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SPECTRAL EVOLUTION OF PULSE STRUCTURES IN GAMMA-RAY BURSTS

J. P. Norris,[1] G. H. Share, and D. C. Messina[2]
E. O. Hulbert Center for Space Research, Naval Research Laboratory

B. R. Dennis, U. D. Desai, and T. L. Cline
NASA/Goddard Space Flight Center

and

S. M. Matz and E. L. Chupp
Physics Department, University of New Hampshire
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ABSTRACT

The Hard X-Ray Burst Spectrometer (HXRBS) and the Gamma-Ray Spectrometer (GRS) on the *Solar Maximum Mission* satellite have independently monitored cosmic gamma-ray bursts since launch in 1980 February. Ten relatively intense events detected by the GRS (four detected by HXRBS) have been studied in an attempt to reveal a basic pattern of spectral variability in gamma-ray bursts. In each of these bursts we find pulses $\gtrsim 1$ s in duration which exhibit a hard-to-soft spectral evolution. We find no evidence for soft-to-hard evolution in any of the pulses. Using the HXRBS data for energies above 144 keV and GRS data above 1 MeV, we demonstrate that this hard-to-soft evolution is not due to time-varying absorption features at energies below 100 keV. Details of the spectral evolution of pulses are presented for two events, 1982 March 1 and November 4. We also show that the KONUS observations of Golenetskii and colleagues, updated in 1983, for which a detailed correlation of intensity and spectral hardness was reported, are actually consistent with our findings if different assumptions are made. Several possible explanations for spectral softening of burst pulses are suggested.

Subject heading: gamma-rays: bursts

I. INTRODUCTION

The *IMP 6* and *IMP 7* gamma-ray burst detectors afforded the first measurements of event-averaged burst spectra. Early experiments found that most burst spectra could be approximated by an exponential with a characteristic energy $E_0 \approx$ 150 keV, plus a power-law tail of photon index approximately unity above 400 keV (Cline *et al.* 1973; Cline and Desai 1975). Instruments with increased sensitivity and finer temporal resolution have demonstrated that burst spectra vary within a given event as well as from event to event (Wheaton *et al.* 1973; Metzger *et al.* 1974; Trombka *et al.* 1974; Nakano, Imhof, and Reagan 1976; Kane and Share 1977; Teegarden and Cline 1980; Dennis *et al.* 1982). The KONUS instruments on the *Venera 11* and *Venera 12* spacecraft detected approximately 150 bursts in 16 months and confirmed that significant spectral evolution within a burst is the rule rather than the exception (Mazets *et al.* 1981*c*, *d*, *e*).

Investigation of the relationship between temporal structure and spectral evolution requires instrumentation with spectral accumulations in times shorter than the times for gross flux variations seen in bursts. The SIGNE experiments on *Venera 11* and *Venera 12* revealed that some events exhibit spectral turnovers at burst onset, at energies as high as $\sim$400 keV, which migrate to lower energies on time scales from tens of milliseconds to a few seconds (Vedrenne 1981; Cline 1984). Recently, Golenetskii *et al.* (1983) have analyzed data from KONUS 13 and 14 detectors with different energy thresholds at 0.25 s resolution and have suggested that there is a detailed correlation between spectral hardness and intensity. In contrast, other observers have reported that the spectral hardness peaks on the leading edges of pulses (Wheaton *et al.* 1973; Norris 1983; Laros *et al.* 1985). However, these analyses did not completely eliminate the possibility of spectral absorption or emission features affecting the apparent evolutionary trends.

We have searched the Hard X-Ray Burst Spectrometer (HXRBS) and Gamma-Ray Spectrometer (GRS) data from the *Solar Maximum Mission* satellite (*SMM*) for gamma-ray bursts with sufficient intensities and relatively simple time profiles such that their spectral behavior may be studied on a time scale of $\sim$1 s. Ten such events were observed with the GRS experiment, and four of these were also detected within the HXRBS field of view. In this paper we present details for two moderately intense bursts with relatively simple structure. The spectral evolution of the remaining events are summarized briefly and will be presented elsewhere. Our results suggest a pattern in the spectral evolution within burst pulses: a tendency for the high-energy emission to lead the low-energy emission, in contrast to the correlation of intensity and spectral hardness reported by Golenetskii *et al.* (1983).

II. INSTRUMENTATION

The primary objective of HXRBS is to study hard X-ray spectra of solar flares on times scales as short as 10 ms. The instrument is also ideal for observing the hard X-ray spectra of gamma-ray bursts which fall within the field of view of the detector. The HXRBS detector (Orwig, Frost, and Dennis 1980) is a CsI(Na) scintillator (radius 4.67 cm and thickness 0.64 cm), surrounded on all sides except for the solar direction by a CsI(Na) shield of thickness 3.2 cm. It continuously monitors the hard X-ray flux received in the central detector. Events are pulse-height analyzed to produce 15 channel energy

[1] NAS/NRC Cooperative Research Associate.

[2] Sachs/Freeman Associates, Inc.

spectra from 30 to 500 keV with a time resolution of 128 ms. The total count rate over the same energy range is recorded every 10 ms.

The GRS was designed for investigation of the gamma-ray spectrum of solar flares (Forrest *et al.* 1980). The main detector is an array of seven gain-controlled 7.6 cm diameter × 7.6 cm thick NaI(Tl) detectors. A complete spectrum is obtained every 16.38 s in the energy range 0.3–9 MeV. The number of counts in three energy windows covering the 4.2–6.4 MeV range are read out every 2.048 s. In addition, the number of counts in an approximately 50 keV wide window near 300 keV is read out every 64 ms. The spectrometer is shielded by a 2.5 cm thick CsI(Na) annulus and a 25 cm diameter × 7.6 cm thick CsI(Na) back detector. The shield elements define a field of view of ~135° (FWHM) in the solar direction. The CsI back detector and the seven NaI detectors together provide a high-energy spectrometer with ~100 cm^2 effective area and four energy channels from 10 to 100 MeV. The number of counts in these high-energy channels are read out every 2.048 s. The experiment is complemented by two 8 cm^2 × 0.6 cm thick NaI(Tl) detectors which measure the X-ray portion of the spectrum every 1.024 s in the range from 13 keV to 182 keV.

The HXRBS threshold for detection of gamma-ray bursts within the detector field of view is $\sim 10^{-7}$ ergs cm^{-2} ($E > 30$ keV). Considering that *SMM* views Earth at satellite night, only about one gamma-ray burst in 40 is detected within a $\pi/6$ sr field of view (60° full width quarter maximum), for which the spectra are not significantly contaminated by the shield-processed contribution. Since launch, more than 15 gamma-ray bursts have been detected within the field of view of the HXRBS detector. The GRS detection threshold for gamma-ray bursts within its field of view is $\sim 5 \times 10^{-6}$ ergs cm^{-2} ($E > 300$ keV). The GRS has detected at least 75 bursts.

III. OBSERVATIONS

In our analysis, only events which attained count rates at least 6 σ above the background in both the 52–182 keV channel and the 50 keV window at 300 keV were selected from the GRS data base to be studied for evidence of spectral variability. Thirteen bursts detected by the GRS satisfied the criteria, and of these, four were observed within the HXRBS field of view. Three of the events detected only by GRS exhibited very significant fluctuations on time scales of $\gtrsim 1$ s in the count rate of the 300 keV window; hence, these cases were eliminated from the study. The times of the remaining 10 events are listed in Table 1. We first discuss in detail our analysis of the 1982 November 4 and March 1 bursts, which reveals a pattern of spectral softening over the duration of resolved pulse structures. We next discuss the supporting evidence for spectral evolution found in the remaining bursts listed in Table 1.

a) 1982 November 4 Burst

Time-of-arrival analysis using information from *SMM* and two additional spacecraft (*Venera 11* and *Venera 12*) indicate that the incident direction of the November 4 burst was approximately 10° from the Sun (K. Hurley, private communication). The relative responses of the HXRBS shield and central detector are consistent with this coarse positional determination. The November 4 bursts attained a peak intensity of 35 counts cm^{-2} s^{-1} above background in the HXRBS detector. Assuming a single power-law form for the HXRBS and GRS spectra and integrating from 30 keV to 10 MeV, we find the burst had a total fluence over a 70 s duration of about 4×10^{-4} ergs cm^{-2}.

Figure 1 illustrates the HXRBS time profile summed over the energy range 37–440 keV with a resolution of 256 ms. The burst consists of four resolved pulse structures with durations (in sequence) of 4, 1, 5, and 15 s. Also shown in Figure 1 are the best-fit power-law spectral indices during the four pulses as obtained from the HXRBS data covering the energy range 144–440 keV (channels 6–14). Other spectral forms, such as optically thin thermal synchrotron and thermal bremsstrahlung, were also assumed in fitting the HXRBS data and gave results similar to those found assuming a power law. The GRS hardness ratios, defined as the count rate in the ~50 keV wide window near 300 keV divided by the rate in the 52–182 keV energy range, are plotted with a resolution of 1.024 s in the bottom panel of Figure 1.

Both the HXRBS power-law spectral indices and the GRS hardness ratios reveal a general pattern of hard-to-soft spectral evolution across the first and last (fourth) pulses. The evolution of the second, 1 s wide pulse, observable only in the HXRBS data, also exhibits a hard-to-soft pattern. For the third, and least intense pulse, the HXRBS data is binned in 0.5 s intervals to reduce the uncertainties. The same evolutionary trend is apparent in this data, but it is less compelling than for the other three pulses; it is not evident at all in the GRS data due to the poor statistics. The basic finding for this event is that the hardest spectra occur on the leading edge in each of the four pulses.

It is important to note that the fits to the HXRBS data were made above 144 keV. Consequently the measured hard-to-soft evolution cannot be attributed to absorption features below 100 keV. Another clear demonstration of this point can be found in the data plotted in Figure 2, which show the fourth (last) pulse plotted on an expanded time scale. The bottom panel repeats the HXRBS rates plotted in Figure 1 at 0.256 s resolution. Shown for comparison are GRS count rates in five energy bands from 13 keV to 40 MeV at 2 s resolution. The peak intensity clearly occurs earlier at higher energies. There is also some indication that the pulse is narrower in the 10–40 MeV range than it is at lower energies. In order to quantify the delays at lower energy in the five energy bands, several func-

TABLE 1

EVIDENCE FOR HARD-TO-SOFT SPECTRAL EVOLUTION IN BURSTS

		GRS		
DATE	TIME (UT)	Count Ratio[a]	Early Peak above 1 MeV[b]	HXRBS[c]
1980 Apr 19	01:20	...	...	Yes
1980 Dec 20	18:31	...	Yes	...
1981 Oct 16	23:53	...	...	Yes
1982 Mar 1	02:36	Yes	Yes	...
1982 May 30	09:49	...	...	Yes
1982 Aug 28	13:49	Yes[d]	...	...
1982 Nov 4	03:30	Yes	Yes	Yes
1984 Aug 5	23:48	Yes	Yes	...
1984 Aug 20	02:01	Yes	...	...
1984 Sep 17	18:52	Yes	...	...

NOTE.—An ellipsis (...) indicates absence of evidence for hard-to-soft evolution.

[a] GRS ratio of count rates in 300 keV window and 52–182 keV energy band.

[b] GRS emission at energies >1 MeV peaks earlier than 300 keV emission.

[c] HXRBS 128 ms data reveals hard-to-soft evolution in pulses ~1 s wide.

[d] Hard-to-soft evolution also evident in KONUS data (Golenetskii *et al.* 1983).

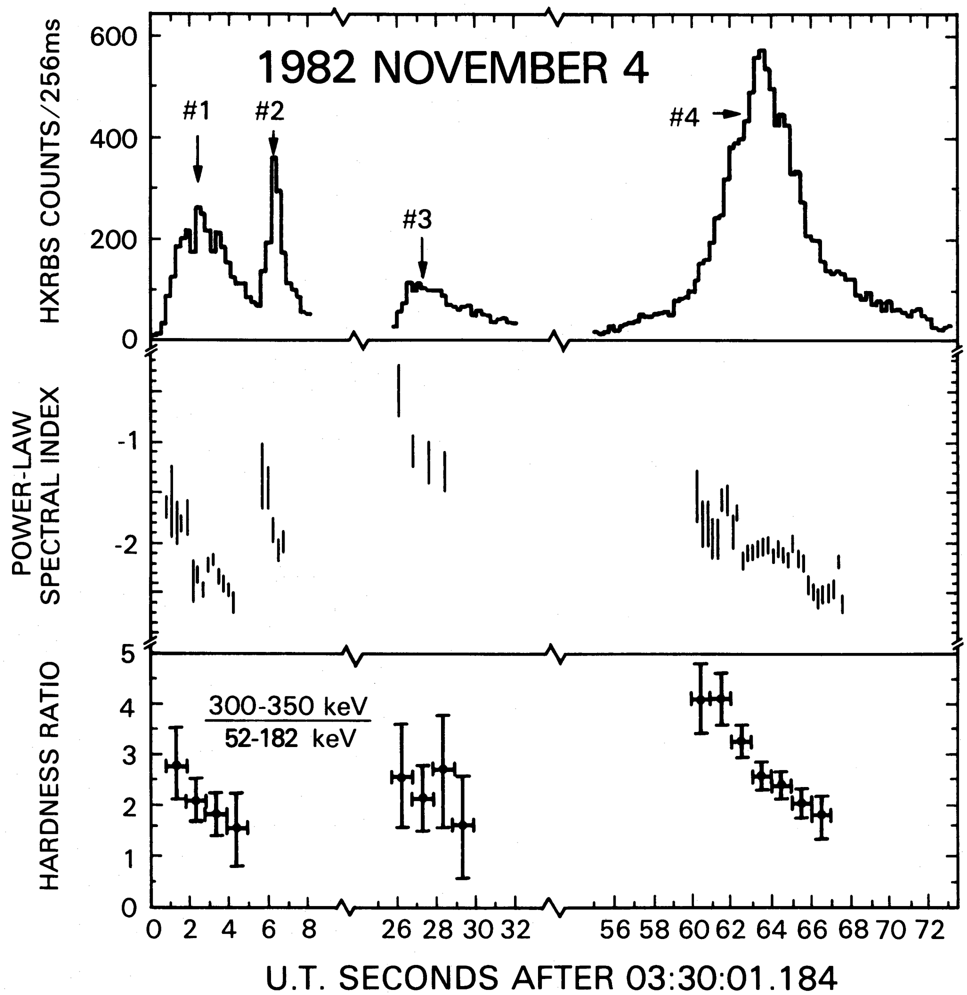

FIG. 1.—Temporal variations in the 1982 November 4 gamma-ray burst. (*top*) HXRBS count rate between 37 and 440 keV with 256 ms resolution. Principal pulse structures are labeled 1 through 4. (*middle*) Spectral power-law indices obtained from fits to the HXRBS count rates between 144 and 440 keV, plotted with 256 ms resolution (512 ms for pulse 3). (*bottom*) The ratio of the GRS count rates in the 50 keV window at 300 keV and the channel between 52 and 182 keV plotted with 1.024 s resolution.

tional forms were used to fit the GRS time profiles. The function which best fits the data in all energy bands is constructed from rising and decaying exponentials with equal time constants. The fits were made to the data with 2 s resolution above 1 MeV and 1 s resolution at lower energy.

The peak times at lower energies are delayed relative to the peak time for the 10–40 MeV range by the following times: 0.0 ± 0.2 s (4–6.4 MeV), 0.50 ± 0.04 s (window at 300 keV), 1.1 ± 0.1 s (52–182 keV), and 1.3 ± 0.1 s (13–52 keV). The width (FWHM) of the fourth pulse derived from the fits for the 10–40 MeV data is 1.6 ± 0.8 s compared to widths of ~ 3–4 s at the lower energies.

Inspection of the 0.256 s time history in the top panel of Figure 1 suggests that the relatively "simple" shapes of the first and last pulses, are in fact composites of subpulses. These subpulses may be responsible for structure evident in the hard-to-soft evolutionary pattern as reflected in the power-law index in the middle panel of the figure.

b) 1982 March 1 Burst

The March 1 burst was about 3 minutes in duration and consisted of at least five separate pulses as observed by the GRS in the 52–182 keV energy range. The burst was not in the HXRBS field of view thus precluding a solar origin. The average spectrum appears to soften progressively from pulse to pulse, so that the last two pulses were barely detectable above 300 keV. However, the early part of the burst was intense enough to allow investigation of the spectral evolution on a 1 s time scale from the GRS data. Figure 3 illustrates the first three pulses of the burst observed during the first minute. The two intense but softer peaks that occurred during the next two minutes are not included. Plotted in Figure 3 are the count rates in four GRS energy ranges: 52–182 keV, the 50 keV window near 300 keV, 350–800 keV, and 800–2000 keV. The time profiles at energies above 350 keV are derived from the GRS spectroscopy data and have a time resolution of 16.38 s. The hardness ratio plotted in the bottom panel clearly shows the pattern of hard-to-soft evolution in the first pulse with the hardest spectra occurring on the rising edge. The FWHM of the first pulse in the window at 300 keV, 8 ± 1 s, is also narrower than the 52–182 keV pulse width, ~ 15 s. Evolution of the second, clearly composite, pulse structure is less well defined due to the poorer statistics. Nevertheless, the second pulse exhibits the same softening trend. This pulse is also wider in

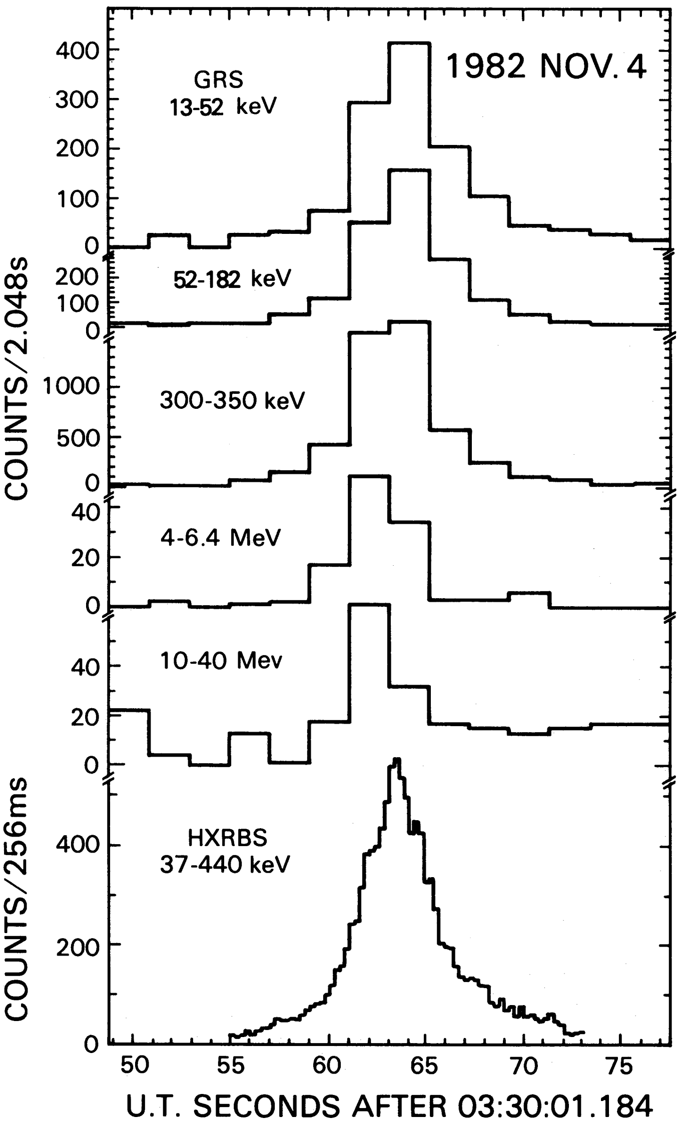

FIG. 2.—Time histories of pulse 4 in 1982 November 4 burst observed in five GRS energy bands with 2.048 s resolution. The HXRBS time history with 256 ms resolution is shown for comparison.

the 52–182 keV band, 16 ± 2 s (FWHM), than in the 300 keV window, $\sim 8 \pm 3$ s.

The March 1 GRS data above 350 keV can be used to show that the spectral softening is an intrinsic property of the continuum emission of the burst and not the result of any distortion of the continuum by absorption features below 100 keV. The time profiles of the 350–800 keV and 800–2000 keV data are also plotted in Figure 3. Although the time resolution in these two energy bands is 16 s, the break in accumulation intervals fortuitously coincided with the rising edge of the first pulse of the burst. It is clear from the figure that the 800–2000 keV emission peaked prior to both the 350–800 keV emission and the lower energy X-radiation. Also, power-law fits to the GRS spectral data from 0.3 to 9 MeV for the first two 16 s intervals of the burst, comprising the onset of the first pulse and its subsequent development, yield spectral indices of 2.2 ± 0.2 and 3.8 ± 0.1 (99.5% confidence), respectively. From this we conclude that the hard-to-soft spectral evolution within the first pulse of the March 1 burst is a general feature of the continuum emission up to energies in excess of 1 MeV.

c) Analysis of Other Bursts

In this section we outline the temporal characteristics of the remaining bursts listed in Table 1, which provide supporting evidence for the hard-to-soft spectral evolution found in the 1982 March 1 and November 4 bursts. It is noteworthy that no example of the reverse trend, soft-to-hard evolution, was found in any of the bursts in this study. In treating these remaining bursts it is best to discuss the results based on three characteristics of pulses found in the analysis of the March 1 and November 4 bursts. These are (1) hard-to-soft spectral evolution in the GRS determined from the ratio of counts in the GRS window at 300 keV and the 52–182 keV channel, (2) spectral evolution evidenced by the early peaking of >1 MeV radiation compared to the <1 MeV radiation as detected by the GRS, and (3) spectral evolution only resolvable using the 0.256 s HXRBS data. Table 1 lists the characteristics displayed by the different bursts.

Four events in addition to the March 1 and November 4 bursts displayed hard-to-soft evolution as evidenced from the GRS 1 s count ratio. This evolution in the relatively simple pulse of the August 28 burst was also observed by the KONUS instrument (Golenetskii *et al.* 1983). However, their analysis of the data led them to a different conclusion (see § IV). The hard-to-soft evolution in the GRS count ratio in the first pulse of the 1984 August 5 burst is supported by the observation of early peaking of the high-energy emission >1 MeV, similar to that observed in the November 4 burst (see Fig. 2). Detailed discussion of this burst will be presented by Share *et al.* (1985). For the two remaining events, 1984 August 20 and September 17, only the GRS count ratio provides the evidence for hard-to-soft spectral evolution.

The 1980 December 20 burst is the sole example of a burst in which hard-to-soft spectral evolution is displayed only by the early peaking of the >1 MeV emission relative to the hard X-radiation. The effect is similar to that shown in Figure 2 for the November 4 burst. The GRS count ratio (1 s time scale) gave ambiguous results because of the complex structure of the burst.

There are three events for which the hard-to-soft evolution in pulse structures only becomes apparent with the 128 ms resolution of the HXRBS data. The 1 s GRS data are not sufficient to resolve the complex pulse structures. The analysis of the 1980 April 19 event has been presented elsewhere (Dennis *et al.* 1982; Norris 1983). In the present study the April 19 event was reanalyzed using only the data above ~ 100 keV, in order to rule out the possibility that the hard-to-soft evolution across the ~ 1 s pulses was due to the presence of absorption features. The current analysis confirms that the same evolution occurred at energies >100 keV. Pulse structures in the bursts of 1981 October 16 and 1982 May 30 observed with 1 s resolution appear to exhibit the correlation of spectral hardness and intensity suggested by Golenetskii *et al.* (1983) as being a characteristic of some gamma-ray bursts. However, all the pulse structures in these bursts varied markedly on a time scale $\lesssim 2$ s. Using the 128 ms HXRBS spectral resolution, the hard-to-soft evolution becomes apparent in the strong pulses. Details of the analysis of these two HXRBS events will be presented in a later publication (Desai *et al.* 1985).

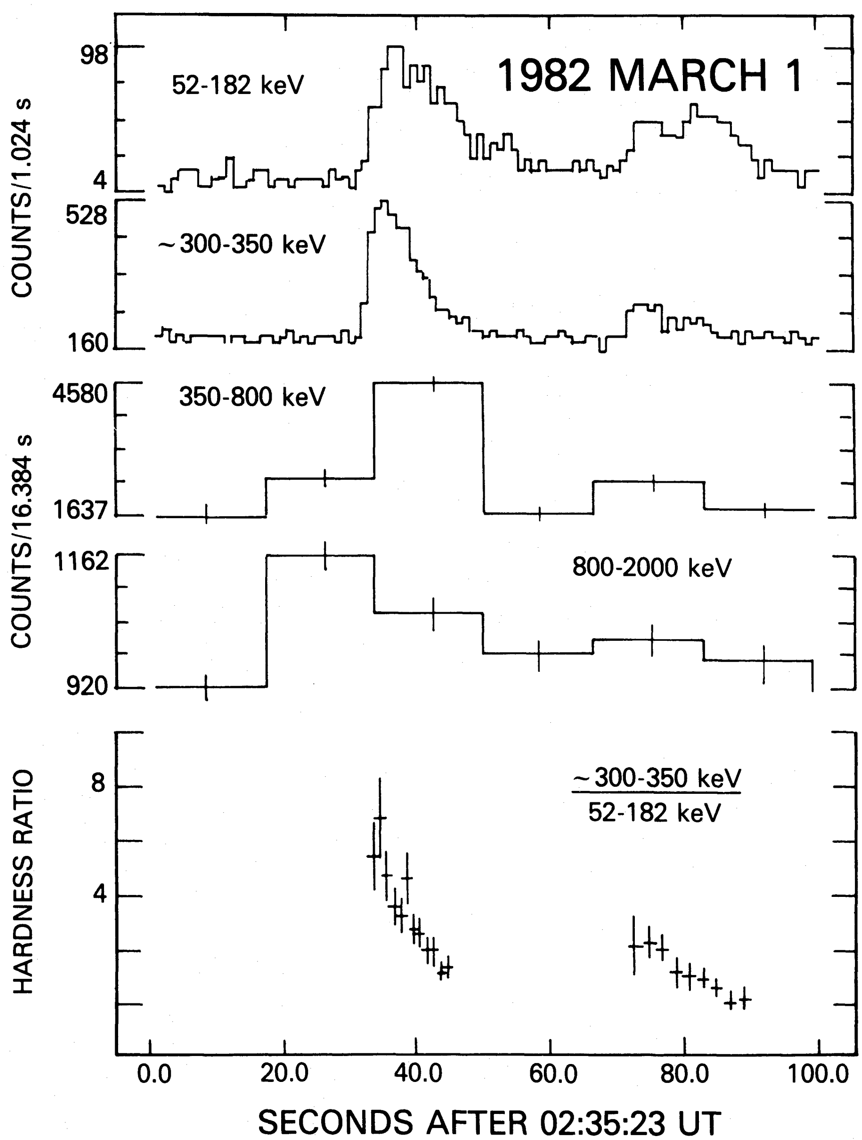

FIG. 3.—GRS time histories of the 1982 March 1 gamma-ray burst in the following energy ranges: 52–182 keV, the 50 keV window near 300 keV, 350–800 keV, and 800–2000 keV. The bottom panel shows the ratio of GRS counting rates in the 50 keV window at 300 keV and the channel between 52 and 182 keV plotted at 1 s resolution for the first pulse and at 2 s resolution for the second pulse.

IV. DISCUSSION

Ten cosmic gamma-ray bursts have been studied using data obtained with HXRBS and GRS on *SMM*. Our analysis indicates that, in the cases where the count statistics are adequate and the pulse structures are resolved, a trend of hard-to-soft spectral evolution during individual pulses is evident. The two moderately intense bursts of 1982 March 1 and November 4 are good examples that show this trend. This spectral evolution has been examined in the observations in three different ways: (*a*) comparison of the GRS count rates in a 50 keV window near 300 keV with the rates observed in the 52–182 keV band; (*b*) peaking of $\gtrsim 1$ MeV rates observed by GRS in comparison with the peaks at lower energies; (*c*) spectral analysis using the HXRBS data above 144 keV with 0.256 s resolution. The 1982 November 4 burst satisfied all three criteria where they could be applied. The remaining bursts listed in Table 1 satisfied at least one of the three criteria. In no case did we find an example of soft-to-hard evolution of pulse structures within bursts. Methods (*b*) and (*c*) are critical in distinguishing between a general pattern of hard-to-soft evolution and apparent evolution caused by the early appearance of absorption features below 100 keV. Seven of the bursts exhibited spectral evolution using methods (*b*) and/or (*c*), indicating that such absorption features are not the primary reason for the observed hard-to-soft evolution within resolved pulses.

We have presented strong evidence for hard-to-soft evolution in pulses on time scales of a few seconds. Instruments with finer temporal resolution, combined with increased sensitivity, often reveal even shorter time scale structure in gamma-ray bursts. Therefore, the relatively simple pulse structures discussed in this paper may be composites of pulses shorter than ~ 0.25 s. However, the gross trend of spectral evolution suggests that these pulses are coherent structures rather than random superpositions of subpulses.

Sustained low-energy emission at energies $\lesssim$10 keV has been reported (Terrell *et al.* 1982; Laros *et al.* 1984*a*). This emission may be evidence for a thermal component which precedes the higher energy impulsive emission to which HXRBS and GRS are sensitive. If this sustained low-energy component extends to high enough energies, it might be detectable in the 13–19 keV energy band of the GRS X-ray detector. We have looked for such sustained emission in the 10 bursts listed in Table 1. In only one case (1980 April 19) is there evidence for such a sustained low-energy component which *precedes* the gamma-ray emission (Share *et al.* 1981). However, because the Sun was in the field-of-view of the detector and there was evidence for weak flaring activity at the time, we cannot be certain that the emission was associated with the gamma-ray burst.

The observed hard-to-soft spectral evolution may also occur for only a specific class of bursts. There may be more than one kind of gamma-ray burst, each powered by a different mechanism. Considerable evidence for a distinct class of very short duration, $\lesssim$0.25 s, bursts has now been accumulated (Cline and Desai 1974; Mazets *et al.* 1981*a*, *b*; Golenetskii, Illyinskii, and Mazets 1984; Norris *et al.* 1984). Investigation of spectral evolution in such short events is beyond present instrumental sensitivity in most cases (exception: event of 1979 March 5, see Cline 1984; Barat *et al.* 1983).

We now turn our attention to the apparent correlation of intensity and spectral hardness in bursts suggested by Golenetskii *et al.* (1983). Their result conflicts with the hard-to-soft evolution evident in the *SMM* data. The 1982 August 28 event listed in Table 1 was cited by these authors as exhibiting a correlation of intensity and spectral hardness. However, as Golenetskii *et al.* noted, the intervals with the highest hardness ratios in the KONUS data for both this event and the two others presented in their paper actually do occur near the onsets of most pulses. But these intervals were excluded from their analysis. Their justification for this approach was that the ratios were higher than the limiting value, 0.7, to be expected from their adopted spectral model, a zeroth order representation of optically thin thermal bremsstrahlung emission, E^{-1} exp $(-E/kT)$. In fact, the intervals near the onsets of pulses which manifested anomalously high hardness ratios were excluded from their analysis because the continuum hardness was believed to be distorted by the presence of cyclotron or annihilation features. As we have shown in this paper, the high hardness ratios found in at least 70% of the *SMM* events are not due to cyclotron absorption features. Norris (1983) has suggested that some of the apparent spectral features in the KONUS data may actually be artifacts which arise from integrating over rapid spectral variations. Evolving spectral turnovers in the energy range from $\sim$400 keV to below 100 keV evident at the onset of some bursts (Mazets *et al.* 1981*c*; Vedrenne 1981; Golenetskii, Ilyinskii, and Mazets 1984; Cline 1984) support this interpretation. The possibility of emission from spatially distinct regions with differing physical conditions also cannot be excluded as an explanation for these features. The following additional considerations argue against a thermal interpretation of burst spectra.

The assumption by Golenetskii *et al.* (1983) of thermalization throughout a burst may not be consistent with recent observations or theoretical arguments. Matz *et al.* (1985) have analyzed the GRS gamma-ray burst data base and found that hard spectra are a common characteristic of bursts. In general, GRS spectra are harder than either thermal bremsstrahlung or thermal synchrotron models. Furthermore, thermal synchrotron and bremsstrahlung cooling times are many orders of magnitude shorter than the observed pulse durations (Lamb 1982); thermalization on shorter time scales than the cooling times is not expected for conditions believed to exist in burst sources unless collisionless plasma processes are invoked (see Bussard 1984; Lamb 1984; Liang 1984).

The above considerations and the observed spectral softening of pulses above 100 keV appear to require one or more of the following: (1) a nonthermal particle injection spectrum, initially skewed toward high energy, which softens with time; (2) an energy reservoir which effectively sustains the lower energy emission; changes in physical parameters which affect radiation and energy losses, e.g., (3) mass movement of the emitting plasma to regions of lower magnetic field strength; or (4) explosive expansion with adiabatic and radiative energy losses. Sustained low-energy components ($E_{char} \gtrsim 10$ keV) on time scales longer than pulse durations, reported by Terrell *et al.* (1982) and Laros *et al.* (1984*a*), support requirement (2). An inflated turbulent photosphere, optically thick to X-rays, may be created during the initial outburst. Radiation from subsequent outbursts must then propagate through this atmosphere, resulting in a sustained X-ray glow. A possible example of this phenomenon is the 1983 August 1 burst, for which spectral coverage was available from 5 keV to 2 MeV (Laros *et al.* 1984*b*). Note, however, that softening of the harder gamma-ray emission for several pulses in a burst can be explained by mechanisms (1), (3), or (4).

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E. L. Chupp and S. M. Matz: Physics Department, University of New Hampshire, Durham, NH 03824-3568

T. L. Cline: Code 661, Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

B. R. Dennis and U. D. Desai: Code 682, Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

D. C. Messina: Sachs/Freeman Associates, Inc., Bowie, MD 20715

J. P. Norris: Code 4121.3, Naval Research Laboratory, Washington, DC 20375-5000

G. H. Share: Code 4152, Naval Research Laboratory, Washington, DC 20375-5000