bursts was emitted in the hard X-ray range. This fraction varied from ~ 0.2 to ~ 0.6 for the six bursts discussed in this paper.

Any model for the source of the γ-ray bursts must explain a variety of characteristics. Perhaps the most constraining characteristics are the short time scales and the erratic nature of the variations in intensity. Coupled with energy considerations, these suggest an origin near some compact object, such as a neutron star or a black hole, Ruderman (1975) and Strong and Klebesadel (1976) have pointed out that the temporal variations and spectra of some of the γ-ray bursts (e.g., 1972 April 27) resemble the hard X-ray emission from Cygnus X-1, a binary system possibly containing a black hole. The hard X-ray number spectrum from Cygnus X-1 exhibits a power-law form with an index $\alpha \approx 1$ up to ~ 150 keV and steepens considerably at higher energies. This compares with indices in the range $1 \leqslant \alpha \leqslant 2.3$ up to ~ 130 keV, with evidence for steepening at higher energies, for the six bursts discussed in this paper. A model recently proposed by Piran and Shaham (1975) is able to reproduce the observed spectral features. In this model, low-energy X-rays produced in the accretion disk are Compton scattered to high energies by a high-energy plasma released during the burst. Whether or not the object is observed as an X-ray source is dependent on its steady-state accretion rate. It is of interest to note that a model developed by Shapiro, Lightman, and Eardly (1976) explains the steady-state hard X-ray emission from Cygnus X-1, also using Compton scattering. In their model, the soft X-rays are produced in a cool and thin outer accretion disk and are Compton scattered to higher energies in the relatively thick and hot ($T_e \approx 10^9$ K) inner region of the disk.

Bursts of low-energy X-rays ($1 \leqslant E \leqslant 15$ keV) have recently been discovered with temporal characteristics similar to the γ-ray bursts (Grindlay *et al.* 1976). A summary of their characteristics can be found in Lewin (1976). Their intensities are about two to three orders of magnitude below the intensities of the γ-ray bursts. Evans, Belian, and Conner (1976) suggest that both the γ-ray bursts and X-ray bursts may be of the same galactic origin and that, due to the limited sensitivities of the γ-ray instruments, only the nearby γ-ray burst sources have been detected. We note, however, that the energy spectra of these two phenomena are very different. The spectra of most X-ray bursts fall off sharply at or above 15 keV (see, e.g., Lewin *et al.* 1976), whereas the spectra of the γ-ray bursts are relatively flat in this energy range. Had there been an additional intense low-energy component (<20 keV) riding on top of the hard X-ray spectrum of the γ-bursts, it would certainly have been detected by the OGO-5 and OSO-6 instruments. The observation of the 1972 April 27 γ-ray burst in the 2–7 keV range (Metzger *et al.* 1974) also rules out an additional intense low-energy component.

Babushkina *et al.* (1975) have reported the observation of two bursts of hard X-rays, each with an intensity of $\sim 4 \times 10^{-6}$ ergs cm^{-2} from 40 to 290 keV. They report that the spectra are consistent with an exponential function [$\sim \exp(-E/E_0)$], where $E_0 \approx$ 40–50 keV, and are therefore considerably softer than the spectra of the γ-ray bursts. However, we note from Table 2 that the spectral shape of the *Cosmos* bursts do not appear to differ significantly from the γ-ray bursts at energies $\leqslant 100$ keV. The OGO-5 spacecraft was not operating at the time of these two bursts. The OSO-6 experiment, which was operating only at the time of one (1971 June 25) burst, did not detect any significant increase in the X-ray flux during that burst. This is not surprising since the intensity of the burst was below the OSO-6 threshold.

V. SUMMARY AND CONCLUSIONS

We summarize the main results of the paper below:

1. Spectral and temporal observations of six γ-ray bursts have been made in the hard X-ray range.
2. For all of these bursts, a significant fraction of the total energy ($\sim 20\%$ to $\sim 60\%$) was detected in the 20–130 keV range.
3. The observations in the 20–130 keV range are consistent with power-law, exponential, and thermal spectra integrated over the duration of the bursts. The power-law exponents, α, fall in the range ~ 1 to ~ 2.5. There is evidence for variability in the hard X-ray spectra from event to event.
4. Combined with higher energy observations, a power-law function steepening at or above 150 keV fitted the time-integrated spectra best. The exponential and thermal bremsstrahlung functions required additional high-energy components.

5. There is no evidence that the bursts >150 keV ride on a more slowly varying, longer lasting hard X-ray component, as has been suggested in the literature.

6. The γ-ray bursts have significantly different spectral characteristics above 20 keV than the bursts observed recently in the 1–15 keV range. Soft X-ray bursts do not appear to ride on top of the hard X-rays emitted during γ-ray bursts.

The research at Berkeley was supported by the National Aeronautics and Space Administration under grant NGL 05-003-017. This work was also partially supported by the Office of Naval Research. One of us (G. S.) wishes to express his appreciation for the hospitality offered by the Center for Astrophysics, Cambridge, Massachusetts, during the time in which the paper was in final preparation.

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