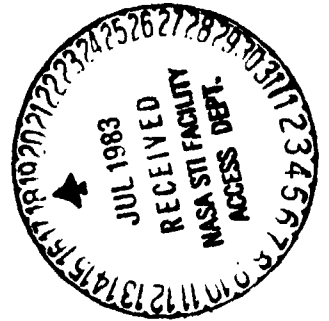




Technical Memorandum 85031

A STUDY OF THE TEMPORAL AND SPECTRAL CHARACTERISTICS OF GAMMA RAY BURSTS

(NASA-TM-85031) A STUDY OF THE TEMPORAL AND
SPECTRAL CHARACTERISTICS OF GAMMA RAY BURSTS
Ph.D. Thesis - Maryland Univ. (NASA) 279 p
HC A13/MF A01

N83-30350

CSCC 03B

Unclass

G3/93 28149

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MAY 1983

National Aeronautics and
Space Administration

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ABSTRACT

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Title of Dissertation: A Study of the Temporal and Spectral
Characteristics of Gamma Ray Bursts

Jay Preston Norris, Doctor of Philosophy, 1983

Dissertation directed by: Donat G. Wentzel,
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Gamma-ray burst data obtained from the ISEE-3 Gamma-Ray Burst Spectrometer and the Solar Maximum Mission's Hard X-Ray Burst Spectrometer (HXRBS) have been analyzed to yield information on burst temporal and spectral characteristics.

A Monte Carlo approach was used to simulate the HXRBS response to candidate spectral models. Energy-loss spectra of those bursts determined to be within the detector field-of-view were deconvolved to produce incident photon spectra. At energies above about 100 keV, the spectra are well fit by exponential forms. At lower energies, 30 keV to 60 keV, depressions below the model continua are apparent in some burst spectra. The depressions are not instrumental or data-reduction artifacts, but rather are an intrinsic property of the spectra. Both the depressions and the continua evolve on a time scale as short as $\sim 1/4$ second.

The event selection criterion of the ISEE-3 experiment is based on the time to accumulate a preset number of photons rather than the photon

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count per unit time and is consequently independent of event duration for a given burst intensity, unlike most conventional systems. As a result, a significantly greater percentage of fast, narrow events have been detected. The ratio of count rates from two ISEE-3 detectors indicates that bursts with durations $\lesssim$ one second have much softer spectra than longer bursts. These short bursts probably require a distinct mechanism to explain their occurrence. A few events exhibit temporal profiles with possible periodic structure.

The burst sources may be neutron stars with typical rotation periods greater than tens of seconds. Since burst durations are comparable to or less than such time scales, detectable periodicity due to source rotation should be infrequent, in agreement with observations. If burst sources are within a few hundred parsecs, as implied by the uniform distribution of localizations in galactic latitude and longitude, the emitting region is probably optically thin. The low-energy depressions are probably not absorption features. Rather, the appearance of depressions may be the result of integrating spectra for intervals longer than the time scale of a rapidly evolving cutoff in the synchrotron spectrum.

A STUDY OF THE TEMPORAL AND SPECTRAL CHARACTERISTICS
OF GAMMA RAY BURSTS

by

Jay Preston Norris

Dissertation submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
1983

To my parents

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to everyone who has in some way helped to make this thesis a reality, but the list is quite long. Among the principals to whom I owe my appreciation for supporting me are the following: Dr. Donat Wentzel, my advisor at the University of Maryland, for his expert guidance and proper sense of literary writing; Dr. Bonnard Teegarden, my advisor at Goddard, for introducing me to gamma-ray astronomy, for the opportunity to tackle the problem and for his advise on many topics; the Solar Maximum Mission investigators, Dr. Brian Dennis and Dr. Larry Orwig for access to the HXRBS spectral data and many discussions; Dr. Thomas L. Cline, who arranged the opportunity to analyze the HXRBS gamma-ray burst data and for many enjoyable discussions, not all of which pertained to astrophysics; Dr. Upendra Desai, for day-to-day advise and countless insights into the mysteries of gamma-ray bursts - without his suggestions many ideas would not have occurred to me; Dr. Upendra Desai and Dr. Graziella Pizzichini, who collaborated with me in the digitization of the KONUS spectra; Dr. Bill Paciesas and Dr. Jack Tueller for always answering my questions; Jenny Jacques, for her creative computer programming necessary for graphics manipulations and many of the illustrations; and Andrew Szymkowiak, whose expertise helped evaporate many computer problems.

I must also thank my friends for their support throughout the years, especially Luther Hartshorn, Connie Winn, and Nancy Brewrink, who also did the proof reading, and the graduate students at Goddard and Maryland. And finally I must thank my parents Dorothy and Bill Brooks, who made many things possible.

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CHAPTER I

INTRODUCTION

A. Province of Gamma-Ray Astronomy

The study of gamma-ray (γ -ray) astronomy is motivated by the direct connection between γ -rays and high-energy astrophysical processes. Mechanisms such as gravitational collapse, accretion onto compact objects, explosive processes, high-energy particle acceleration, nucleosynthesis, and matter-antimatter annihilation all produce γ -rays.

The usual demarcation between hard X-rays and low-energy γ -rays is $\sim 10^5$ eV. γ -rays from celestial objects have been detected at energies as high as 10^{11} eV (Fichtel and Trombka 1982). The list of identified γ -ray sources includes the sun, the moon, neutron stars, the interstellar medium, the galactic center, and active galactic nuclei. γ -rays have been predicted from black holes and from the newly synthesized radioactive species produced in supernovae explosions.

Cosmic γ -rays can be produced by a number of physical processes. Cosmic-ray electrons interacting with matter can produce bremsstrahlung radiation. Cosmic rays can also inverse Compton scatter with starlight photons producing γ -rays. Cosmic-ray - matter interactions can produce π^0 mesons which decay into two γ -rays with energy 68 MeV in the rest frame. These processes contribute to the diffuse galactic plane emission from about 10 keV to 10^3 MeV. Line radiation from nuclear transitions (~ 10 keV to several MeV) and positron-electron annihilation radiation has been observed from solar flares (Chupp et al. 1975; Chupp et al. 1981), and is predicted to be observable from the interstellar medium (Ramaty, Kozlovsky, and Lingenfelter 1979).

Annihilation radiation has also been detected from the galactic center region (Riegler et al. 1981) and possibly from γ -ray burst sources (Mazets et al. 1981e). The continuum spectrum of γ -ray bursts is probably dominated by synchrotron radiation produced by $\sim 10^9$ K plasma interacting with very strong magnetic fields, $\sim 10^{12}$ G.

Synchrotron and inverse Compton radiation from highly relativistic electrons are probably responsible for the emission from the nuclei of active galaxies. On a cosmological scale, the diffuse extragalactic γ -ray background may be due to the superposition of emission from active galaxies from distant epochs (Bignami et al. 1979), or alternatively, may be the remnant of matter-antimatter annihilation radiation at the boundaries of primordial superclusters (Brown and Stecker 1979).

1. Early History

In most fields of astronomy the tendency has been for observations to precede theory. In the adolescent discipline of γ -ray astronomy, however, the reverse usually has been true. While γ -ray detection techniques lagged, theory of astrophysical γ -ray production progressed. In particular, most theoretical developments relevant to high energy astrophysics of the interstellar medium were expounded before confirming observations were made. Feenberg and Primakoff (1948) discussed the effect of Compton scattering of low energy photons off high energy electrons. Hayakawa (1952) discussed the production of π^0 mesons, which decay into γ -rays, via the interaction of cosmic rays and interstellar gas. Hutchinson (1952) considered bremsstrahlung radiation from cosmic electrons. Morrison (1958) addressed several γ -ray processes applicable in astrophysical settings.

In one of the first γ -ray observations of a celestial object, Haymes et al. (1968) extended the previously known power-law spectrum of the Crab Nebula to ~ 500 keV. In the first detection of an astrophysical γ -ray line, Johnson, Harnden, and Haymes (1972) reported the observation of an emission feature at an energy of ~ 0.5 MeV from the direction of the galactic center. Jacobson et al. (1975) reported a γ -ray transient which lasted for about 20 min. Spectral lines at energies of 0.41, 1.79, 2.22, and 5.95 MeV were detected during the event. The first three were interpreted as the annihilation line and the deuterium formation line redshifted by a factor of 0.24, and the unshifted deuterium line, respectively. The 5.95 MeV feature is near the energy of an excited state of ^{16}O (6.12 MeV). No other (non-solar) γ -ray transients of such long duration have since been observed.

11. Recent Observational Discoveries

a. Diffuse Emission

At energies greater than a few MeV, the intergalactic medium is practically transparent; the total absorption for a path length through the universe is about 1%. Similarly, the galactic disk is transparent. Hence, the structure of the galaxy again becomes discernable in γ -rays as it is at radio frequencies. Recently, the galactic plane has been well mapped at high γ -ray energies (Hartman et al. 1979; Mayer-Hasselwander et al. 1980). The region $50^\circ > l^{\text{II}} > 310^\circ$ along the galactic plane is much more intense in high-energy γ -rays than would be expected if only atomic hydrogen were present in the inner galaxy. The excess is consistent with a higher proportion of molecular hydrogen in the inner 5 kpc (see Gordon and Burton 1976). Even when

spiral structure and radial density dependences are included in galactic models, an enhanced cosmic-ray flux, relative to the local flux, is probably required in order to reproduce the excess γ -ray flux in the inner region. Large scale features familiar in the radio and optical pictures, such as Gould's belt, the galactic disk warp, and concentrations in directions tangent to spiral arms, appear in the γ -ray picture as well (Fichtel and Trombka 1981).

In the energy regime 100 keV to 100 MeV a diffuse radiation is observed which is not galactic in origin. A correlation of galactic 21 cm radiation with high energy γ -rays as a function of latitude shows that the γ -ray intensity is nonzero for 21 cm radiation extrapolated to zero column density (Fichtel et al. 1978). Also, the differential spectral shape of the diffuse radiation above 1 MeV ($dN/dE \propto E^{-3}$) is much steeper than the galactic plane emission ($dN/dE \propto E^{-1.7}$). Among the several possible explanations for the extragalactic radiation are matter/antimatter annihilation in the context of a baryon symmetric big bang (Brown and Stecker 1979), and active galaxies (Bignami et al. 1979). The angular resolution of present observations is not good enough to distinguish between the predictions of various theories.

b. Point Sources

The sparse localized extragalactic γ -ray detections attest to the problems (not all of which are technological) in orbiting sufficiently sensitive instrument payloads. Some bright active galaxies have been detected: the radioactive galaxy Cen A; the Seyfert galaxy, NGC 4151; and the quasar 3C273.

Beyond the solar system, the first galactic compact object detected at γ -ray energies was the Crab pulsar (Brenning et al., 1971). Over a wide range in the X-ray/ γ -ray spectrum (10^4 to 10^{11} eV) the pulsed emission from the Crab is described by a power law, $dN/dE = 1.0 \times 10^{-2.1}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ (Fichtel and Matzka 1981). The total emission (nebular plus pulsed) is a factor of ten higher than the pulsed emission at 10 keV, however the pulsed emission dominates above 10 MeV. Vela X-1, a binary X-ray pulsar, has also been detected at γ -ray energies.

Several other persistent localized sources have been detected by the SAS-2 and COS-B satellites, including notably the strong source designated by its coordinates $(l, b)^{\text{II}} = 195 +5$. For many such sources detected at energies greater than 100 MeV (with positional uncertainties $\sim 2^\circ$), no counterparts are evident in other portions of the spectrum (Fichtel et al. 1975; Masnou et al. 1977).

Evidence for a time-varying localized source of annihilation radiation near the galactic center has been presented (Riegler et al. 1981). Refined 511-keV observations, when combined with galactic center results obtained in the radio and infrared regions of the spectrum (Riegler and Blandford 1982) should help determine the nature of processes at work in the core of the galaxy.

The active sun is also a source of γ -rays. The first observations of γ -ray spectral lines were made by the OSO-7 satellite in 1972 during two large solar flares. The transitory spectral features included: a 511-keV annihilation line, a 2.2-MeV line due to deuterium formation, and less statistically significant, 4.4-MeV and 6.1-MeV lines from collisionally excited ^{12}C and ^{16}O , respectively (Chupp et al. 1975). Recently, the Solar Maximum Mission (SMM), a satellite incorporating

coordinated solar instruments operating in the UV, X-ray, and γ -ray portions of the spectrum, has confirmed the presence of these features in solar flare spectra (Forrest et al. 1980; Chupp et al. 1981).

iii. Experimental Considerations

The measurement of γ -ray spectra is accomplished by detection of energy lost by the incident photon within the mass of the detector. When an individual γ -ray interacts, the photon energy is transferred to charged particles. In an ideal detector, the total charge produced would be collected and analyzed and would be proportional to the energy of the incident γ -ray photon. In reality not all photons encountering the detector interact, and for those which interact, the total energy of the photon may not be deposited in the detector.

The probability of absorption of a photon by a given interaction process is exponentially dependent on the path length, x , traversed within the detector material, $I(x)/I_0 = e^{-\mu x}$, where μ the absorption coefficient depends on energy and material. A photon may interact by one or more of three charge-producing processes. Photoelectric absorption, principally in the K shell, is the dominant mode of interaction below ~ 100 keV. The X-ray produced by the ensuing K-shell fluorescence then may also interact via the photoelectric effect in higher shells. The photoelectric absorption coefficient is proportional to Z^α with $\alpha \sim 4$ to 5 (Z = nuclear charge). Photoelectric absorption falls sharply with energy. Between ~ 100 keV and several MeV Compton scattering is the predominant interaction process. Compton scattering is proportional to the electron density and therefore to Z . The scattered photon, degraded in energy, then has a higher probability of

interacting via the photoelectric effect. Above $2m_e c^2$, electron-positron pair production becomes energetically possible. The cross section for this process, proportional to Z^2 , rises sharply, overtakes the falling Compton interaction at ~ 10 MeV, and flattens at higher energies. The positron may annihilate with an electron to produce two 511-keV photons which may then interact in the detector via the other processes.

At low to medium energies (~ 10 keV to ~ 10 MeV), two types of detectors are widely employed. Crystal scintillator detectors, usually NaI or CsI doped with Tl, convert electron-hole pairs produced in the γ -ray interaction into light. The light is collected and amplified by photomultiplier tubes (PMT's) and the resultant signal is registered by an analog-to-digital converter. Several factors determine the energy resolution of scintillator detectors: the intrinsic energy required to produce an electron-hole pair in the crystal material, the detector size, light collection technique, and PMT conversion statistics. Typical good energy resolution $[\Delta E(\text{FWHM})/E]$ is $\leq 10\%$ at ~ 1 MeV.

High purity Ge [Ge(HP)] detectors are replacing scintillators in some applications. Narrow astrophysical γ -ray lines (Ramaty, Kozlovsky, and Lingenfelter 1978) which may be observable with future instruments require resolution on the order of 1% or better. Ge(HP) detectors afford the resolution necessary to detect these lines. Two principal factors contribute to the improvement over the resolution of scintillators: (1) the required energy to produce an electron-hole pair in Ge is about 3 eV, compared to 300 eV required to make a photoelectron in a PMT, and (2) the charge is collected directly obviating the use of PMT's. A high voltage is applied to the electrodes on the Ge

crystal to collect the charge. The use of Ge(HP) (1 part impurity in 10^{13}) reduces the effect of trapping centers on the mobility of the charge carriers. To achieve optimum signal-to-noise, Ge(HP) must be cooled to liquid nitrogen temperatures. Currently, single Ge crystals are smaller than scintillators. Multiple Ge detector configurations are necessary to achieve sensitivities comparable to those of scintillator detectors.

γ -rays with energies of a few hundred keV may penetrate several cm of high Z material before being absorbed. In order to obtain directional information, detectors must be collimated with thick active or passive absorbing material. An active collimator configuration, composed of scintillator crystals operated in anticoincidence with the detector, allows rejection of detector events which also interact within the collimator.

Above about 10 MeV, pair production is the dominant interaction mode. Spark chambers exploit the fact that the pair continues in approximately the same direction as the incident γ -ray. A detector is typically constructed of several stacked grids of wires interleaved with thin high-Z plates. The plates serve two purposes: (1) to provide a medium in which the γ -ray annihilates, and (2) to measure the Coulomb scattering of the pair to obtain the incident γ -ray energy. The paths of the electron and positron are traced through the three dimensional lattice to also yield the direction of the incident γ -ray (Fichtel and Trombka 1981).

As is well known, the earth's atmosphere severely attenuates frequencies above $\sim 10^{16}$ Hz. Also, low celestial γ -ray fluxes and high ambient charged particle flux combined with scattered γ -radiation from

the earth's atmosphere (albedo) lead to a low signal-to-background ratio. This renders γ -ray observations generally very difficult, even at the top of the earth's atmosphere. In fact most γ -ray data are now derived from earth-orbiting or heliocentric satellites. Sometimes observing stations with large detector systems are carried aloft by balloon. Such experiments float at $\sim 25,000$ feet for about 1 day. Pointed balloon observations can achieve significantly better sensitivity than smaller satellite experiments.

For comprehensive treatises on the experimental situation, the reader is referred to two excellent texts, Adams and Dams (1970) and Fichtel and Trombka (1981). The detectors which provided the γ -ray burst data for this work are discussed in chapter II.

B. Gamma-Ray Bursts

In 1969 several short bursts of low energy γ -radiation were detected by the Vela 4 and 5 satellites (Klebesadel, Strong, and Olsen 1973). The Velas were intended to monitor the earth's surface and nearby space for violations of the 1963 Nuclear Test Ban Treaty. The nearly simultaneous recording of similar temporal structure by two or more Velas for a given burst insured that it was not an artifact of the detection systems. The Vela satellite sensors give quasi-omnidirectional coverage. In order to determine approximate burst directions, the differences in wavefront arrival times for pairs of satellites were analyzed ("triangulation"). The first source location error boxes were typically several degrees in extent, which sufficed to exclude the sun and planets as sources.

Succeeding generations of spacecraft have flown more sophisticated electronics and detectors, some tailored specifically for γ -ray burst detection. Many of these sensors were designed to record bursts with absolute timing precision to several milliseconds. Helios-B carried the first γ -ray burst sensor into solar orbit establishing a much longer baseline for triangulation than previous earth-orbiting satellites had provided (Cline and Desai 1976). In 1979 as many as 12 spacecraft with baselines extending up to ~ 1000 light-seconds were operating in a burst detection network. A few of the triangulated source location error boxes which resulted from the network are as small as a few square arcminutes. With the exception of the unique 5 MAR 79 event (see Cline 1980), no particularly outstanding radio, optical, or X-ray source (however, see section iii) has been found within or adjacent to the smaller error boxes (Laros et al. 1980; Cline et al. 1979a; 1979b; 1981).

Without associations with known objects, the nature of γ -ray bursts remains uncertain. However, their temporal and spectral characteristics appear to limit possible sources to compact stellar objects, most likely neutron stars within the galaxy. The galactic hypothesis is reinforced by the constraints implied by the distribution in galactic coordinates and the frequency of occurrence versus size relation ($\log[N(>S)] - \log[S]$). These attributes of γ -ray bursts are outlined below.

1. Temporal Characteristics

The temporal profiles ("time histories") of γ -ray bursts are usually characterized by apparently stochastically distributed pulses. The pulses have an explosive appearance with rapid rises and equally

sharp decays. When observed with very good time resolution, individual pulses manifest rapidly varying substructure on time scales down to the instrumental resolution limit (typically 10's of ms). The peaks of bright bursts are one to three orders of magnitude above the γ -ray background. Sometimes the intensity falls to the background level several times during a burst. In Table 1.1 characteristic time scales for bursts are listed. These time scales are much shorter than the corresponding ones for solar flares. For some bursts individual pulses exhibit a longer decay at low energies than at high energies. This spectral softening is addressed in section 11.

Some bursts are very brief. Their time histories consist of a single spike of duration less than 1 s. These short bursts almost always have very soft spectra. The short bursts may constitute a separate class (Mazets et al. 1981f), requiring a distinct mechanism to explain their occurrence.

Periodic behavior has been observed in at least one event. The famous 5 Mar 79 event exhibited an eight-second periodicity for ~ 22

Table 1.1

Characteristic Time Scales in Gamma-Ray Bursts

Total duration	0.1 - 100 s
Pulse duration	0.01 - 10 s
Pulse rise time	few ms - 1 s
Pulse decay time	few ms - 1 s
Quasi-periodicity	~ 0.1 - 15 s

cycles (Cline 1980). Another burst, 29 Oct 77, has been interpreted as displaying a 4.2 s period modulating an exponential decay (Wood et al. 1981). There have been other observed bursts with possible periodicities not lasting long enough for their periodicity to be definitely established (Loznikov and Kuznetsov 1982). Sometimes what may be periodic structure is dubious because the time history drops to background level for a few (apparent) pulse periods. Examples of aperiodic, quasi-periodic, and periodic time histories are illustrated in Figures 1.1 - 1.4.

11. Spectral Characteristics

The IMP 6 and 7 satellites provided the first γ -ray burst spectral data. Spectra integrated in time over an entire event were consistent with an exponential with characteristic energy 150 keV, and a power law tail above 400 keV to ~ 2 MeV with a photon index ~ -2.5 (Cline et al. 1973; Cline and Desai 1975). An equally good fit to the early burst data was obtained with two power laws with indices -1.0 and -2.5 , the spectral break occurring at 200 to 300 keV (Cline and Desai 1976).

Later experiments, some utilizing detectors with improved sensitivity, have shown that burst spectra not only vary during a given event (Nakano, Imhof, and Reagan 1976; Trombka et al. 1974; Metzger et al. 1974; Wheaton et al. 1973; Teegarden and Cline 1980; Dennis et al. 1981) but also vary from event to event. The most impressive evidence for this is contained within the KONUS catalog (Mazets et al. 1981a; b; and c - hereafter referred to as the KONUS catalog). For KONUS events which were intense enough to allow time sequences of spectra to be produced, the spectra usually soften with time. Sometimes the onsets of

individual pulses appear hardest with subsequent softening. There is a tendency for intense portions of a burst to exhibit harder spectra. Some bursts do not display any significant spectral evolution. Mazets and coinvestigators find that the spectra may be represented by a thermal bremsstrahlung form throughout the burst evolution (Mazets et al. 1981d).

In contrast, for several events detected by the SMM γ -ray spectrometer (Share et al. 1981) the event-averaged spectra from ~ 300 keV to 1 - 8 MeV have the appearance of power-laws. The published count-rate spectra are uncorrected for the instrumental response.

Although TTB appears to provide a good fit to the data it is not likely to be the actual emission mechanism. The arguments against it are as follows: First, if the KONUS features at ~ 50 keV are due to cyclotron absorption, the line formation occurs in a region with magnetic field strength $\sim 4 \times 10^{12}$ G, i.e., a region approximately the size of a neutron star. For the spectrum to remain optically thin to Compton scattering requires $\tau_{cs} < 1$. This constraint, combined with the emissivity for TTB (see eq. 3.5), the observed fluxes and the implied size of the source region, yields distances ~ 10 pc, probably an inadmissably short range to contain the burst sources (Fenimore et al. 1982a). Second, representation of the continuum as TTB is suspect in itself. Bussard and Lamb (1982) derived a required source area and depth in the ratio $> 10^3:1$ if the spectrum is generated by TTB. They remark that this geometry may be realized in thin sheets or filaments if the sources are not too distant ($\lesssim 100$ pc).

The ISEE-3 gamma-ray spectrometer was the first high-purity germanium high spectral resolution detector flown for astrophysical

observations. One of the first γ -ray bursts detected (19 NOV 78) with this instrument was found to have emission lines in its spectrum. The lines appear at energies of ~ 420 keV and 740 keV. They have been interpreted as the 511 keV electron-positron annihilation line and the 847 keV line caused by the first excited state of iron, both redshifted by $\sim 20\%$ (Teegarden and Cline 1980). The redshifted annihilation line (at ~ 420 keV) also has been observed in the spectra of several bursts by the KONUS experiment (Mazets et al. 1981e). There are no other likely candidate astrophysical γ -ray lines with rest energy ~ 420 keV. If the features are in fact due to annihilation radiation, it is an exciting discovery for stellar astrophysics. The percentage redshift for radiation emitted at the surface of a neutron star observed at infinity is approximately 20%. High spectral resolution detectors with increased sensitivity would be able to measure the position of this line more accurately; the corresponding redshift would directly yield the ratio of mass to radius of the neutron star.

In addition, the KONUS experiment has recorded bursts with absorption features (and in one case an emission feature) at energies ~ 30 to 70 keV in the spectra of several bursts (Mazets et al. 1981e). These features have been interpreted as "cyclotron" resonance lines. Cyclotron features have been observed in the spectra of the persistent source Her X-1 and other X-ray pulsars (Trumper et al. 1978; Tueller et al. 1981; Wheaton et al. 1979; Pravdo et al. 1979). The requirement of very high magnetic fields ($\sim 10^{12}$ G) for the production of cyclotron resonance features at these energies strengthens the case for neutron stars as the burst source objects. Usually the absorption feature evolves or disappears as the burst progresses (Mazets et al. 1981e),

however, bursts have been recorded which exhibit persistent "cyclotron" absorption features. A broad time-varying absorption feature was observed by SMM's HXRBS in the spectrum of the 19 APR 80 burst (Dennis et al. 1981). The burst lasted only about 4 s during which time the absorption feature and the spectrum as a whole continuously evolved. This event is analyzed in detail in Chapter V. Recently, another detection of a low-energy absorption feature in a γ -ray burst was reported (Gruber and Hueter 1982). The spectrum was accumulated over the 10 s duration of the event.

Fenimore et al. (1982a) have suggested that the KONUS low-energy features may be instrumental artifacts. Kirk and Trumper (1982) note several reasons why this is probably not the case: the central energies of the features vary from burst to burst (~ 30 to 70 keV); the spectra evolve with the feature usually disappearing at later stages; two spacecraft detect essentially the same spectra; and, most bursts do not display any features, only smooth continua.

It is also possible that several-second spectral accumulations obscure spectral evolution and/or produce illusory detail. For example, the 19 Nov 78 event spectra reported by Mazets et al. (1981a), for the initial 4 s, and by Teegarden and Cline (1980), for the initial part of the event (~ 3 s), exhibit continuous form down to ~ 20 keV and ~ 100 keV, the respective lower channel limits. Both also display emission features, the KONUS spectrum displaying a broad $300 - 800$ -keV feature with an equivalent width about ten times that of the narrower 420 -keV ISEE-3 feature (an adjacent, spectrally resolved feature at about 740 keV was also observed by ISEE-3, see above). However, the first two sequential ~ 1 s spectra for the same event reported by Vedrenne (1981)

exhibit low-energy turnovers at ~ 350 to 450 keV. In subsequent intervals, the spectra "unfold", becoming monotonically decreasing with energy. In this event the longer spectral accumulations may have produced the apparent broad emission feature near 400 keV. A spectrum with shape similar to the initial 4 s accumulation of Mazets et al.'s Figure 67 can be obtained by summing the spectra A, B, C of Vedrenne's Figure 5, corresponding to approximately the same time interval. The implications of the possibility of evolution of low-energy turnovers may extend to the absorption features as well. This problem is addressed in chapter VI.

Another potentially interesting form of spectral behavior was observed during the 19 APR 80 event. For ~ 10 s before and ~ 3 m after this event, SMM's γ -ray spectrometer detected soft emission (10 to 15 keV). Share et al. (1981) have suggested that the origin of this soft component may be solar.

Woosley (1982) predicts observable X-ray emission on a time scale of minutes subsequent to a γ -ray burst caused by helium detonation on a neutron star. Steady-state X-ray emission due to interstellar accretion onto neutron stars is also a consequence of this model. However, on the basis of X-ray observations by HEAO-2 (Helfand et al., 1980) some variations on the thermonuclear model for γ -ray bursts may be ruled out unless the source objects are more than 1 kpc distant (Ventura 1982).

111. Searches For γ -ray Bursts at Other Frequencies

Bursts have been detected at energies as low as ~ 5 keV (Metzger et al. 1974). Recently, a few bursts with spectra extending up to ~ 25 MeV were detected by the Gamma Ray Spectrometer experiment on SMM (Share et

al. 1983). There have been burst searches conducted in other regions of the spectrum. Lack of detections may rule out some burst models.

During a few Vela events, for which source localizations were performed, the relevant regions of the sky were coincidentally photographed by the Prairie Network (Grindlay et al. 1974), whose purpose is to assist in the recovery of meteorites. None of the gamma-ray bursts were detected, setting upper limits which preclude burst spectra with indices $\alpha > 2$ ($E^{-\alpha}$ photon $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$) continuing into the optical regime. Grindlay et al. remark that this spectral constraint implies the hard X-ray to optical flux ratio is ≥ 100 . This would appear to eliminate scaled-up solar flare type γ -ray burst models, for which the predicted flux ratio is < 1 (Stecker and Frost 1973).

The $1' \times 2'$ error box for 5 MAR 79 lies inside N49, a supernova remnant in the Large Magellanic Cloud at a distance of 55 kpc (Cline 1981). Observations with the HEAO-2 Einstein Observatory found no point source of X-rays within the remnant (Helfand and Long 1979). From the flux upper limit, a transient to steady-state X-ray ratio $> 10^9$ is derived, independent of distance. A nearby galactic neutron star accreting interstellar matter is probably ruled out as the source since steady-state X-rays would be observable. The great distance of the LMC would require a luminosity of $\geq 5 \times 10^{44}$ ergs s^{-1} for 5 MAR. Indeed, if γ -ray burst sources were extragalactic, and if the 5 MAR luminosity were representative of most bursts, the isotropic burst distribution (see section iv below) would indicate that N49 is a relatively close source. The vast majority of bursts would originate in the nearby galaxies and their luminosities would be $\geq 10^{51}$ ergs s^{-1} . It seems more feasible to consider 5 MAR as representative of a separate phenomenon,

albeit exceptionally powerful. In fact, Felton (1981) presented a convincing statistical argument in favor of the 5 MAR - N43 association, and also argued for the validity and sufficiency of convective transport for liberating $\sim 10^{44}$ erg in 0.1 s from a neutron star atmosphere.

There is an interesting piece of evidence that classical γ -ray bursts have optical and/or X-ray counterparts. On one plate in a series taken in 1928 (Harvard Patrol Plates), a transient image appears within the $8' \times 1.5'$ error box of the bright burst 19 NOV 78 (Shaefer 1981). Densitometer scans indicate that the image is not an artifact of the imaging system. Comparison with stellar images on the same plate, which are slightly trailed, imply the duration of light that caused the image was significantly shorter than the total exposure time. A possible persistent optical counterpart to the 19 NOV 78 burst which is variable ($\geq 23^{\text{rd}}$ mag) has been identified (Shaefer 1981; 1983). Also, a persistent X-ray source whose position coincides with the 1928 optical image has been found by the HEAO-2 Einstein Observatory. The implied recurrence time (~ 50 yr), ratio of optical to X-ray luminosities, and optical variability are interpreted as being consistent with episodic accretion onto a neutron star at a distance of ~ 1 kpc (Grindlay et al. 1982).

There is further evidence for sources repeating on a time scale of days to months. Following the 5 MAR 79 event, three events occurred (6 MAR, 4 APR, 24 APR) which were coarsely localized by the KONUS experiment (Mazets et al. 1981f). These four events have error boxes which are mutually consistent with one source. Disregarding the relatively low-amplitude oscillating portion of the 5 MAR event, all four event durations were ≤ 1 s. The spectra were unusually soft

compared to the spectra of "classical" γ -ray bursts (longer duration events displaying complex temporal profiles). Thermal bremsstrahlung fits with $kT \sim 35$ keV were obtained for all four events. The total fluence ratios (450:6.5:0.7:0.6) and intervals between events (14 hr, 29 d, 20 d) suggest a relaxation mechanism.

The KONUS Venera 11 and 12 sensors ceased operation in January 1980. A second pair of KONUS burst experiments was launched on Venera 13 and 14 in November 1981. Eight more fast events, which can be grouped into two 3- and 5- event series, with fluences, spectra, and intervals between occurrence similar to the three events following 5 MAR, were detected by KONUS 13 and 14 (see Table A.3). The intersection of the twelve $\sim 10^\circ \times 0.03^\circ$ localizations is consistent with the 5 MAR source position reported by Cline et al. (1982). Several other fast, spike-like events were detected by KONUS 13 and 14 (Mazets, private communication). This apparently separate class of repeating, spike-like, soft γ -ray bursts is discussed in chapters IV and VI.

Another series of events (24 MAR, 25 MAR, 27 MAR 79) detected by the KONUS experiment have error boxes consistent with a single-source. The event durations and spectra are very similar to the 5 MAR series.

A posteriori searches of data records for coinciding bursts at radio frequencies have been conducted with negative results (Baird et al. 1975; 1976; Ciapi et al. 1979). Upper limits to fluxes of $\sim 10^{-12}$ to 10^{-13} erg cm $^{-2}$ s $^{-1}$ MHz $^{-1}$ imply that less than 10^{-6} - 10^{-10} of an estimated 10^{39} - 10^{41} ergs/burst (Fishman's luminosity estimate, 1978) is emitted at microwave frequencies. This argues against stellar flare mechanisms since in these models γ -ray and radio emission are expected to be associated (Stecker and Frost 1973; Bai and Ramaty 1976).

Searches for coincident bursts at energies > 10 GeV were also being performed during the Vela period (O'Brien and Porter, 1976; Bhat et al., 1979; Fegan et al., 1979). All produced negative results. Not only were one-source localizations for several Vela events undetected (Fegan et al.), but no bursts of gamma radiation of short duration (> 10 ms, < 1 s) have ever been observed during several years of monitoring at GeV energies. If one assumes a burst energy spectrum above 400 KeV proportional to $E^{-2.5}$, a large burst ($\sim 10^{-4}$ erg cm^{-2}) is about two orders of magnitude too small to be detected at energies greater than ~ 1 GeV by any of the above mentioned experiments. Hence, the upper limits constrain only those models which predict bursts at those energies (e.g. evaporating primordial black holes) and not traditional gamma-ray bursts.

iv. Constraints on γ -ray Burst Sources

An important constraint on burst sources is the maximum size of the emitting region implied by the short temporal variations observed in the time histories. Statistically significant flux variations are typically observed to be as short as the instrumental limits. The shortest flux variations so far observed ($\tau \sim 5$ ms) imply an emitting region $l \sim ct \lesssim 1500$ kilometers. The emitting region may be a small area (hot spot) of the total surface of the source.

Photons with energies above several MeV have been observed in γ -ray bursts. According to an argument by Schmidt (1978), lack of a cutoff in burst spectra above ~ 1 MeV requires the source to remain optically thin to $\gamma\gamma$ pair production; i.e., the photon density must not exceed a critical value. The upper limit on source sizes therefore limits the

luminosity $L = 4\pi d^2 F$ (d = distance, F = observed flux) and hence the distance. Schmidt calculated a limiting distance of ~ 2 kpc for fluxes $\sim 10^{-4}$ erg cm $^{-2}$ assuming an emitting region $\sim 10^4$ km. This argument is not conclusive. The implications of pair production in dense photon fields may represent more a limitation on the details of burst evolution and therefore spectral shape than on source size. In fact, Herterich (1974) noted that $\gamma\gamma$ pair production would be followed by pair annihilation, anticipating the observation of annihilation radiation in gamma-ray bursts. In addition, there are of course other viable mechanisms for pair production. Also, Schmidt's argument may be mitigated by a radiative transfer argument presented by Katz (1982) which proposes that annihilation radiation may escape from a plasma optically thick to $\gamma\gamma$ pair production through angle and frequency window.

The frequency of occurrence versus size distribution, $\log[N(>S)] - \log[S]$, distinguishes, in principle, between geometrical distributions of sources. An isotropic and homogeneous three dimensional distribution is reflected in an $N \propto S^{-\alpha}$ law with $\alpha = 1.5$. An homogeneous planar distribution results in $\alpha = 1.0$. Hence, the $\log[N(>S)] - \log[S]$ relation may be used to distinguish between halo and disk source distributions. Fishman (1979) computed an array of variations on the isotropic, homogeneous case using a Monte Carlo code. Realistic parameters are incorporated including burst distribution scale heights for galactocentric coordinates z and r , spiral arm structure and termination of the distributions at a galactocentric radius of 15 kpc. Jennings (1982) incorporated intrinsic luminosity distributions in disk and halo models.

In Figure 1.5 most observations are plotted for comparison with representative disk and halo models (Jennings 1982). In fact, since one does not know a priori if there is a range in burst luminosities, the present observations only constrain the burst sources to a galactic distribution. Further sensitive observations are required at low fluences in order for a $\log[N(>S)] - \log[S]$ analysis to distinguish between a high luminosity halo population or low luminosity disk population.

The KONUS experiment, flown on the Veneras 11 and 12, was capable of source localization to within a few degrees. The Vela and IMP satellites and the Venera KONUS experiment combined account for about 85 coarse source localizations. A plot in galactic coordinates of all uniquely localized γ -ray bursts is illustrated in Figure A.1. There does not appear to be a concentration of sources towards the region of the galactic center. An excess of sources near $b^{\text{II}} = 15^\circ$ is evident. In Figure A.2 a histogram of $\sin(b^{\text{II}})$ versus number of sources (unique localizations) makes this more apparent. In fact this excess may be attributable to a nonuniformity in the KONUS directional sensitivity (Larson et al. 1982). The consequent isotropic distribution may be the result of at least two possible galactic configurations: 1) present instruments sample nearby burst sources from a low-luminosity disk-shaped population (sensitivity limited), or 2) the instruments see a large portion of a high-luminosity halo population. If the second possibility were the case, a center/anticenter bias should be apparent. In Figure A.3 a histogram of bursts in longitude is shown: no center excess is observed. Hence the observed bursts are probably produced by sources within the galactic disk.

The phenomenon most similar to the γ -ray burst is the X-ray burst. X-ray bursts exhibit durations of seconds to minutes, which suggests a relationship to γ -ray bursts. However, the X-ray bursts (Lewin and Joss 1981) and γ -ray bursts are definitely not associated individually or as a class. X-ray bursts tend to be repeaters and in some cases are identified with persistent X-ray sources and/or blue stellar objects. Currently, γ -ray bursts, other than the spike-like class of bursts exemplified by the 5 MAR 79 event, are not known to repeat nor do positive identifications of any kind exist presently. The X-ray bursters cluster around the galactic center with $b^{\text{II}} \lesssim 35^\circ$. The γ -ray burst distribution appears isotropic. γ -ray bursts exhibit much harder spectra than do X-ray bursts (Lewin and Joss 1981; Wheaton et al. 1973; Trombka et al. 1974). Blackbody fits with temperatures of a few keV are found for X-ray bursters (Swank 1977; Hoffman 1977) whereas characteristic energies for gamma-ray bursts are ~ 150 keV. A comparison of total X-ray burst flux to total γ -ray burst flux, for a typical γ -ray burst extrapolated to soft X-ray energies (Evans et al. 1976), shows X-ray bursts to be too faint by a factor of 100 to be the same phenomenon as γ -ray bursts. Even if the two kinds of bursts originate from similar objects, the conditions of burst generation or occurrence must be quite different.

C. Gamma-Ray Burst Models and Astrophysics

It is important to distinguish between the cause(s) of γ -ray bursts and the ensuing observable event. While it is possible to improve detector spectral resolution and sensitivity and thereby derive more information from burst observations, determining the cause of bursts

from these observations may be difficult. This inherent difficulty is reflected in the variety of speculations advanced to explain γ -ray burst characteristics. Part of the problem is the present state of knowledge of neutron star physics. On the other hand, intense magnetic and gravitational fields at the surface of neutron stars may camouflage otherwise observable characteristics which are specific to certain burst scenarios.

1. Radiation Mechanisms

The γ -ray burst phenomenon has been part of the motivation for recent theoretical developments in astrophysical high-energy plasmas. The familiar problem of radiative transfer becomes rather complex in the context of strongly magnetized neutron stars.

The spectral fits assuming thin thermal bremsstrahlung published in the KONUS catalog did not incorporate a gaunt factor. Gould (1980) has published relativistic corrections (applicable at 10^7 to 10^9 K) to the bremsstrahlung gaunt factor. Inclusion of the gaunt factor significantly increases the spectral temperatures of Mazets et al. (1981d). The deduced higher temperatures exacerbate the discrepancy with the low temperatures implied by the narrow widths of the cyclotron absorption lines.

Several authors have pointed out that synchrotron emissivity exceeds bremsstrahlung emissivity in a magnetic field of $\sim 10^{12}$ G if the electron density is less than $\sim 10^{31} \text{ cm}^{-3}$ (Gould 1982; Lamb 1982; Liang 1982). Recently, Petrosian (1981) derived a simple expression for the synchrotron emissivity of a thermal distribution of electrons ($kT \leq$

$m_e c^2$). Liang (1982) has successfully utilized this function to fit γ -ray burst spectra from the KONUS catalog and from other experiments.

The appearance of absorption features in X-ray pulsar spectra (Kirk and Trumper 1982) and possibly both absorption and emission features in γ -ray burst spectra has spurred development of self-consistent radiative transfer theory of strongly magnetized neutron stars (Meszaros, Nagel, and Ventura 1980; Nagel 1981). The effects of hot plasmas and strong magnetic fields on annihilation spectra have also recently been developed. For the 5 MAR 79 burst, the very high luminosity and interpretation of the emission feature as redshifted annihilation radiation constrain the temperature of the annihilation region. The observed widths of the 400 to 450 keV features would require that the pairs are cooled by synchrotron emission to $\lesssim 3 \times 10^8$ K before annihilating (Ramaty and Meszaros 1981).

Benimore et al. (1982b; c) have proposed a radiative transfer mechanism for γ -ray bursts which does not require a strong magnetic field. An X-ray burst is inverse Compton scattered by an overlying hot plasma of mildly relativistic temperature to produce the observed γ -ray spectrum. The origin of the suspended hot plasma is unspecified.

The time-dependent Compton problem has been studied by Guilbert, Fabian, and Ross (1982). Their model spectra, which can be described by quasi-power-laws with exponential-tails, are similar to the Monte Carlo results of Pozdnyakov, Sobol and Syunyaev (1977). The time-dependent treatment indicates that, because of cooling, Wien peaks in the spectra are not produced even for large optical depths.

ii. Gamma-Ray Burst Scenarios

The minimum requirements for plausible burst models (Ruderman 1975) would appear to be the following: 1) source objects within a few $\times 100$ pc, 2) total energy release $E \sim 10^{37}(d/100 \text{ pc})^2$ ergs, 3) characteristic photon energies ~ 150 keV (with spectra continuing in some cases to ~ 10 MeV), and 4) fast temporal variations. The characteristic dynamic and cooling time scales near the surfaces of a neutron star are faster than observed temporal variations. Consequently, a common problem of neutron star models is explaining the total event durations of several seconds. In addition to Ruderman's requisites, Lamb (1982) emphasizes the implication of optical depth. If the emission region is optically thin, energy regeneration or matter replenishment during the event is necessary. Also, Lamb reminds us that event durations and (bremsstrahlung) spectral temperatures both have dynamic ranges greater than 10^3 . These large variations in fundamental attributes may indicate that more than one mechanism is responsible for generating γ -ray bursts. Additional constraints must be met by models proposed to explain the 5 Mr 79 burst, since this source repeats on a time scale of ~ 1 day to months.

Ruderman's (1975) review of γ -ray burst models lists many combinations of high-energy producing processes occurring on or near stellar objects.

The interpretation of features in burst spectra as cyclotron and annihilation lines has narrowed attention to scenarios involving neutron stars. These can be grouped into several generic classes: thermonuclear explosions (Woosley and Taam 1976; Tsygan 1980; Woosley 1982), episodic accretion of gaseous matter (Lamb, Lamb, and Pines 1973), accretion of

asteroids or comets (Newman and Cox 1980; Van Buren 1981; Colgate and Petschek 1981), neutron star quakes or glitches (Pacini and Ruderman 1974; Tsygan 1975; Fabian, Icke and Pringle 1975), and magnetic instabilities in pulsar magnetospheres (Pacini and Ruderman 1974). A major motivation for many later models has been the modelling of impulsive bursts like 5 MAR 79. I shall describe the main attributes of two representative models.

The thermonuclear model (Woosley 1982) involves the accretion ($\sim 10^{-13} M_{\odot} \text{ yr}^{-1} \text{ km}^{-2}$) and steady burning of 10^{20} to $10^{22} \text{ g km}^{-2}$ of hydrogen into helium. A strong magnetic field ($\sim 10^{12} \text{ G}$) focuses the accretion flow onto the polar caps and restrains the accreted material from diffusing across field lines above and below the surface. A detonation wave or convective deflagration front propagates across the helium lake fusing the matter up to ^{56}Ni and releasing 10^{38} to $10^{40} \text{ erg km}^{-2}$ in a γ -ray burst. The model differs from thermonuclear X-ray burst models in that helium is the fuel rather than hydrogen and that the total energy released is much greater. The duration depends upon the mechanism of propagation: about 0.1 ms for a detonation wave or 10's of seconds for convective deflagration. Recurrence times, which depend on variations in model parameters, range from less than a year (deflagration model) to $\sim 10^3$ years (detonation model). This model predicts an observable steady-state X-ray source resulting from the accretion flow (these two models are discussed in chapter VI in connection with short and long duration bursts).

Ventura (1982) maintains that, because Woosley neglects both cooling through the neutron star and the effect of magnetic opacity, the required temperature for CNO-mediated burning of hydrogen is not

achieved. Furthermore, Ventura points out that IPC X-ray observations (Helfand et al. 1980) of γ -ray burst error boxes have yielded results inconsistent with Woosley's models unless sources are at distances ≥ 1 kpc. Ventura postulates a binary system evolutionary sequence in which a low-luminosity (originally $0.1 M_{\odot}$) companion star, presently undetectable ($d \sim 300$ pc), slows the neutron star rotation by mass exchange. The system eventually becomes unbound. The advantages of this scenario are that more efficient gaseous accretion is possible due to slower rotation (typical pulsar rotation rates result in the magnetosphere repelling accreting matter at the Alfvén surface, Illarionov and Syunyaev 1975), and normal stellar space velocities are envisaged (as opposed to runaway supernova-generated pulsar velocities). The slower interstellar accretion rates result in unobservable X-ray sources and much longer recurrence times.

The asteroid-accreting neutron star model of Colgate and Petschek (1981) is intended to explain the 5 Mar 79 event. In this scenario a solid body of $\sim 10^{18}$ gm impacts on a strongly magnetic neutron star. The body is initially elongated and then tidally broken up in its fall toward the neutron star. The magnetic field compresses the material in longitude and allows expansion in latitude so that upon impact the cross section is ~ 1 cm $\times$ few km. The ensuing collision is predicted to result in an observable turbulent plume interaction. The impulsive peak and subsequent ~ 3 min oscillation phase of the 5 Mar 79 burst both require the radiating plasma to be magnetically entrained. Without a strong magnetic field, the accreted material would expand and cool and no γ -ray burst would be produced. The total energy released, $\sim 10^{38}$

ergs, places the source at a distance of only 100 pc, rather than at 55 kpc in the LMC.

The probability of asteroid capture by high-velocity neutron stars is probably insufficient to explain the observed frequency of γ -ray bursts. However, the capture cross-section is significantly increased for stars possessing $\sim 10^{12}$ G fields (Van Buren 1981). Ventura's (1982) arrangement (see above) would increase the probability of capture of asteroids or comets whose orbits are perturbed by the companion star.

D. Present Work

γ -ray burst spectra from SMM's Hard X-Ray Burst Spectrometer (HXRBS) and time histories from the ISEE-3 Teegarden experiment were made available to the author. The instrumentation for these experiments is described in chapter II and the methods of analysis are presented in chapter III.

In chapter IV the ISEE-3 time histories are analyzed. From the ratios of the count rates of two ISEE-3 detectors with different energy thresholds it was possible to calculate hardness indices as a function of time for some events. A tendency for some bursts to exhibit hard-to-soft spectral evolution was found.

The time histories were examined for periodicities. A few ISEE-3 bursts with relatively long durations exhibit possibly periodic structure. It has been suggested that the reason periodicities are infrequently observed in burst time histories is that most burst durations are shorter than the source rotation periods (Wood et al. 1981).

The ISEE-3 data base contains a much larger fraction of short duration (≤ 1 s) spike-like events than do previous experiments. Estimates of the spectral hardness of these events were obtained by calculating the ratios of the peak counting rates of the two ISEE-3 detectors. These events are similar temporally and spectrally to the very intense 5 MAR 79 burst and other KONUS spike-like bursts. Probability analysis and comparison of ISEE-3's unique burst triggering mechanism with conventional experiments (KONUS) indicates that the ISEE-3 data base more accurately represents the true proportion of spike-like bursts ($\sim 33\%$) than do previous experiments.

In chapter V the HXRBS spectral analysis is presented. Only events which were observed close enough to the center of the detector field-of-view for the shield-processed contribution to be negligible were analyzed in detail. Three relatively large events met this criterion, the bursts of 19 APR 80, 21 APR 80, and 01 MAR 81. In the April events, depressions below an exponential model continuum are evident at energies ~ 40 to 60 keV.

Three spectral forms are found to fit the data equally satisfactorily in some cases: thin thermal bremsstrahlung, thin thermal synchrotron, and power-law with exponential tail. Determination of the correct radiative mechanism(s) cannot be made from the fitting analysis alone with existing observations.

For the thermal bremsstrahlung and thermal synchrotron models, inclusion of broad low-energy absorption lines is required for some spectral intervals in order to adequately fit the low-energy portions of the spectra.

For the 19 APR 80 event (~ 4 s duration), both the continuum and the low-energy depression evolve on a time scale $\sim 1/4$ s. The event as a whole exhibits hard-to-soft evolution. A tendency for the rising portion of pulses to be spectrally harder than the decaying portions is found. The 21 APR 80 event (~ 20 s duration) exhibits soft-to-hard evolution. The low-energy depression persists throughout the event.

In chapter VI a self-consistent interpretation of the results of this work combined with the discoveries of previous investigations is attempted. From the available evidence, it is concluded that the sources of spike-like and the longer "classical" γ -ray bursts are probably slowly rotating neutron stars located at distances of a few hundred parsecs. However, the burst mechanisms for the two classes of bursts probably differ. Thermal synchrotron radiation is shown to be the most self-consistent and viable energy-loss process for γ -ray bursts.

The reality of absorption features is examined. The possibility of explaining these features as artifacts of spectral evolution due to 1) low-energy synchrotron cutoffs, or 2) source self-absorption is discussed. If the burst sources are within a few hundred parsecs, then the source region is optically thin, and the low-energy features may be the result of accumulating spectra for intervals longer than the time scale of rapidly evolving low-energy cutoffs.

The most extensive γ -ray burst data base available is the published results from the KONUS experiment. Event durations and peak intensities were measured from the KONUS catalog. Also, thermal bremsstrahlung and thermal synchrotron models were fit to the spectral data. These data are assembled in Appendix I for reference in the main text.

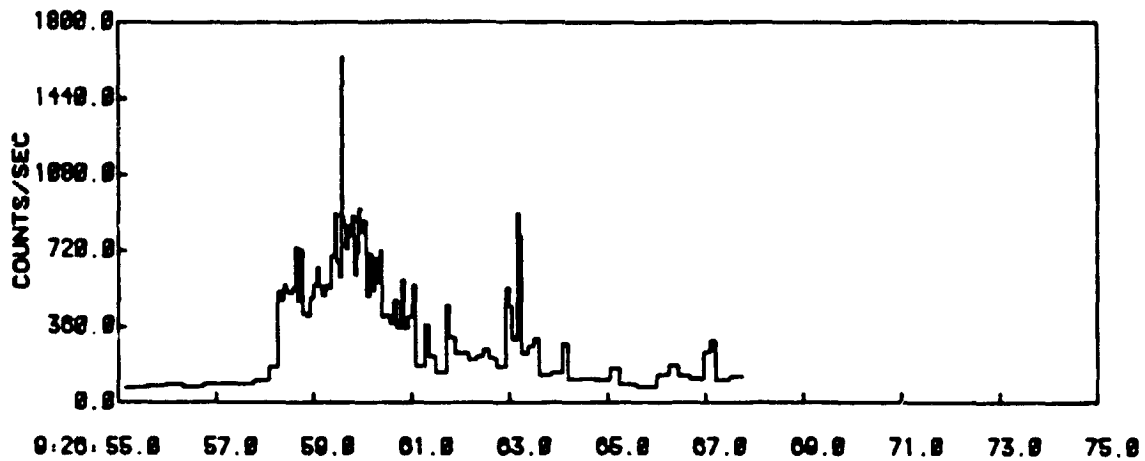


FIG. 1.1 NV1978.TH2

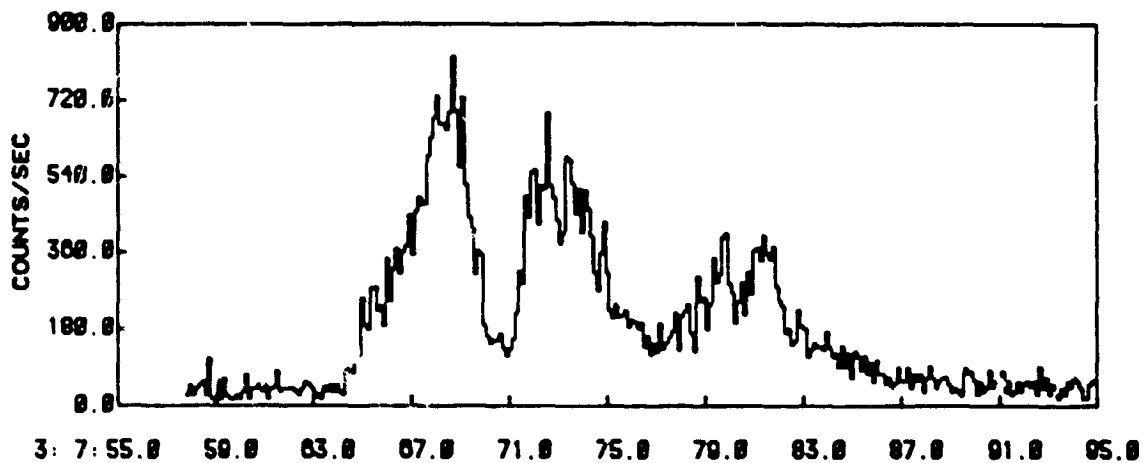


FIG. 1.2 AP2180.SMM

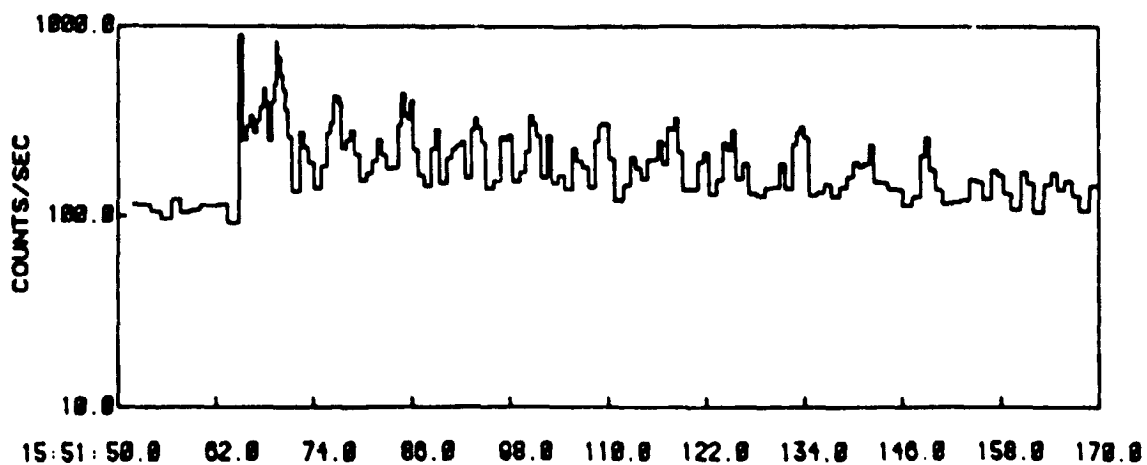


FIG. 1.3 MR0579.TH1

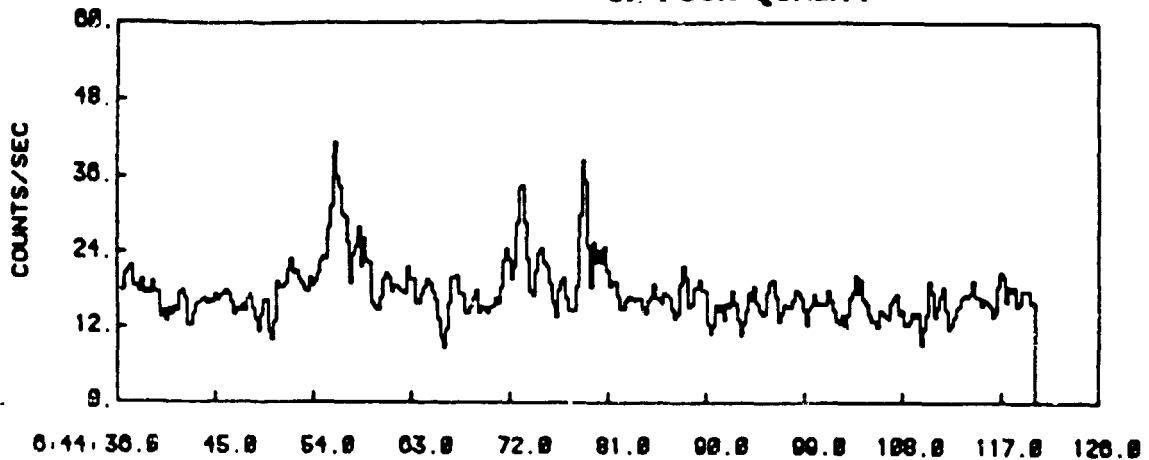


FIG. 1.4 JA1379.HLB

Fig. 1.1. Example of aperiodic temporal structure (19 NOV 78 event), characteristic of many gamma-ray bursts. ISEE-3 Ge detector.

Fig. 1.2. Example of quasi-periodic structure (21 A R 80 event). The quasi-period for three cycles is ≈ 6.5 seconds. HXRBS detector.

Fig. 1.3. The famous 5 MAR 79 burst. The initial peak, $\sim 6 \times 10^4$ cts/s, is truncated to emphasize the 8.0-second oscillating decay, discernable for > 22 cycles (Cline 1980). ISEE-3 Hovestadt CsI detector.

Fig. 1.4. Burst displaying a temporal profile suggestive of periodic structure (13 JAN 79 event). A double-peaked pattern with 5.5-second period is evident. A running average of 5 (1/4 s) points has been performed. Courtesy of U. D. Desai. Helios-B detector.

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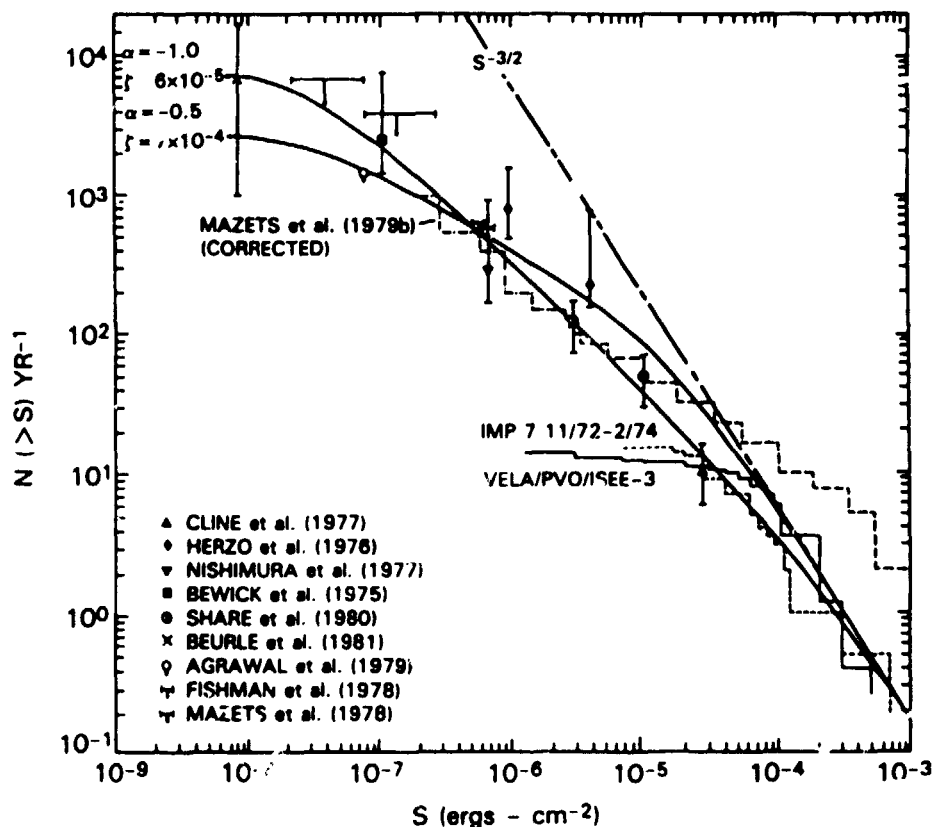


Fig. 1.5. The $\log N(>S) - \log(S)$ curve for gamma-ray bursts. Several balloon observations, the KONUS (Mazets et al. 1979b), IMP 7, and Vela/PVO/ISEE-3 curves are compared with two of Jennings's (1982) model source distributions limited to the galactic disk. The models have a range in intrinsic luminosity described by $n(L) = \alpha(1 - \zeta^\alpha)^{-1} L^{\alpha-1}$ where $n(L)$ is the number of bursts $\text{pc}^{-3}\text{yr}^{-1}\text{ergs}^{-1}$ and L is the integrated burst luminosity. α and ζ govern the luminosity distribution shape and width, respectively. The discrepancy at high S between the KONUS and other experimental curves is discussed by Jennings (1982).

CHAPTER II

INSTRUMENTATION

A. General Remarks

The γ -ray burst data analyzed in this work are derived from experiments on two satellites. The first, the Teegarden ISEE-3 (Third International Sun-Earth Explorer) Gamma-Ray Burst Spectrometer, provided temporal information from two detectors. These "time histories" are useful in analyzing the characteristic structure of individual pulses within a burst, revealing dynamical and dimensional constraints of source objects. Also, for bursts observed in common with other experiments, the time histories may be used to localize source directions by the method of wavefront-arrival-time analysis ("triangulation"). The second, Solar Maximum Mission's (SMM) Hard X-Ray Burst Spectrometer (HXRBS) provided temporal and spectral information for γ -ray bursts occurring within the detector field-of-view.

The relevant details of the instrumentation and operation of these two experiments are described in this chapter. In addition the KONUS experiment (aboard the spacecraft Venera 11 - 14) is outlined since several properties of γ -ray bursts are investigated using data published by the KONUS experimenters.

B. The ISEE-3 Detectors

The ISEE-3 satellite was launched in August 1978 and guided into a halo orbit about the Lagrangian point on the sunward side of the earth-sun line. The distance to the spacecraft is approximately 0.01 A.U., 230 earth radii, 1.5×10^6 km, or 4.9 light-seconds. The location is particularly advantageous for γ -ray observations; the time-varying

exposure to trapped particle radiation within the magnetosphere and the earth-albedo problem are completely avoided. The light-travel time to the earth affords γ -ray burst localization in conjunction with earth-orbiting stations with accuracies $\sim (\Delta t/4.9)$ radians, where Δt (s) is the finest temporal feature of high statistical weight within the burst. The spacecraft is spin-stabilized with a period of about 3 s. The spin axis is aligned with the ecliptic poles.

The Teegarden experiment (Teegarden et al. 1978) is a "piggyback" to the Hovestadt Low-energy Charged Particle experiment. The intended purpose of the γ -ray burst experiment was to search for narrow γ -ray lines in γ -ray bursts. For two events spectral information was recorded (Teegarden and Cline 1980). Subsequently, an electronic malfunction rendered the spectral memory inoperative. The time history memories were unaffected.

Primarily, three detectors contributed to the Teegarden experiment. One high-purity Ge and one CsI scintillator detector continue to operate. A second CsI detector, the shield for a particle detector experiment, was found to be too sensitive to charged particles. Due to the detector's large effective area, single high-energy particles very frequently impinged on the detector. The resulting light scintillations were large enough to frequently trigger the burst recording electronics, simulating true spike-like events. The detector was therefore not used in collection of data.

1. The Germanium Detector

The Ge spectrometer is recessed within the lower body of the spacecraft (Figure 2.1). Its axis is approximately aligned with the

spacecraft spin axis. The detector is housed within two nested radiatively-cooled stages (Figure 2.2). The cooler stages were designed so that as the detector progressed to thermal equilibrium, the inner and outer stages separated leaving the inner stage and sensor thermally isolated from the spacecraft. The outer stage is conically shaped to define a 126° (thermal) field-of-view for the inner stage. The field-of-view does not contain the sun, earth, or any significant portion of the spacecraft. The inner stage was predicted to reach an equilibrium temperature of 100 K whereas the actual operating temperature is about 130 K.

The spectrometer was the first high resolution Ge detector dedicated to astrophysical observations to be flown on a satellite. The crystal is relatively small compared to scintillators. However, in principle, the use of high-purity germanium (1 part in 10^{13} impurities) permits the attainment of unprecedented energy resolution at γ -ray energies (~ 3 keV at 1 MeV). The detector crystal is p-type co-axial high-purity germanium, 4 cm diameter $\times$ 3 cm depth, with an active volume of 33 cm^3 . The crystal possesses a dead layer of approximately uniform thickness, 0.7 mm, (cf. Figure 3.3, Chapter III). The dead layer is necessary to make electrical contact to the crystal. γ -rays with energies less than ~ 70 keV interact within this outermost portion of the crystal, and are not detected. An electric field bias applied to the crystal does not pervade the dead layer; hence, the charged photoionization by-products of the γ -ray interaction are not collected from the dead layer. The lower and upper energy thresholds for analysis of an energy deposition event are adjustable by command. The thresholds

for the Ge detector have been ~ 105 keV and ~ 6.5 MeV, respectively, during most of the lifetime of the experiment.

Although the ISEE-3 spectral information is no longer transmitted, it is of general interest to note the history of the detector energy resolution. In section B.iii of this chapter the background and trigger modes of operation are described. In the background mode, pulse height analysis (PHA) data were collected in order to obtain upper limits on the variability of the cosmic 511-keV flux (Norris, Cline, and Teegarden 1982). To measure the line flux it was necessary to know both the channel/energy (gain) relationship and energy resolution as a function of time. An onboard ^{207}Bi source provided two calibration lines at 570 and 1064 keV. In a plot of the width of the 570 keV line versus time (Figure 2.3), significant deterioration of the resolution is seen to have occurred in the first 600 days of operation. The 570 keV line broadened from an initial ~ 8 keV to ~ 50 keV (the predicted operating temperature, and corresponding optimum resolution of 3.5 keV, were never reached). The relative magnitudes of the gain and resolution changes observed are consistent with a decreasing charge collection efficiency, evidently caused by detector radiation damage from high-energy charged particles and fast neutrons.

The position and alignment of the Ge detector make it particularly suitable for recording γ -ray burst time histories on a spinning platform. At energies greater than 100 keV, the effect of spin modulation is negligible for bursts arriving from the southern ecliptic hemisphere; the cooler stages and spacecraft well into which the spectrometer is recessed are virtually transparent (Figure 2.1). For

arrival directions from the northern ecliptic hemisphere the spacecraft mass attenuates the burst flux significantly.

For a detailed treatment of γ -ray detection systems, see Applied Gamma-Ray Spectrometry (Adams and Dams 1970). For a complete description of radiations interacting with matter the reader is referred to Nuclei and Particles (Segre 1977). In Chapter III the details of simulating the geometrical configuration and physics of the Ge and HXRBS detectors by the Monte Carlo technique are discussed.

ii. The Cesium Iodide Detector

The operational CsI detector was designed and incorporated into the spacecraft by the collaborating Max Planck Institute (MPI) group. The 3.65 cm diameter $\times$ 1.98 cm depth crystal (Figure 2.4) is viewed by a PMT (photomultiplier tube). The PMT collects the scintillation light from by-products of the γ -ray interaction in the crystal. The MPI scintillator was intended only to record the time histories of γ -ray bursts. The energy resolution of scintillators is much worse than that of high-purity Ge detectors ($\Delta E/E$ at 100 keV is typically 0.15 - 0.18 for a small crystal).

The low and high energy thresholds for the CsI detector are ~ 70 keV and ~ 1 MeV, respectively. The CsI detector is therefore sensitive to the hard X-ray photons from 70 to 105 keV to which the Ge electronics do not respond. Since the γ -ray background and solar flare spectra are essentially monotonically decreasing with energy, the CsI detector sees higher statistical fluctuations than the Ge detector. γ -ray bursts manifest significant portions of their energy in photons harder than 100 keV. Also, as mentioned before, scintillators are sensitive to high-

energy charged particles. For these reasons, the Ge detector was finally selected as the one which would provide the least false triggers due to statistical fluctuations in the γ -ray background, or "burst simulations" caused by charged particles.

The CsI detector is located on the periphery of the spinning spacecraft (Figure 2.1). The hard X-ray photons to which it is most sensitive are nearly completely absorbed by the spacecraft mass when incident from $> 90^\circ$ (azimuth) from the detector field-of-view. Hence, the CsI time histories are spin-modulated. In Figure 2.5 the fractional transmission versus phase is plotted for a typical solar hard X-ray burst (Feb. 8, 1980). Thirteen cycles of the relatively constant-rate event were normalized relative to the most intense cycle and summed to produce the modulation curve. Each cycle displayed qualitatively similar features. The "side-lobe" peaks at 90° and 270° are due to effective holes in the arrangement of adjacent masses at the periphery of the spacecraft. The modulation limits the usefulness of CsI time histories to essentially demarcating the onset and cessation of a burst if indeed the burst is longer than a spin cycle.

Since the two detectors have different low-energy thresholds, the ratio of Ge-detector to CsI-detector count rates (during unmodulated portions of the spin cycle) provides a relative measure of spectral hardness of ISEE-3 events.

iii. Data Collection and Modes of Operation

Since the experiment was allocated a very low data transmission rate (1.5 bits s^{-1}), and the burst information is stored in a 100

kilobit memory, the time to transmit the time history memory contents to the ground is approximately ten hours.

Each detector event is PHA'd by a 4096 channel analog-to-digital converter (ADC) and time-tagged by verniered clock counters. That is, individual events within sets of nine are labelled with a time-offset from a long term clock. This method reduces the number of bits necessary to record the time of an event. The absolute time of each event is determined by adding the individual offset to the long term clock; the clock time is then related to UTC. The total PHA count rate is registered by counting the clock pulses necessary for an event counter to overflow. The clock frequency (FT) and event overflow values (N) are command adjustable by factors of 2 within limits. The most often used frequency has been 1024 Hz with an overflow count of 32. A small circulating memory records the event information.

The trigger circuit is an adjustable clock pulse counter. When the current accumulation of clock pulses per N events is less than the trigger value (TR), that is, when

$$\text{Event Rate} > N(FT/TR) = N/\Delta t, \quad (2.1)$$

a trigger occurs. The circulating memory freezes, preserving the time history interval immediately prior to the trigger. Simultaneously, recording of burst information is transferred to the larger static memory. A schematic of the data flow is shown in Figure 2.6.

During the mission the trigger value had usually been set at 95 clock pulses which for $N = 32$ corresponds to a trigger threshold of 345 cts/s. The false trigger rate due to statistical fluctuations is

extremely sensitive to the trigger setting. In July 1981 I noticed that, assuming Poisson statistics, a false trigger due to statistical fluctuations would occur on the average once in ~ 25 years for $TR = 95$. A new value for TR of 128 (rate = 256 cts/s) was calculated to give an acceptable false trigger rate of once per month. Since the threshold was lowered, a few events have been detected which otherwise would not have triggered the experiment.

The instrument also records the Ge low and high threshold rates as well as the CsI low threshold rate. These rates give a measure of the γ -ray background.

In the absence of a burst trigger, the experiment operates in the background mode, PHA'ing about 1 photon of 550 incident on the Ge detector. A small buffer (36 events) fills up very quickly, succeeding events are ignored, and the background buffer is emptied into the telemetry stream periodically. The background PHA data transmission was unaffected by the failure of the burst spectral memory. Background data continued to be transmitted regularly until July 1981 at which time new satellites began to preempt receiving time.

iv. Sensitivity

From September 1978 to July 1982 the GE detector triggered on 24 γ -ray bursts, or about 6 γ -ray bursts yr^{-1} . This relatively low detection rate is a consequence of the small detector area. The instantaneous flux required to trigger may be roughly calculated by assuming an incident two power law photon spectrum for a typical γ -ray burst: $\propto E^{-1.5}$ for $E < 200$ keV and $\propto E^{-2.5}$ for $E > 200$ keV. From Monte Carlo simulations it was determined that incident photon power laws are

transformed into detector count spectra that are also power laws with the shift in spectral index roughly constant (Figure 2.7). Utilizing the simulation transformations and a Ge detector cross section of 12.5 cm^2 , one obtains a required instantaneous flux of about $1.2 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$ for a detector trigger threshold of 256 cts s^{-1} .

C. The Hard X-Ray Burst Spectrometer

The HXRBS experiment (Orwig, Frost, and Dennis 1979) was flown on Solar Maximum Mission, a coordinated satellite designed to investigate solar phenomena during the recent maximum in the sun's activity. The SMM is in a nearly circular earth orbit at an altitude of 530 km with a period of 95 minutes and inclination to the earth's equator of 28.5° .

The HXRBS's primary objective is to study solar X-ray flare events in the energy regime 20 keV to 1 MeV with significantly better absolute time resolution (as short as 1 ms) than previously achieved. The experiment makes continuous measurements of the energy-loss spectrum of detector events with a time resolution of 128 ms. The instrument is ideal for observing the hard X-ray/low-energy γ -ray portion of γ -ray burst spectra.

1. Detector System

The HXRBS sensitive elements consist of a central disk-shaped CsI(Na) crystal and a surrounding can-shaped CsI(Na) anti-coincidence shield (Figure 2.8). Fifteen-channel energy spectra are obtained from the central detector. The shield is designed as a collimator for viewing the sun. It strongly attenuates the photon and charged particle fluxes from directions other than the 40° FWHM solar

aperture. Also, the shield is operated in anticoincidence with the detector so that only events which are seen in the detector, but not also in the shield, are PHA'ed and included in the detector count rate. The shield and detector are each viewed by four PMT's. An additional charged-particle detector monitors the particle flux and averts damage to the PMT's during periods of high flux (e.g., during passage through the South Atlantic Anomaly) by temporarily turning off the PMT high voltage.

The detector dimensions are 4.67 cm radius $\times$ 0.635 cm depth, the sensitive area, 68.6 cm². A detector dead layer of thickness $\sim$ 0.13 mm and 0.14 g cm⁻² of aluminum above the detector reduce the efficiency of photon detection for energies below 30 keV. The aluminum absorbing material serves to attenuate the large flux of soft X-rays which would otherwise cause pulse pile-up effects. Details of the detector response are developed in Chapter III.

Pre-launch measurements of the energy resolution indicated 30% FWHM at 122 keV whereas the operational resolution is found to be described by the relation $\text{FWHM} = 1.76(E^{.75})$, with E and FWHM in keV (Orwig, private comm.). The actual in-flight resolution is $\sim$ 53% at 122 keV. The degradation in resolution is probably the result of some degree of decoupling of the PMT assembly from the detector crystal.

For flares which exceed count rates of $\sim 10^4$ cts s⁻¹, corrections to the spectra must be applied to account for pulse pile-up effects. Pulse pile-up refers to counts spilling into a higher energy channel from a lower energy channel when the count rate is high enough that randomly coincident small pulses add together and masquerade as large pulses. The spectrum is thereby distorted. So far, the largest γ -ray

burst seen in the HXRBS field-of-view briefly attained a count rate of 3000 cts s⁻¹. γ -ray bursts have significantly harder spectra than solar flares; hence for γ -ray bursts the counts are distributed towards higher channels than for flares. Consequently, pulse pile-up is not foreseen as a problem for γ -ray bursts.

The shield dimensions are 4.92 cm inner radius, 8.09 cm outer radius $\times$ 24.75 cm length, with a bottom thickness of 3.17 cm. The shield operates at a lower discriminator threshold of about 200 keV. All events which exceed the 200 keV shield threshold and which also interact in the detector are vetoed. The 200 keV threshold is not sharply defined since the efficiency of the PMT's light collection is a function of the region of interaction of the incident photon. The PMT's are positioned at the top of the shield (Figure 2.8); hence the effective threshold for anticoincidence is lowest for incident directions near the field-of-view.

In-flight detector gain calibration is achieved by monitoring the 59.6 keV X-ray line from an ²⁴¹Am source. The source decays by emitting a 5 MeV alpha particle and a 60 keV X-ray. The alpha particle is captured within a plastic scintillator button which is viewed by a PMT. A coincidence between the 5 MeV light pulse and a detector event (the 60 keV X-ray) generates a calibration tag for the event. In Figure 2.9 the history of the gain over the mission's first 800 days is plotted. The scatter is attributable to the difficult task of fitting a gaussian line to the small number of points (~ 3) comprising the line in the calibration spectrum. During a short period (March 1981) the experiment was in a low gain state with the highest channel ~ 1.3 MeV. The 511-keV annihilation line was measured at that time and its position

was in good agreement with the gain relationship computed from the ^{241}Am source (Orwig, private comm.). Two ^{241}Am sources are used in an identical manner to calibrate the shield threshold level. Integral spectra with increasing low thresholds are accumulated in adjacent time periods; these spectra are differenced to generate a differential calibration spectrum for the shield.

It is estimated that γ -ray bursts with fluxes $\geq 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ should be detectable with the HXRBS. However, only for those bursts which directly illuminate the detector, i.e. near or within the 40° FWHM field-of-view, are spectra obtained which are not substantially contaminated by the shield-processed contribution. A 60° full-width-quarter-maximum field-of-view is approximately $1/24$ of the sky. With a $\geq 50\%$ duty cycle (the SMM views the earth at night), about 1 γ ray burst in 40 is seen in the detector FWQM field-of-view.

11. Data Collection

The HXRBS continuously monitors the hard X-ray flux received in the central detector with a time resolution of 128 ms. The shield count rate is accumulated every 64 ms. The experiment live time ($\sim 95\%$) is obtained by counting 500 kHz clock pulses during periods when the detector is capable of registering an event. Detector spectra are PHA'd by a 15 channel ADC. In principle, spectra are produceable at the time resolution of the experiment. The current and most often used gain state for the 15 channel ADC corresponds to the energy regime 30 to 550 keV.

A 32768-byte memory can store time history information with a resolution as fine as 1 ms. This memory is used to study fast X-ray

solar phenomena. At night the memory may be set to trigger on shield rate increases in order to record any γ -ray bursts which may occur.

Five data rates are also recorded on a longer time scale (16 s). These are 1) total PHA counts, 2) counts in channel 2, a sensitive indicator for solar flares, 3) counts above the detector lower threshold, 4) shield counts, and 5) counts in the charged particle detector.

D. The KONUS Experiment

The Leningrad group has flown the very successful KONUS γ -ray burst experiment on four Venera spacecraft (11 - 14). The spacecraft were launched in pairs, Venera 11 and 12 in September 1978, and Venera 13 and 14 in November 1981. The KONUS experiments were responsible for the prodigious detection rate of ~ 150 γ -ray bursts yr^{-1} . Almost half of the events were crudely localized (uncertainties $\sim 5^\circ$) by a method which uses the detectors on only one spacecraft. With the events detected by this experiment the size spectrum has been extended to fluences $\sim 10^{-7}$ erg cm^{-2} and the distribution of sources has assumed a nearly isotropic appearance.

From the large number of γ -ray bursts detected by the KONUS experiment a separate class of bursts has been defined with characteristic durations < 1 s and significantly softer spectra than classical γ -ray bursts. Also, ~ 450 keV emission features and 30 to 70 keV features, interpreted as cyclotron absorption lines, have been observed in the KONUS spectra.

The KONUS detector system is designed to have quasi-omnidirectional response (Mazets and Golenetskii 1981). Six large NaI(Tl) crystals,

each 4 cm radius $\times$ 3 cm depth, are arranged on the three orthogonal space axes. The cylindrical side of each crystal is shielded with lead and tin and the back is faced with heavy lead glass which is viewed by a PMT. A detector then sees preferentially the photons arriving from the front of the crystal. The spacecraft were operated in two modes, spin-stabilized and triaxially stabilized (non-spin). In the non-spin mode the angularly dependent responses of three detectors on one spacecraft which view a given burst (Figure 2.10) permitted the rough localization of the burst. In the spin-stabilized mode, the source locus becomes an annulus for one detector system, and two spacecraft are required to obtain a two-position localization.

The burst spectra were recorded in 16 channels in the energy range 30 keV to 2 MeV. For eight consecutive 4 s intervals from the burst trigger, spectra were measured, affording the study of spectral variability, not statistically feasible with the smaller γ -ray burst detectors previously in operation.

Time histories were recorded for a maximum of 66 s. During the first 2 sec the time resolution capability was 1/64 s; subsequently the resolution was 1/4 s for 32 s, decreasing to 1 s for the remainder of the 66 s record.

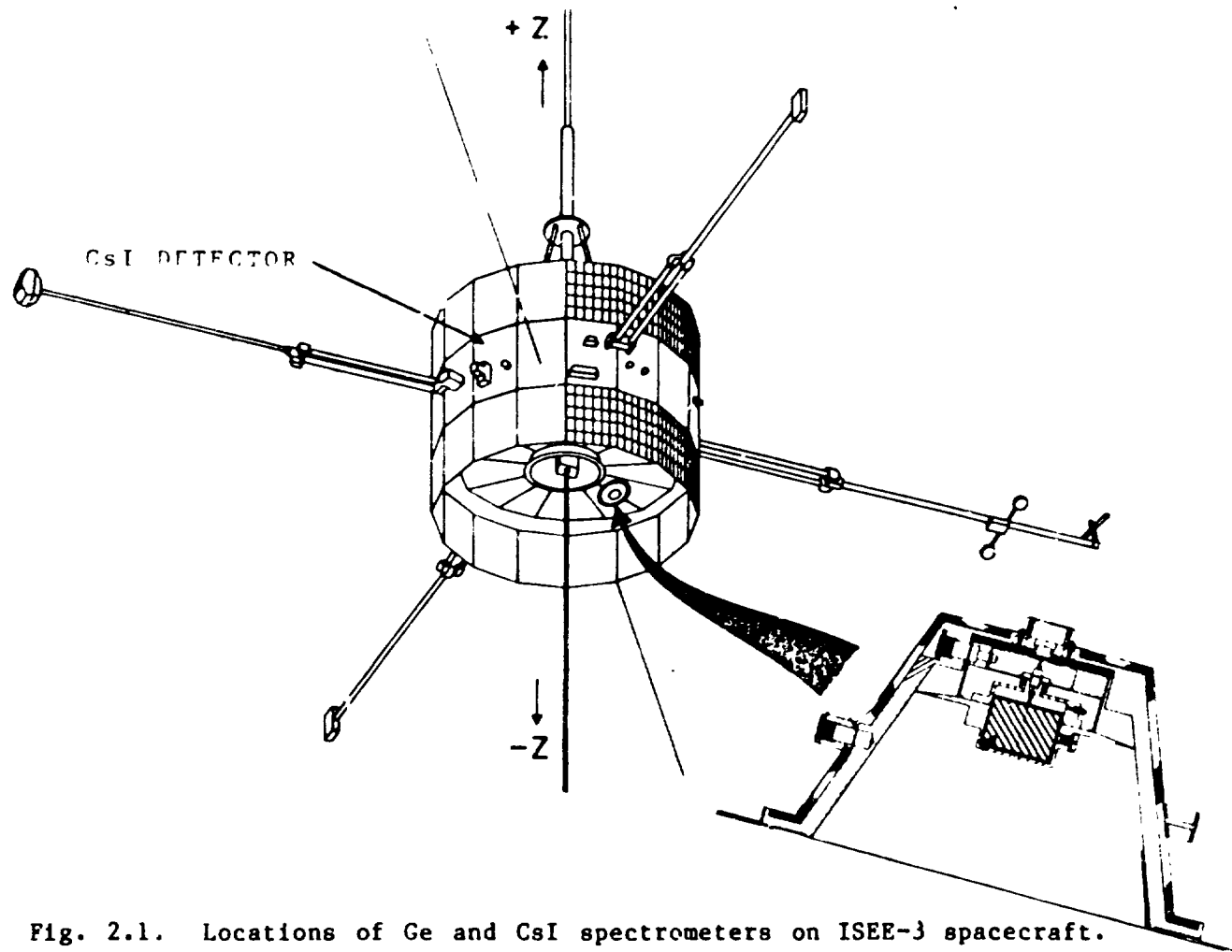


Fig. 2.1. Locations of Ge and CsI spectrometers on ISEE-3 spacecraft.
The Ge spectrometer points approximately towards the south ecliptic pole.

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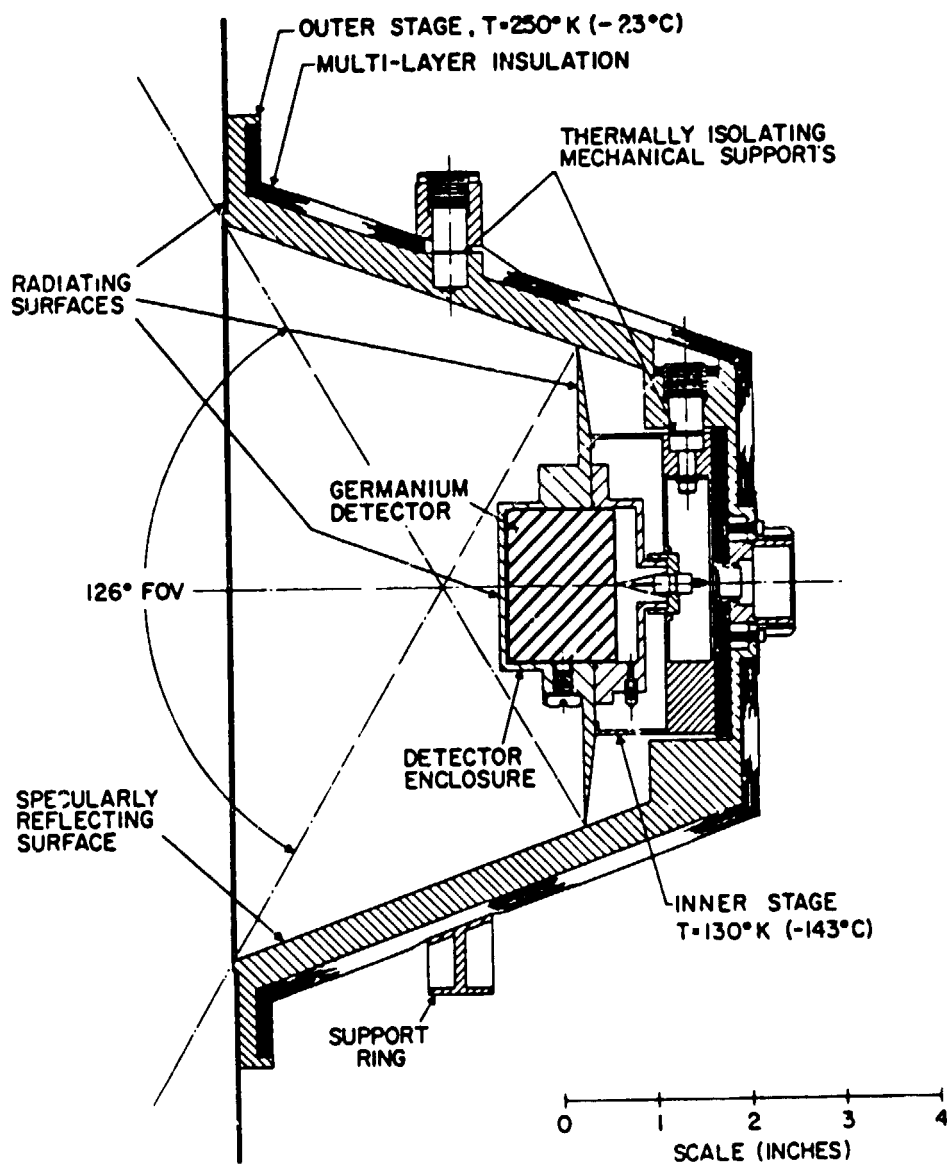


Fig. 2.2. Cross section of the ISEE-3 radiatively-cooled germanium spectrometer.

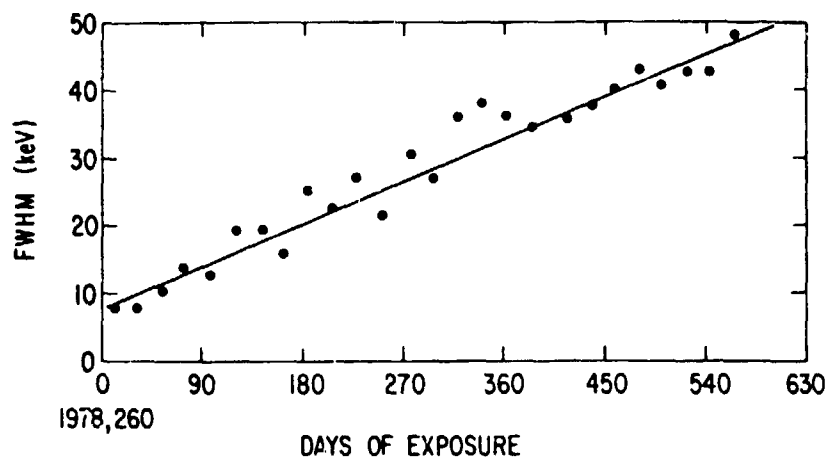


Fig. 2.3. History of energy resolution of the 570 keV calibration line in the Ge detector spectrum. The FWHM increased approximately linearly with time.

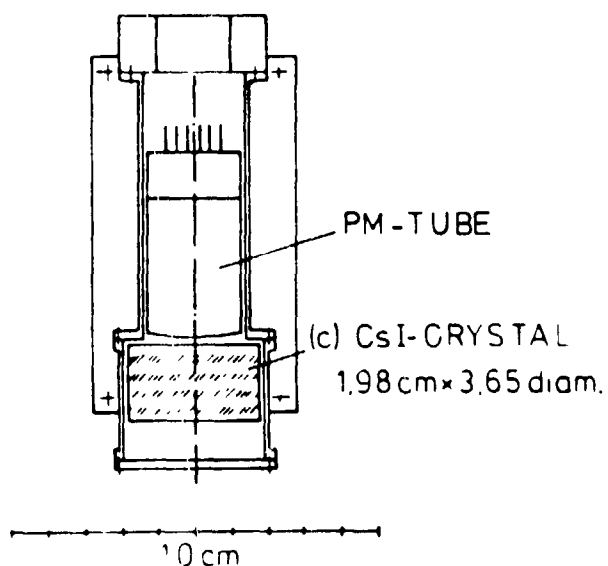


Fig. 2.4. Cross section of CsI spectrometer.

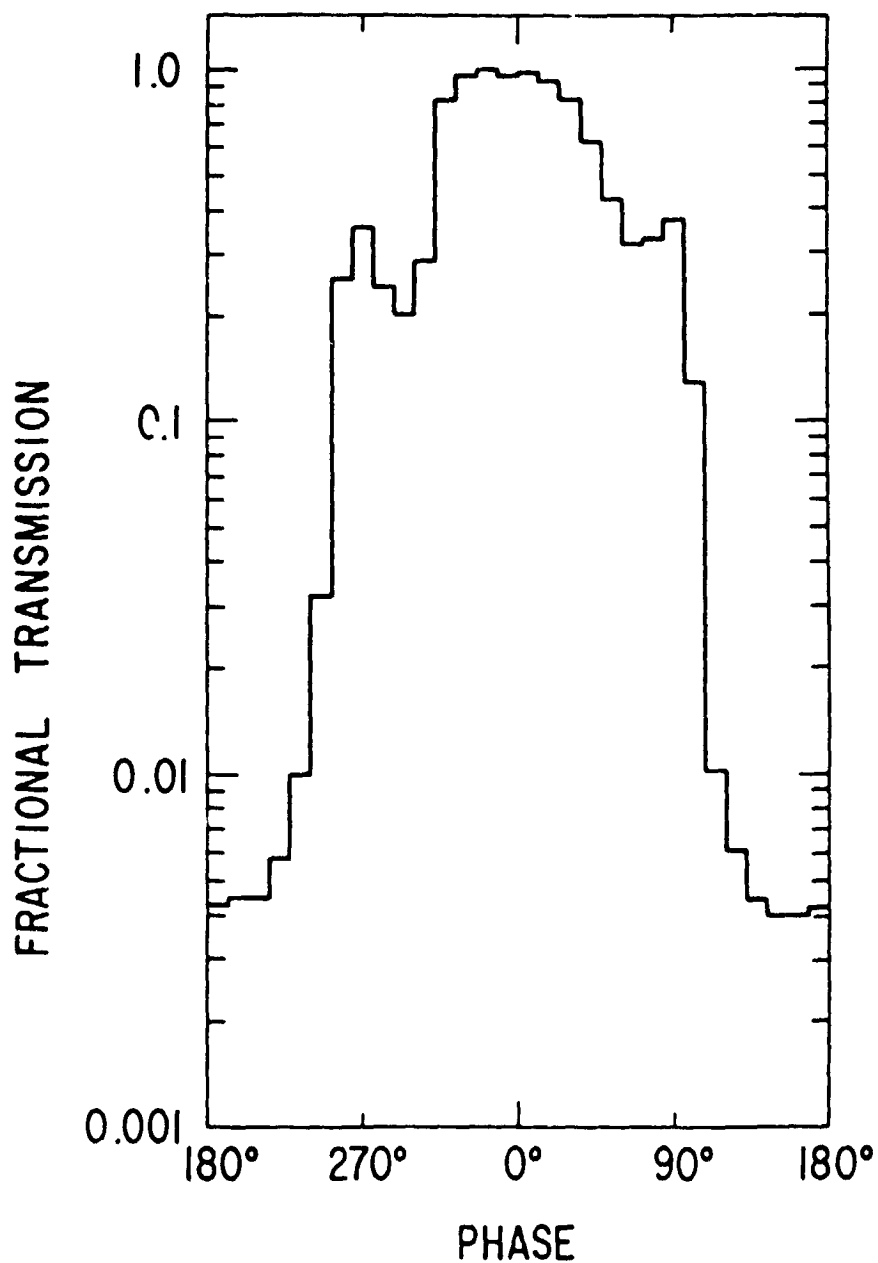


Fig. 2.5. Spin modulation of CsI detector response as a function of phase. The response was obtained for a solar flare with a relatively flat time profile by normalizing and averaging 13 spin cycles.

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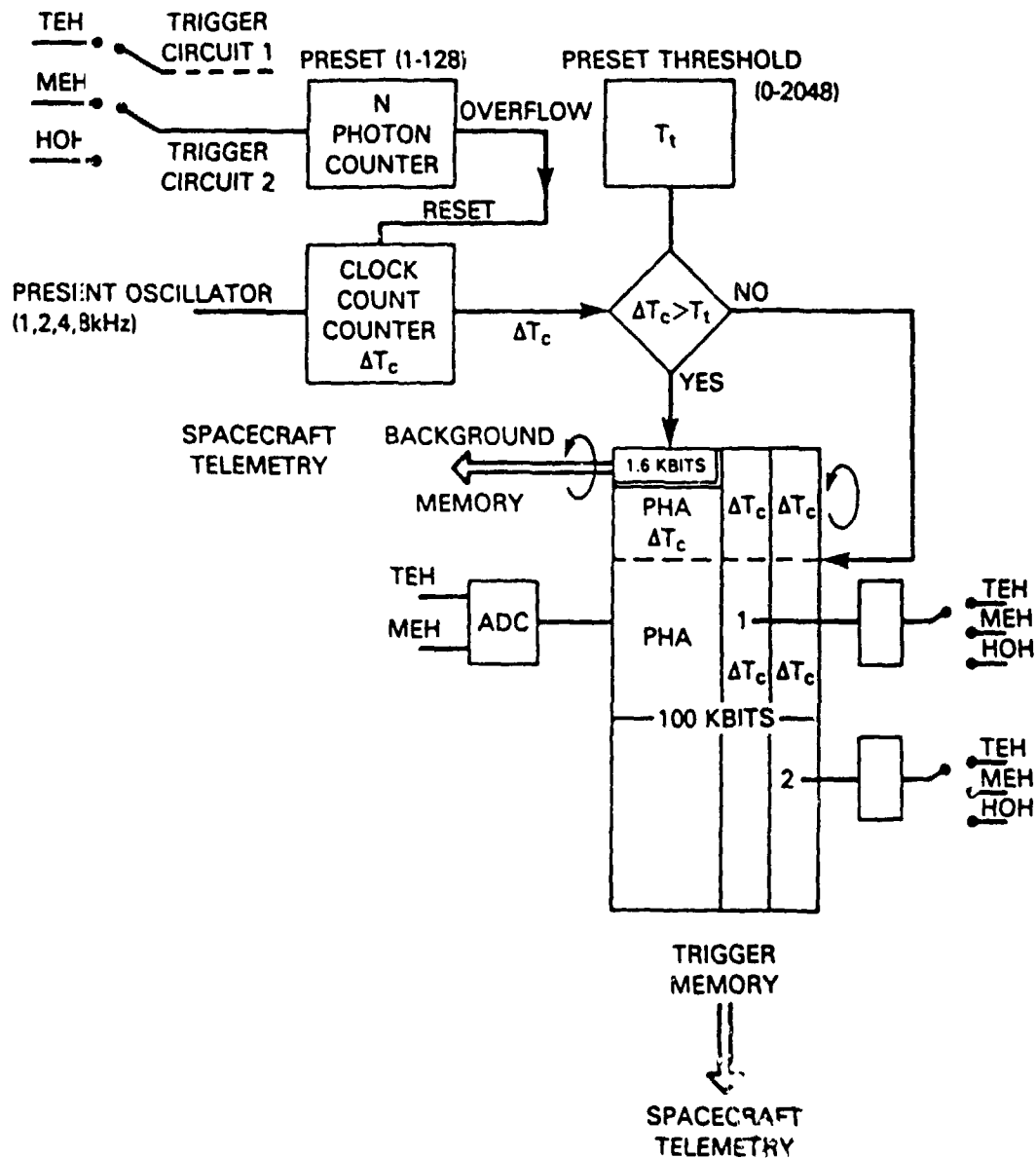


Fig. 2.6. Satellite electronic data processing for ISEE-3 Gamma-Ray Burst Spectrometer.

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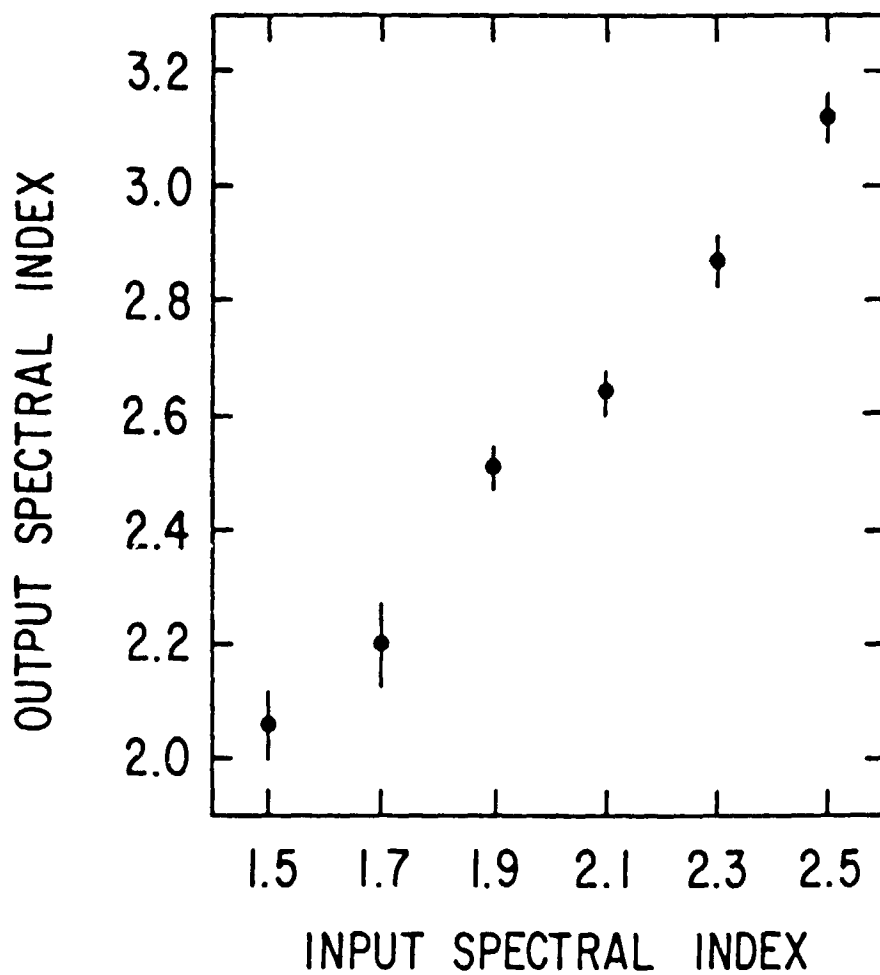


Fig. 2.7. Incident power-law index versus detected power-law index for ISEE-3 Ge detector. The detected spectral index is increased by ≈ 0.55 .

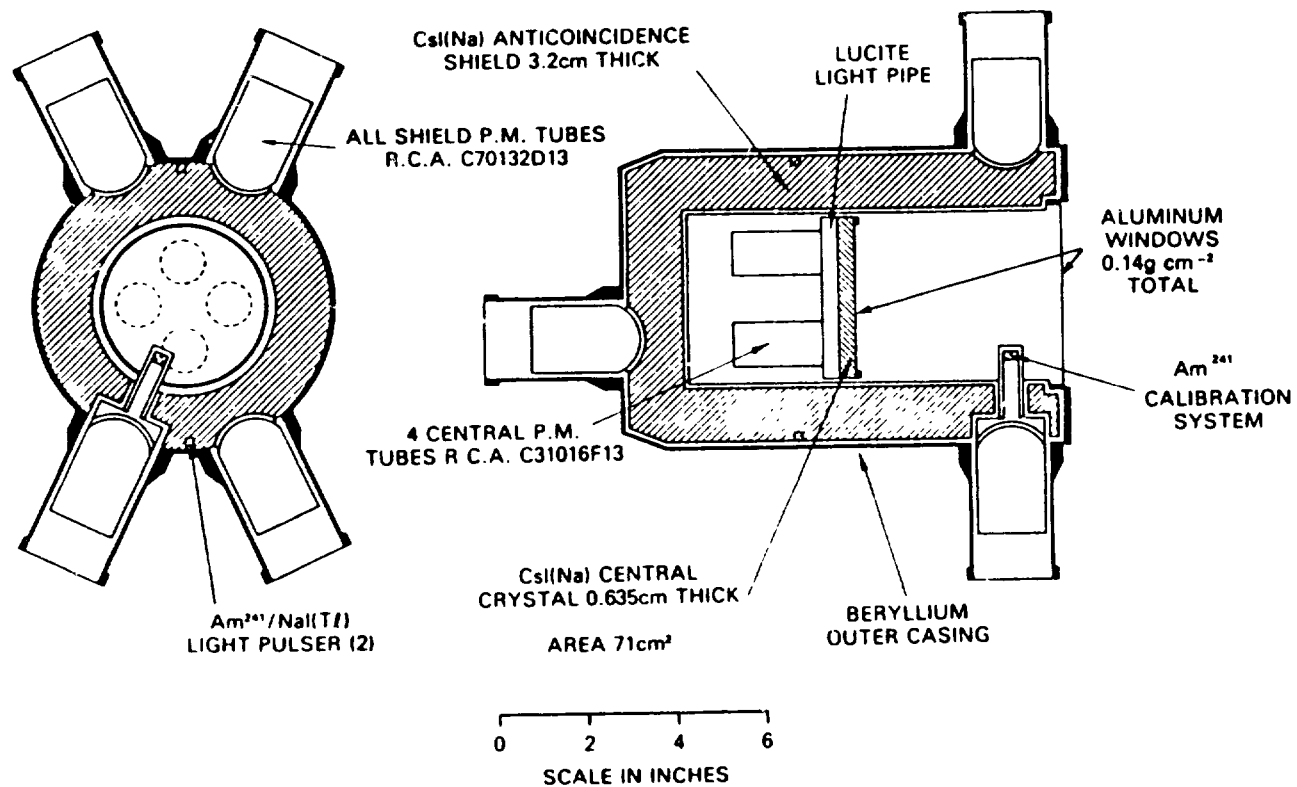


Fig. 2.8. Cross-sectional view of SMM's Hard X-Ray Burst Spectrometer.

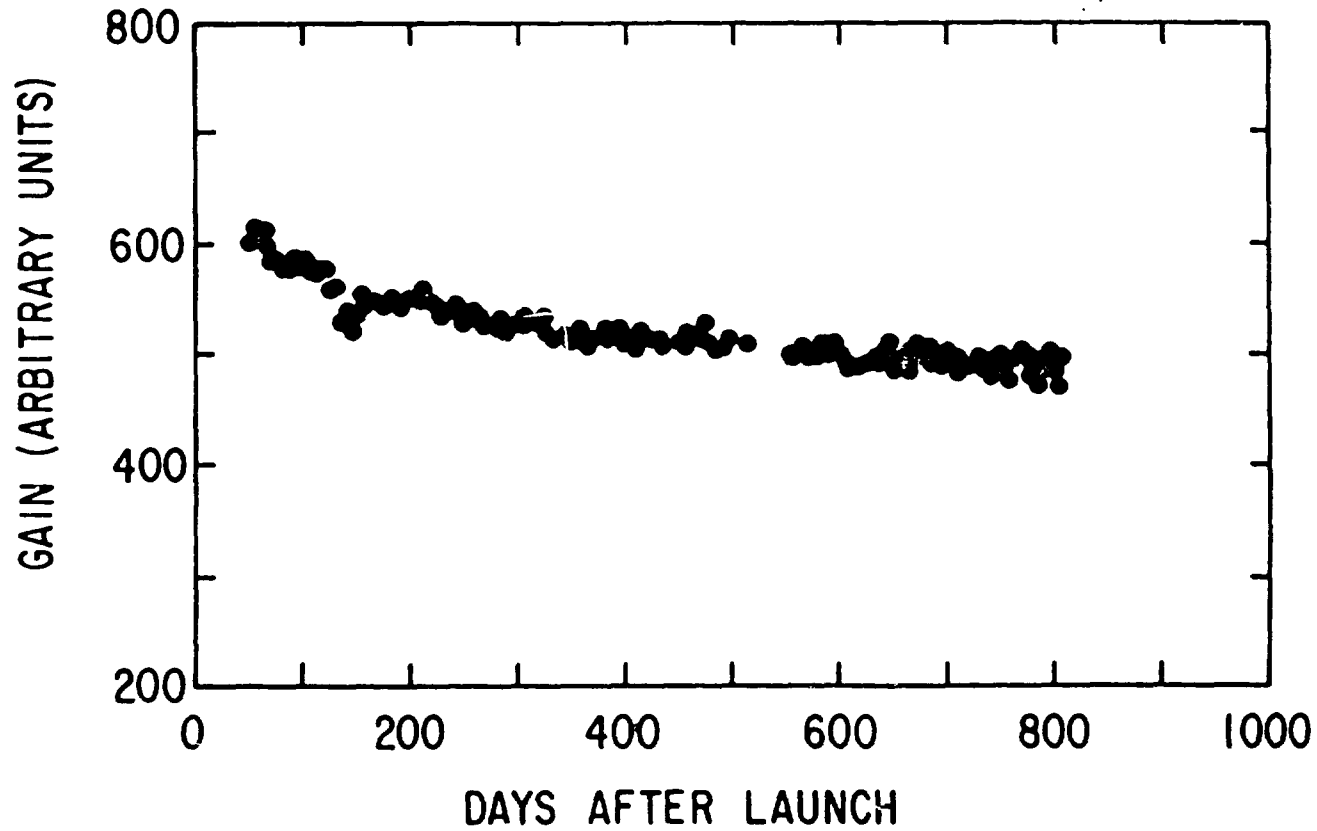


Fig. 2.9. HXRBS gain versus time. The gain decreased exponentially during the early phase and then decreased at a nearly constant rate.

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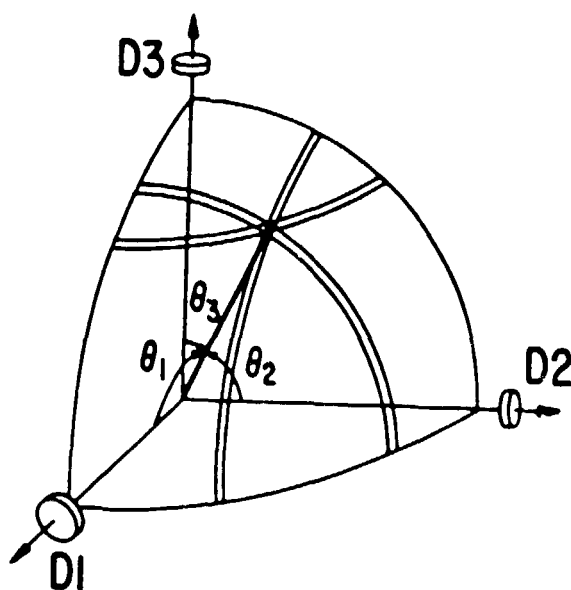


Fig. 2.10. Schematic of the Venera KONUS detector system. The anisotropic response of three detectors enables a crude localization of the source.

CHAPTER III

METHODS OF ANALYSIS

A. Introduction

The γ -ray burst data used for analysis in the present study are the count rates within the upper and lower energy thresholds as a function of time (time histories), available from ISEE-3 and SMM satellites, and detector count rates within fifteen energy channels (energy spectra), available from the SMM detector. Reduction of the temporal information to time histories is a straightforward task. The deconvolution of detector count-rate spectra into incident photon spectra is considerably more complicated. This process involves several detailed steps, sometimes iterative. Moreover, the derived incident spectrum is not unambiguously unique, a fact which will become apparent when the procedure is described at some length. I describe first the temporal analysis and then the method of spectral analysis.

B. Time History Reduction

The computer program package which extracts ISEE-3 γ -ray burst temporal information from the data stream and reduces the information to recognizable count rates and associated times was created by the Computer Science Corporation for the Low Energy Gamma-Ray Group at Goddard Space Flight Center (LEGG/GSFC). The program procedure is amply described in Chryssa Kouveliotou's Ph. D. thesis (1981). In connection with temporal information processing, the primary interest is in the accuracy of absolute timing for the purpose of triangulating γ -ray burst source positions in conjunction with data from other spacecraft. The initial timing information and satellite positions received for ISEE-3

analysis were based on predicted orbital parameters. These predictions were thought to be sufficiently different from the true values to enlarge the potentially arcminute-sized source error boxes. Therefore, the experimenters requested that accurate ex post facto positions and associated times be published by the ISEE-3 satellite command after the burst data are received. It was found that the total error introduced by using the predicted orbital data rather than the ex post facto data is much less than the 1 millisecond resolution limit of the Teegarden experiment for recording of the temporal information.

The ISEE-3 time histories are produced on an IBM 360/3081. The time history produced from the raw time interval data is not entirely chronological due to the order of data in the small pre-trigger circulating memory. Also, a typical γ -ray burst lasts 1 to 60 seconds whereas the memory contains ~ 10 minutes of rate data. I reordered the IBM-produced time histories chronologically and trimmed the time histories to include some γ -ray background data before and after the event. For convenience of manipulation and display, the time histories were then transferred to a PDP 11/70 with a graphics facility.

The SMM time histories are extracted from a nearly continuous temporal record which is produced in real time with no complications of timing predictions. The software procedure is completely described in an HXRBS in-house manual entitled "Flare Analysis Procedure User's Guide" (FLREX). Candidate γ -ray bursts are located in the time records by examination of the five coarse count rates (see chapter II). These records are routinely searched by HXRBS experimenters for solar flares. Events exhibiting very hard spectra and short durations (compared to solar flares) usually prove to be γ -ray bursts. Sometimes,

information from other γ -ray burst experiments provided to the LEGG/GSFC either confirmed a burst or lead to its discovery in SMM records.

For γ -ray bursts the duration of the transient is so short that the background rate is constant for all practical purposes. The background does vary from event to event however. A background rate was computed for each event by averaging several rate values in short intervals before the onset of a burst and after its subsidence.

C. Energy Spectra Reduction

As with all detector systems which record electromagnetic radiation, the observed γ -ray energy spectrum is the convolution of the incident energy-loss spectrum with the instrumental response. At optical frequencies the intensity of detected radiation as a function of energy, $D(\nu)$, is related to the incident radiation, $I(\nu)$, by an efficiency factor $\epsilon(\nu)$;

$$D(\nu) = \epsilon(\nu)I(\nu). \quad (3.1)$$

Photons incident at an energy $h\nu$ are either detected at $h\nu$ or are lost by the system. At γ -ray energies the situation is more complicated. For X-ray energies up to ~ 100 keV, photoelectric absorption in the detector crystal is the predominant interaction, the efficiency decreasing with energy. Above the hard X-ray regime, $\gtrsim 100$ keV, Compton scattering of incident photons to lower energies becomes a significant effect. Figure 3.1 illustrates the response of a Ge crystal to an incident monoenergetic beam of photons with energy 662 keV, revealing a Compton continuum at energies below the photopeak incident energy. For

photons with energies greater than $2m_e c^2$ another interaction channel opens, pair production. Moreover, incident photons may first scatter in material surrounding the detector and subsequently deposit only a fraction of their initial energy in the detector crystal. It is evident that the relation between detected and incident spectra at γ -ray energies must be represented by a response matrix:

$$D(v^-) = \epsilon(v^-, v) I(v). \quad (3.2)$$

For configurations other than the simplest detector geometries, analytic functions of the detector response may be greatly improved by Monte Carlo calculations. For the present analysis a Monte Carlo approach was utilized to create the detector response matrix.

Generally it is not possible to find a unique inverse matrix, $\epsilon^I(v, v^-)$, and thereby perform the multiplication

$$I(v) = \epsilon^I(v, v^-) D(v^-), \quad (3.3)$$

completing the task of spectral deconvolution. Instead one is compelled to select trial incident spectra, multiply these by the detector response matrix and compare the "detected trial spectrum" with the data. The quantitative comparison is accomplished by a program which seeks the minimum chisquare parameter for a family of test models by iterating the multiplication procedure while adjusting trial incident spectral values.

The construction of the detector response matrix by the Monte Carlo method and the spectral fitting program will be described in turn.

D. Computation of Detector Response Matrix

1. Monte Carlo Code

In 1979 the LEGG/GSFC received from the Gamma-Ray Group at UCSD a Monte Carlo code designed to simulate the response of detection systems to gamma radiation. The program has survived in approximately the initial form except for a few corrections and adaptations. All of the physical data used in the program as well as the correctness of all geometrical expressions and techniques have been verified or recoded. Some of the basic kinematical sections have also been verified. To my knowledge no errors remain in the program.

The detector-radiation interaction simulation can be divided into five elements: 1) geometry and composition of the detection system, 2) geometry of the beam, 3) incident spectral characteristics, 4) physical interactions, and 5) detected spectrum. The simulation proceeds precisely as one might visualize the relevant interactions as depicted in textbook drawings. The simulation consists in replacing the beam geometry, incident spectrum, and quantum mechanical probabilities of kinematical processes with appropriately chosen random number distributions. If the simulations are sufficiently accurate and a large number of incident photons are tracked through the system, the detected spectrum will reflect the physical situation it is intended to represent. The operation and use of the Monte Carlo program and tests which confirm its accurate correspondence with experimental results are described below.

The program allows one to define up to seventeen material or vacuum shells. Each shell is composed of a single substance such as cesium iodide. The geometry is restricted to cylindrical symmetry such that

the $(i+1)^{\text{th}}$ shell encloses the i^{th} shell. A few slight deformations from the real detector system geometry are usually necessary to comply with this restriction. It is permissible to have tops, sides or bottoms of shells with infinitesimal thickness. Hence, two contiguous, consecutively numbered disks of equal radii are interpreted by the program as the $(i+1)^{\text{th}}$ disk enclosing i^{th} disk, around the side and on the top or bottom, with an infinitesimal layer. Presently, the program is coded for the more frequently encountered detector materials and absorbers: NaI, CsI, Ge, Al, Pb, Fe, Be, Sn, plastic scintillator, air, and vacuum. Also, substances of organic composition that are sometimes used must be replaced with equal grammage, nearly equal Z materials. Thus, the simulation can be made quantitatively acceptable.

The incident photon beam geometry can be plane parallel, point source, or isotropic. For the plane parallel case, applicable for a source at infinity, the beam impinges on the system at a specified angle θ with respect to the cylindrical axis of symmetry. For the point source case, appropriate to simulating an experimental situation with a nearby radioactive source, the beam is a cone of half angle α arriving at the detector system from a point (r, z) . An isotropic beam illuminates the system from all azimuthal angles between the specified polar angles θ_1 and θ_2 . If $\theta_1 = 0$, $\theta_2 = \pi/2$, the beam is truly 4π isotropically incident. This case would be utilized to simulate an isotropic background. For the plane parallel or isotropic cases, one specifies a target shell, the shell which is to be illuminated uniformly per projected area according to the selected beam geometry. The target shell may be designated to be an interior shell of smaller area (i.e., the detector shell) than the outermost shell in order to economize on

photons. To include the effects of scattering from outer shells, the outermost shell should be the target shell. The direction of each photon is determined by one or more uniformly distributed random numbers which are arguments of the specific integrated angular/projected-area distribution of each beam case.

The distribution in energy of incident photons can be specified to be either monoenergetic or power-law. By combining several program runs, any distribution can be built up.

Once a photon is simulated, the program propagates it through the detector system shells until it interacts via the photoelectric effect, Compton scattering, or pair production processes or until it is lost out of the system. The interaction length for each of these processes within the various material shells characterizes the exponential distribution for penetration. Again a random number is employed to create the distribution. Upon interaction, the photon's by-products, electrons, positrons, and degraded photons, are followed through the system. The propagation and accounting is continued until the n^{th} generation photon is entirely absorbed or is lost and until all by-products have deposited all their energies within the shells or have escaped the system. The chase then begins anew with another incident photon.

The detected spectrum is a histogram of total energy deposited per incident event in shells labelled "detector". The physical detector resolution can be convolved into the final binning, as a gaussian distribution, thus simulating photomultiplier characteristics, associated electronic processing, and/or charge collection efficiency. Also, shells which represent active shields, that is, scintillators used

to collimate the system and reduce background counts, may have low level thresholds specified. For photons which scatter in an active shield and deposit energy greater than the threshold value, the event would be rejected if it also interacted within a detector shell.

11. Verification of Code Accuracy

Two initial tests of the Monte Carlo program were performed to insure validity of results derived from its use. First, I simulated experimental tests performed with a Ge(Li) detector as described in Seyfarth et al. (1972). This article reported efficiencies of "photopeak" absorption of incident monoenergetic radiations. The photopeak energy is the energy of the incident radiation. The Monte Carlo simulations and Seyfarth's results are in very good agreement (Figure 3.2).

Second, I performed experimental runs with monoenergetic radiations incident on a high-purity germanium crystal encased in a cryostat with a few cm of material (mainly aluminum and steel) forming the base of the detector holder. The significance of the base plate material is that some photons backscattered ($\sim 180^\circ$) from the steel plate and were detected by the crystal. The usual Compton scattering of photons within the crystal, the backscattered spectrum and the photopeak were recorded with a multichannel analyzer. The experimental configuration was then simulated as closely as possible (Figure 3.3). The Compton and backscatter Compton continua were adequately reproduced by the Monte Carlo program (Figure 3.1). The slight discrepancy between the experimental and simulated continua in the backscatter region may be

attributed to an imprecise knowledge of the thicknesses and distribution of materials within the sealed cryostat.

iii. Simulation of HXRBS

A primary consideration in computing the detector response is economy of time and cost; it is not feasible to construct a detector matrix for several angles of incidence relative to the system axis of symmetry. Section G describes the use of the Monte Carlo program to determine the effect of angle of incidence on detected spectra. For the response matrix construction the beam direction was chosen parallel to the axis of symmetry. A second consideration of economy was forgone since it appeared that accuracy might have been sacrificed at lower energies; it was decided to illuminate the entire detector system, including the shield, an area three times the detector area. This was deemed necessary since some higher energy photons scatter in the shield near the aperture and continue approximately in the forward direction toward the detector. Since there is a negligible amount of spacecraft material near the instrument aperture and since the shield severely attenuates radiation from directions other than the detector field-of-view, the spacecraft was not included in the simulation.

To create the response matrix, 85 energies, forming a column vector, were provided to the program. These energies were logarithmically spaced from 20 keV to 1 MeV. The log spacing factor was chosen to cover adequately the first SMM detector channel, only 4.5 keV wide, and at the same time not over-represent the high energy channels. With the resultant spacing there are ~ 10 input channels for each detector channel at low energies (below 100 keV). There are at

least four input channels per detector channel at the higher energies. With this choice, an incident spectrum to be multiplied by the response matrix will be sufficiently continuously transformed by the matrix. In particular, the discontinuous effect of the CsI K absorption edges, at ~ 33 and 36 keV, is properly accounted for since the input binning is much finer than the detector channels at low energies. The input energies extend up to 1 MeV in order to include the contribution of Compton scattered photons at ≤ 1 MeV energies into the SMM detector energy regime.

For a Monte Carlo approach, the matrix smoothness is also determined by statistics; a sufficient number of counts must be accumulated in each output column vector of the matrix to represent the detector response accurately. The detector efficiency at low energies is of order unity. The more penetrating γ -rays with energy ~ 500 keV are detected by the relatively thin crystal with only about 5% efficiency. To accumulate a large number of counts in each output bin, 25,000 photons were fired for the monoenergetic inputs from 20 keV to 200 keV. Above 200 keV, the number of incident photons was increased quasi-exponentially to 500,000 for the highest input energy (~ 1 MeV). The resulting matrix, without any smoothing, produces a representation of the detected spectrum which is estimated to be accurate to better than 3% in each detector channel (see section F below).

The Monte Carlo output spectrum for each monoenergetic input is a column vector in the efficiency response matrix. This is evidently correct since, if said column vector were normalized by dividing by the total number of incident photons (and all other column vectors set to

zero), then multiplication of the matrix and the original monoenergetic incident spectrum would yield just the simulated Monte Carlo output spectrum for that monoenergetic input energy. The full normalized matrix then represents the detector response to any spectrum extending up to 1 MeV. The detector response to photons above 1 MeV is negligible. The output spacing is linear with 5 keV intervals from 20 keV to 590 keV, covering the HXRBS energy regime. The conversion of output channels to HXRBS detector channels is described in section D below.

The simulated detector configuration is presented in Table 3.1 and illustrated schematically in Figure 3.4. Necessarily, low Z materials other than those which the program accommodates have been replaced with aluminum which has an atomic number comparable to such materials. The overall configuration of the detector system was very nearly exactly reproduced in the simulations.

The anticoincidence shield low-level threshold was specified to be 200 keV in the program, an estimate of the true value. In fact, the physical shield threshold may change with time. Also, the 200 keV estimate is a value applicable to photons impinging on the shield near the aperture where the PM tubes are strategically positioned to collect the scintillation light (see Figure 2.8).

The thickness of the dead layer on the front surface of the detector crystal is uncertain by a factor of two. The extreme estimates, 0.00635 and 0.0127 cm (2.5 and 5.0 mils), were used to create two response matrices. If the lower value were in fact the true value, the use of a thicker dead layer in the Monte Carlo program would have the effect of absorbing more low energy (25 to 70 keV) photons from

the incident beam, with a consequent overcorrection. Therefore, any depression in the true spectral continuum at these low energies would tend to be deaccentuated. Since such depressions are evident in the deconvolved data, the reason for simulating two thicknesses becomes clear; perhaps the depression could be made to disappear with the use of the thicker layer. It was found that effect on the spectrum due to the uncertainty in the dead layer thickness is small compared to the depressions present in some of the spectra (see section II below).

The detector resolution is a function of energy. The resolution is approximately represented by the functional form

$$\text{FWHM}(\text{detector}) = 1.76E^{0.75} \quad (3.4)$$

with FWHM and E in keV (Dennis, private comm.). The shield resolution is assumed to be twice that of the detector at all energies. The relatively poor resolution has the effect of significantly smoothing the detector response matrix column vectors; any spectral features present in incident spectra would therefore be shallower and broader after multiplication by the matrix. In fact, at low energies (~ 50 keV) the instrumental resolution is approximately the width of one detector channel, about 30 keV. There is no possibility of distinguishing features of much smaller width. Table 3.2 lists the FWHM resolution for the detector and shield for several energies.

E. Spectral Fitting Program

As stated in section C, it is generally not true that one spectral function is found which best fits the data; several different functional

forms may give approximately equivalent fits. The investigator must consider what physical processes and conditions are the probable origin of the observed detected spectrum, given all constraints and inferences available. These problems are examined in Chapter VI in an attempt to determine the energy-loss mechanism(s) operating in γ -ray bursts. Presently I describe the method of (nonunique) deconvolution of detected spectra.

A particularly suitable and convenient spectral fitting program, LSPEC, has been developed by the X-Ray Group (LHEA/GSFC). This program utilizes a modification of the CURFIT routine of Bevington (1969).

Two basic adaptations were made for the purpose of deconvolving the SMM spectra. First, it was necessary to modify LSPEC to accommodate the HXRBS response matrix. Also, the 114 output bins (20 - 590 keV) of the $D(v)$ column vector had to be apportioned to the 15 HXRBS detector channels. Since the detector channel edges change with time, the program performed an interpolation between output bins and detector channels for each γ -ray burst event. Where the counts in one output bin were to be divided between two detector channels, a linear interpolation in energy space was computed.

Second, candidate spectral models were added to the program. The existing program already included several spectral models: one- or two-temperature black body or thermal bremsstrahlung; exponential; power-law with exponential tail; and one- or two- (broken) power laws. The program also has the capability of including gaussian absorption and emission lines in the model spectrum. For γ -ray bursts an exponential form has been recognized as providing a good representation of the data (Cline, Desai, Klebesadel and Strong 1973). A physical mechanism which

exhibits approximately exponential energy dependence is thermal bremsstrahlung (TB). Previously, investigators have neglected to incorporate Gaunt factors appropriate to semi-relativistic electron temperatures in TB models (Gilman et al., 1980; Mazets et al. 1981d). The existing X-ray TB model in LSPEC (Quigg, 1968) included a Gaunt factor useful only up to X-ray energies. Since the HXRBS spectra extend up to ~ 500 keV, it was decided to use the recent relativistic corrections calculated by Gould (1980). In Gould's expression, the correction factor includes 1) the relativistic expression for a thermal electron velocity distribution; 2) relativistic and spin corrections to the electron-ion cross section, $f(a)$; 3) an electron-electron bremsstrahlung term, $\psi(a)$; 4) a first order Born approximation correction, $\phi(a)$. The resulting expression for the TB emissivity in photon space is (there were several errors in the original paper)

$$\frac{dN}{dV dt d\epsilon} = \frac{\rho(\epsilon)}{\epsilon} \left\{ 1 + \left[\frac{1}{4} f(a) + \frac{2\sqrt{2}}{5} \left(\frac{n_e}{\sum Z^2 n_z} \right) \psi(a) \right] \frac{\epsilon}{mc} \right. \\ \left. + 2\sqrt{2} \left(\frac{\sum Z^3 n_z}{\sum Z^2 n_z} \right) \phi(a) \sqrt{\left(\frac{\pi R_y}{kT} \right)} \right\} \quad (3.5)$$

with $\rho(\epsilon) = \frac{16}{3} \sqrt{\left\{ \frac{2}{\pi} \right\}} \alpha^3 \Lambda^2 c n_e \left(\sum Z^2 n_z \right) \sqrt{\left\{ \frac{mc}{kT} \right\}}^2 e^{-a} K_0(a)$

$$f(a) = \frac{1}{4a} + \frac{K_1(a)}{K_0(a)}$$

$$\psi(a) = \frac{3}{4a} + \frac{K_1(a)}{K_0(a)} + \frac{14.63 e^{-a}}{16a K_0(a)}$$

$$\phi(a) = \frac{\pi \{ \sqrt{2} + \sqrt{(\pi a)} \} \operatorname{erfc} \sqrt{(2a)} - e^{-a} / 2}{e^{-a} \{ K_1(a) - K_0(a) \}}$$

The parameter a is $\epsilon/2kT$, ϵ is the energy; α is the fine structure constant; Λ is the Compton wavelength; erfc is the complimentary error function; R_y is the Rydberg constant, and the K_1 are modified Bessel functions. Solar system abundances were used to compute the summations over Z . The factor multiplying $\rho(\epsilon)/\epsilon$ is Gould's correction, a gaunt factor. From the formula one can see that effects 1), 2), and 3) are of order $\epsilon/mc^2 \sim kT/mc^2$ whereas 4) is of order $\sqrt{R_y/kT}$. At energies ~ 200 keV, characteristic of γ -ray burst spectra, the first three corrections are significant. At much higher temperatures second-order corrections should be included. Also, pair production in the photon field becomes important above $2m_e c^2$ (some γ -ray burst spectra extend up to ~ 25 Mev, Share et al. 1983).

Serious objections to the applicability of the TB mechanism to γ -ray bursts have been raised by several authors (Lamb, 1982; Fenimore, 1982a; Liang, 1982). Therefore, another candidate model was incorporated into the LSPEC program. Because high magnetic fields ($\sim 10^{12}$ G) may be present at the surfaces of neutron stars, thermal synchrotron radiation from semirelativistic electrons is also a competing process considering the implied luminosities of γ -ray burst sources if they are at moderate galactic distances (Liang, 1982). Recently, Petrosian (1981) derived a simple but accurate expression for the thermal synchrotron emissivity applicable to the region of high harmonics:

$$\frac{dN}{dV dt d\epsilon} = \frac{\pi e^2 n_e}{3\sqrt{2}hc} K_2^{-1}\left\{\frac{1}{T}\right\} \exp\left\{-\left(\frac{4.5\epsilon}{\epsilon_c \sin\theta}\right)^{1/3}\right\} \quad (3.6)$$

with $\epsilon_c = \frac{ehB}{2\pi mc} T^2$ (cgs) = $11.6 B_{12} T_*^2$ keV

In this equation $T_* = kT/m_e c^2$ with T the electron temperature, ϵ_c is the synchrotron critical energy, B , the magnetic field, h , Planck's constant, and K_2 , a modified Bessel function. In order to utilize this expression, the direction of emission with respect to the magnetic field, θ , was assumed to be $\pi/2$ since the bulk of radiation is emitted perpendicular to the magnetic field. Since neither the magnetic field nor the plasma temperature are independently known, ϵ_c becomes a single adjustable parameter.

The operation of LSPEC is straightforward. For a given detector spectrum and response matrix, one specifies a spectral form with starting values for the adjustable parameters. The efficiency matrix output bins are interpolated with the detector channels for each event and the matrix rows are compressed into the 15 detector channels. That is, the matrix is shrunk from 114×85 to 15×85 so that upon multiplication with the incident model spectrum, a column vector with 15 elements is produced - the "detected model" spectrum. This spectrum may be directly compared with the data.

The comparison results in the generation of the chisquare parameter,

$$\chi^2 = \sum \frac{1}{\sigma_i} (y_i - y(x_i))^2 \quad (3.7)$$

indicating the goodness of fit. The (x_i, y_i) are the counts per channel (y_i) and the central energies of the channels (x_i). The σ are the statistical errors of the y_i . $y(x)$ is the candidate spectral function. Reduced chisquare, χ^2/ν (ν = number of data points minus number of adjustable parameters), is a measure of the probability that a

random set of n data points will yield a χ^2/ν larger than that obtained with the actual data. This probability is tabulated in many references (see e.g., Bevington, 1969).

Generally a $\chi^2/\nu \sim 1$ reflects an acceptable fit to the data points by the candidate function. To obtain a good fit the program adjusts the variable parameters of the model function. The adjustments are determined by taking derivatives with respect to the parameters in χ^2 space and incrementing the parameters, seeking a χ^2 minimum. If χ^2 is not converging sufficiently fast, the program automatically switches to a linear grid search method of incrementing parameters. In this mode, without the benefit of a derivative, χ^2 sometimes diverges if the program initially increments a parameter in the wrong direction. Usually, however, χ^2 converges quickly. If χ^2 is diverging, one must enter better estimates for the model function parameters. Each time the program adjusts the parameters, a new incident spectrum is calculated based on the parameters' values, and the spectrum is multiplied by the response matrix to generate a new detected model spectrum for comparison with the data.

The ratios by channel of detected model spectrum to incident model spectrum are called the channel efficiencies. The detector count spectrum divided by the channel efficiencies yields the deconvolved incident spectrum. Since the channel efficiencies are a function of the model spectrum (and of the detector matrix), the deconvolved spectrum is also a function of the model spectrum. This point will be elaborated in Chapter V especially with respect to the effect of including absorption features in the model spectrum.

F. Confirmation of the Accuracy of the Method

To insure that the changes implemented in LSPEC were correctly made and that the response matrix indeed represented the detector-radiation interaction, comparisons of LSPEC runs and SMM's FLREX runs were made. For the TB model the FLREX uses a function $\propto E^{-1.4} \exp(-(E-50.)/kT)$. The $E^{-1.4}$ factor incorporates a zeroeth-order-approximation Gaunt factor. This function was included in LSPEC and several HXRBS γ -ray burst spectra were deconvolved using both programs. The resulting spectral temperatures, associated errors, normalization coefficients, and χ^2 parameters are presented in Table 3.3. The remarkably good agreement is an indication that both (independent) programs have represented the detector response very accurately, or that both are coincidentally in error. The fits were performed only on the higher channels since at the lower energies the spectra departed significantly from a simple TB model. To confirm agreement between the programs at lower energies, a solar flare exhibiting a TB form was also fit using both programs. For the solar flare, the FLREX and LSPEC agreement was very good in all 15 channels. The results of the solar flare fit are also shown in Table 3.3.

G. Dependence of Detected Spectra on Incident Angle

It is not known a priori where, or if, a gamma-ray burst is observed in the HXRBS field-of-view. The unknown incident angle introduces an additional degree of freedom into the deconvolution procedure. That is, to self-consistently deconvolve detected spectra, one must use a response matrix which is generated with the incident beam impinging on the detector system at the same angle the burst arrived at

the physical system. As stated above in section C, it is not economically feasible to compute response matrices at several angles.

In order to determine what fraction of the flux reaches the detector as a function of incident angle (θ), the aperture and detector crystal can be viewed as seen by a parallel beam and the ratio of unshadowed to total area calculated. The geometry shown in Figure 3.5 depicts what fraction of the detector is unshadowed as a function of θ . Table 3.4 lists the projected, unshadowed area, in the low-energy limit for several values of θ . The effective area increases with energy since higher energy photons can penetrate greater lengths of the shield material near the aperture. The path length through the shield as seen from the detector increases quickly with increasing θ . The effective area for nonzero θ was estimated to be only a few percent larger at energies ~ 200 keV than at 20 keV.

Fortunately, several spacecraft detected the 19 APR 80 burst and its direction of arrival was triangulated. The source was determined to be $\sim 18^\circ$ from the sun (the sun is the HXRBS center of f.o.v). The shield-to-detector counts ratio for the 19 APR event serves to establish the relative orientation of burst arrival directions with respect to the HXRBS center of f.o.v. Events which have larger (smaller) ratios than that of 19 APR are assumed to arrive at lesser (greater) angles than 18° .

The effects of nonzero angles of incidence with respect to the HXRBS symmetry axis were investigated using the Monte Carlo program. Spectra with a power-law dependence $\propto E^{-1.0}$ with incident beam angles 0° , 20° , 30° , and 45° were fired at the same HXRBS configuration as described in section C. A hard spectrum was chosen in order to maximize

the effect of high-energy Compton scattered photons. γ -ray burst spectra are considerably harder than solar flare spectra which do not appear to deviate from simple functional forms at lower energies as burst spectra sometimes do. The resulting detected spectra are illustrated in Figure 3.6. The spectra have been normalized to agree in the high energy region (where the spectrum is less affected by shield absorption) with the 0° incident spectrum. At nonzero angles of incidence the forward part of the shield intercepts some fraction of the beam. The shadowing of the detector necessitated the normalization. It is the spectral shape we are concerned about, however. At an incident angle of 20° , one-half of the beam is intercepted by the shield (the HWHM). At angles greater than 44° , the beam is entirely intercepted by the shield; the beam must penetrate the shield to reach the detector. The effect of the shield-processed contribution on the total detector spectrum can be understood as follows. First, that part of the beam which passes through the shield is attenuated by a factor ~ 225 to ~ 90 for energies 25 keV to 100 keV, but only by a factor of ~ 2 in the highest HXRBS channel. Hence, if a substantial fraction ($\gtrsim 1/3$) of the beam is not intercepted by the shield, the total detected spectrum at low energies will not be significantly altered by the shield-processed contribution. Second, some photons with energies $\lesssim 200$ keV will Compton scatter in the shield and be detected at lower energies resulting in a slight building up of the lower portion of the spectrum. As with the matrix construction runs, the veto threshold was set at 200 keV for these runs. The program tabulates those events which passed through the shield and would have been detected had the veto threshold not been set. This "non-contribution" for the 45° run is also plotted to show

the effect of the shield threshold; a significant fraction of the scattered photons, compared to the number detected for the 45° spectrum, are in fact vetoed by the shield. It was concluded that, for bursts with incident angles up to $\sim 20^\circ$ from the center of the field-of-view, the spectral shape is not significantly altered. For incident angles $\geq 30^\circ$, the admixture of shield processed flux has begun to influence the shape of the spectrum, creating a depression relative to the 0° incident spectrum. At 50 keV, the 30° spectrum is about 25% below the 0° spectrum. This is to be compared to the $\leq 20\%$ effect at ~ 50 keV resulting from halving the dead layer (section H below), and to the $\sim 50\%$ depression below model continuum at 30 to 70 keV for some HXRBS spectra (see Chapter V).

H. Effect of Detector Dead Layer Thickness on Model Fits

The problem of the uncertainty of the detector dead layer thickness was mentioned in section D.iii. Essentially, the dead layer preferentially absorbs low energy photons, flattening the detected spectrum in the lowest channels. In Table 3.5 fits of thermal bremsstrahlung continuum plus absorption line for several spectral intervals are listed for two dead layer thicknesses. The spectra selected for this comparison exhibit absorption features or depressions below the continuum in the energy range ~ 30 to 70 keV (except the 29 MAR 80 solar flare). For the thick dead layer, lower values of kT (i.e. steeper continua) and lower co-efficients (C_2) for the absorption line equivalent widths were fit to the data than for the thin dead layer. The fractional change in the equivalent widths is small, ranging from 5% to 21%. The same effect is evident when the continuum is

thermal synchrotron radiation. It is emphasized that since the thicker dead layer was used to create the detector response matrix for the HXRBS analysis, the strengths of the low-energy depressions observed in some spectra are certainly not overestimated due to the dead layer effect.

TABLE 3.1

HXRBS Shell Configuration for Monte Carlo Simulation

<u>SHELL</u>	<u>MATERIAL</u>	<u>ELEMENT</u>	<u>ZTOP</u>	<u>ZBOT</u>	<u>RADIUS</u>
1	Al	absorber	1.588	0.0	4.674
2	CsI	detector	2.216	0.0	4.674
3	CsI	dead layer	2.229	0.0	4.674
4	Al	absorber	2.672	0.0	4.674
5	Void		12.102	-9.170	4.760
6	Al	absorber	12.109	-9.488	4.919
7	CsI	shield	12.109	-12.663	8.094

TABLE 3.2

HXRBS Spectral Resolution for Several Energies

<u>ENERGY</u>	<u>DETECTOR</u>	<u>SHIELD</u>
<u>(keV)</u>	<u>FWHM (keV)</u>	
20	17	33
40	28	56
60	38	76
80	47	94
100	56	112
200	94	188
300	127	255
500	187	374

TABLE 3.3a

Comparison of Computed Spectral Parameters for Spectra
Deconvolved with LSPEC and FLREX

EVENT	C (ph keV ⁻¹ cm ⁻² s ⁻¹)		kT (keV)		χ^2/ν	
	LSPEC	FLREX	LSPEC	FLREX	LSPEC	FLREX
AP2180.A	35.3± 3.5	35.4± 3.4	158.3±26.1	163.4±23.6	7.85/ 7	7.99/ 7
AP2180.B	32.1± 2.6	32.7± 2.7	181.4±25.2	182.9±22.9	6.76/ 9	6.99/ 9
AP2180.C	23.3± 3.6	23.8± 3.5	192.0±44.3	193.1±39.0	3.99/ 8	4.31/ 8
MR2980	293.9± 9.2	296.8±12.7	65.5± 1.4	65.9± 1.5	31.8 /13	29.3 /13

Assumed Functional Form: $dN/dE = C \times E^{-1.4} \times \exp(-(E-50.)/kT)$

The spectral intervals for the γ -ray burst of 21 APR 80, designated .A, .B, and .C, are illustrated in Figure 5.10a. The event 29 MAR 80 was a solar flare.

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TABLE 3.3b
Computed Incident Fluxes in HXRBS Channels
For March 29, 1980 Solar Flare

CENTRAL ENERGY	Photons $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$		Ratio
	LSPEC	FLREX	LSPEC/FLREX
29	0.610E+01	0.601E+01	1.017
41	0.243E+01	0.236E+01	1.033
63	0.819E+00	0.792E+00	1.034
85	0.351E+00	0.344E+00	1.021
108	0.173E+00	0.172E+00	1.005
131	0.884E-01	0.891E-01	0.993
155	0.472E-01	0.471E-01	1.002
180	0.270E-01	0.271E-01	0.997
206	0.162E-01	0.162E-01	0.994
233	0.873E-02	0.874E-02	0.999
261	0.514E-02	0.523E-02	0.981
290	0.339E-02	0.341E-02	0.994
321	0.199E-02	0.197E-02	1.006
351	0.176E-02	0.173E-02	1.019
414	0.431E-03	0.409E-03	1.054

TABLE 3.4
Effective HXRBS Detector Area
For Several Incident Angles*

θ	$A/A_{\theta=0^\circ}$
0°	1.00
10°	0.80
20°	0.53
30°	0.26
35°	0.15
40°	0.05
44°	0.00

$$A_{\theta=0^\circ} = 68.62 \text{ cm}^2$$

* In low energy limit

Table 3.5
Comparison of Spectral Fits with
Detector Dead Layer 2.5 and 5.0 Mils

Spectrum	Thin Thermal Bremsstrahlung		w/ w/o		Absorption line		χ^2 / ν
	C_1 $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	kT (keV)	C_2 (keV)		Energy (keV)	Width (keV)	
AP1980.RS2							
2.5 mils	2.83 ± 0.32	847 ± 85	38.3 ± 5.5		48.1 ± 2.8	33.0 ± 11.0	11.9/10
5.0 mils	3.19 ± 0.05	781 ± 11	36.0 ± 1.0		48.5 ± 1.0	33.0 ± 2.2	12.0/10
AP2180.A							
2.5 mils	4.67 ± 1.31	121 ± 15	34.6 ± 5.1		43.6 ± 1.4	46.8 ± 33.5	19.0/10
5.0 mils	5.83 ± 0.91	111 ± 9	30.7 ± 4.9		44.4 ± 2.0	50.0 ± 28.3	16.0/10
AP2180.B							
2.5 mils	2.71 ± 0.06	170 ± 3	41.0 ± 1.1		47.1 ± 0.8	50.0 ± 7.1	15.3/10
5.0 mils	2.85 ± 0.06	166 ± 3	32.5 ± 1.5		48.3 ± 1.4	50.0 ± 9.6	11.9/10
AP2180.C							
2.5 mils	1.28 ± 0.03	222 ± 5	37.6 ± 1.4		44.4 ± 1.1	50.0 ± 12.9	10.1/10
5.0 mils	1.56 ± 0.12	199 ± 11	33.7 ± 3.5		45.1 ± 2.6	50.0 ± 26.4	7.3/10
MR2980 (Solar Flare)							
2.5 mils	61.7 ± 3.9	67.2 ± 2					
5.0 mils	79.7 ± 5.9	62.3 ± 2					
Thermal Synchrotron							
Spectrum	C_1 $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	ϵ (keV)	C_2 (keV)		Absorption Line		χ^2 / ν
					Energy (keV)	Width (keV)	
AP1980.RS2							
2.5 mils	6.09 ± 0.26	11.6 ± 0.4	33.8 ± 2.7		50.2 ± 2.7	33.0 ± 6.1	11.6/10
5.0 mils	6.23 ± 0.26	11.6 ± 0.4	26.8 ± 3.4		51.4 ± 4.3	33.0 ± 10.1	13.3/10

The parameters in this table are described in the legend of Table 5.2 on page 169.

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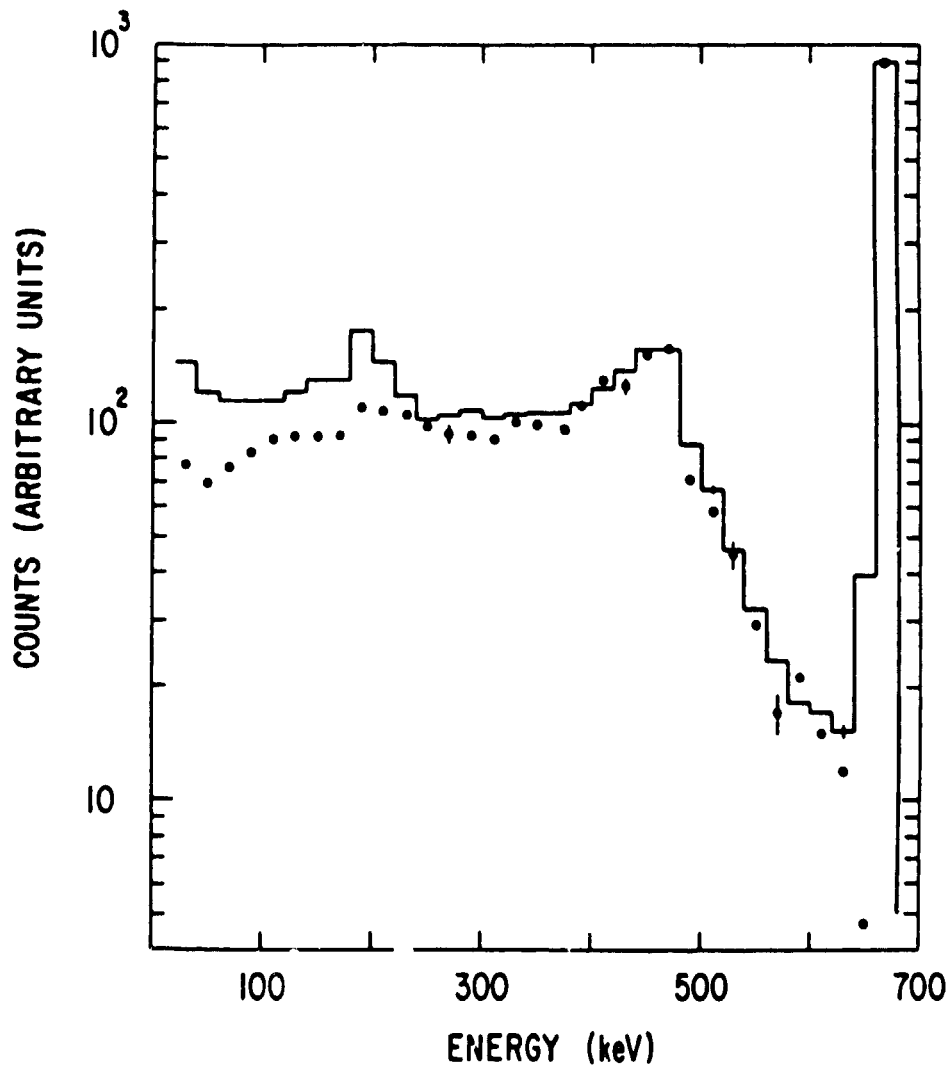


Fig. 3.1. Response of a Ge(HP) detector to 662 keV photons from a ¹³⁷Cs source (points) compared to Monte Carlo simulation (histogram). The photopeak and the Compton and backscatter continua are evident.

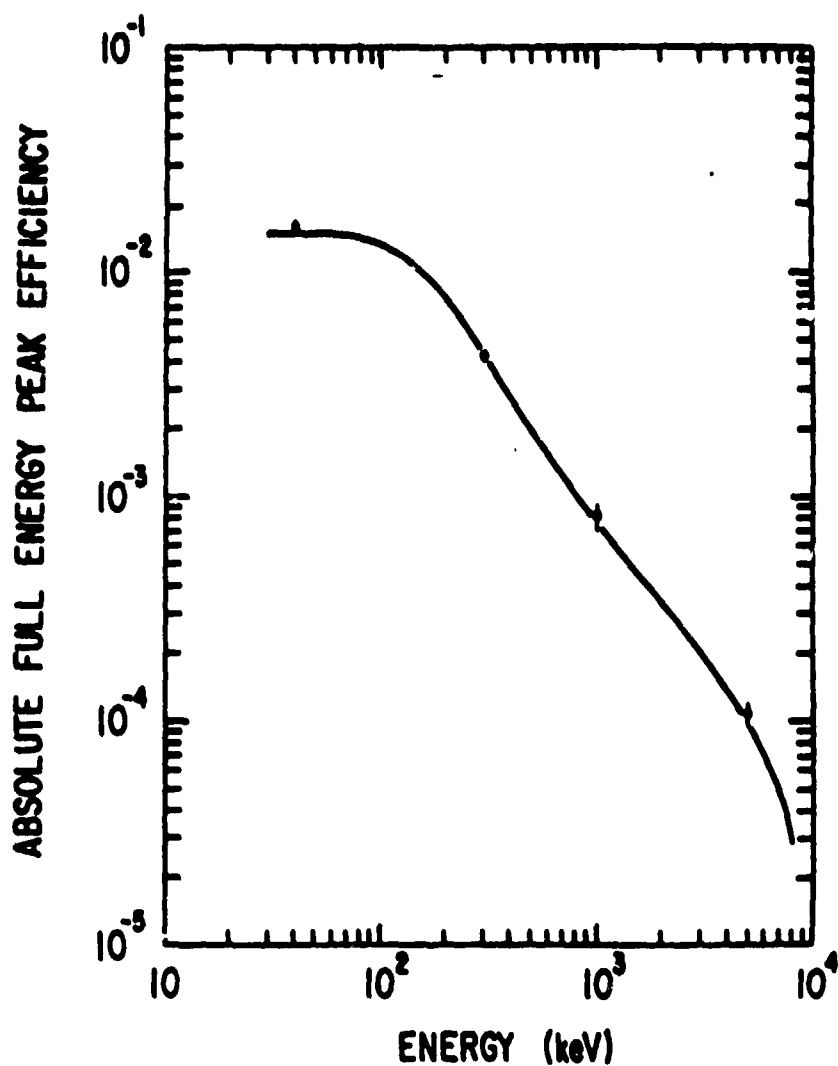


Fig. 3.2. Comparison of photopeak efficiencies determined from Monte Carlo simulation of Ge(HP) detector response (points) to results of Seyfarth et al. (1972), indicated by solid curve.

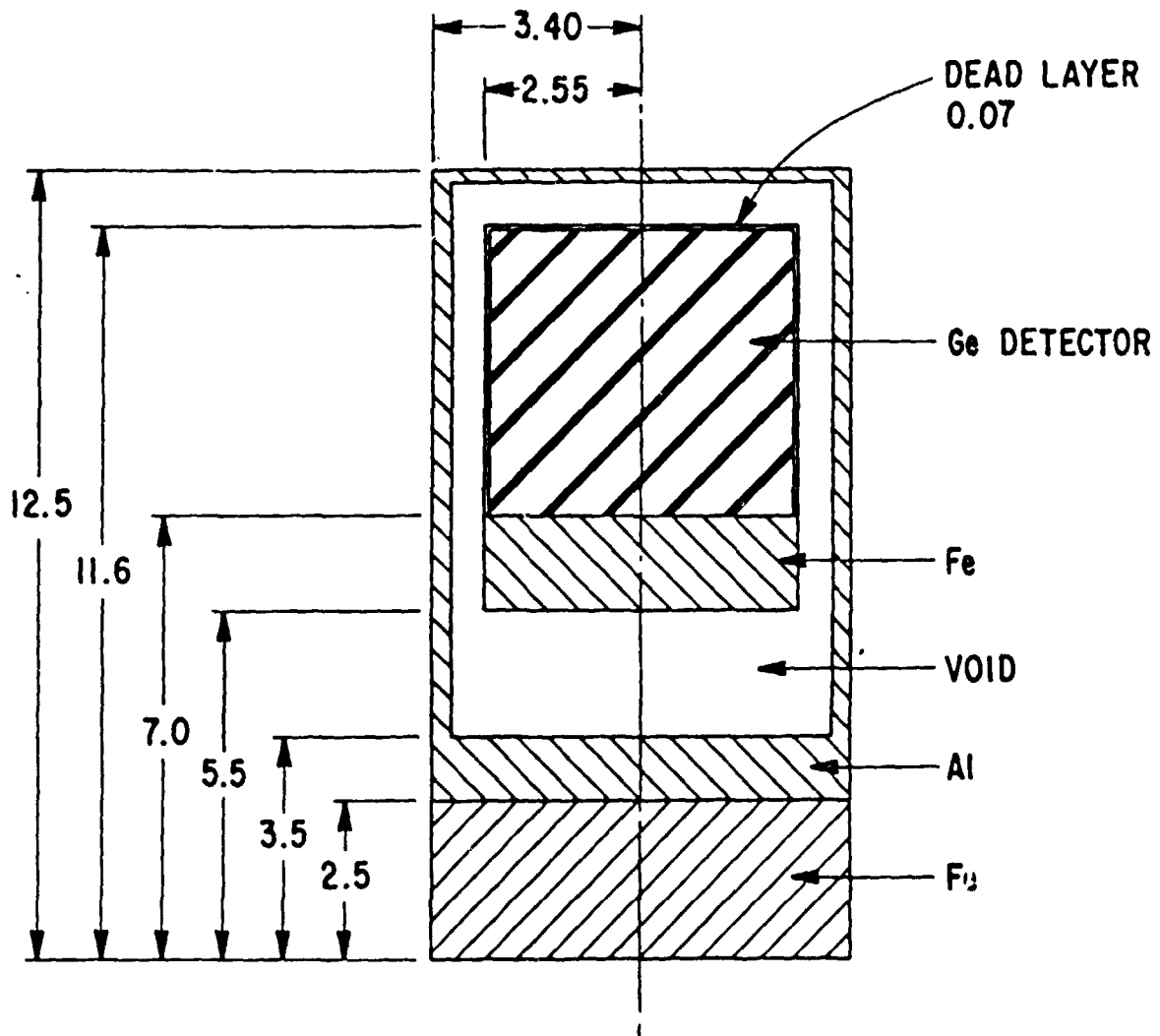


Fig. 3.3. Schematic of simulated arrangement for a Ge(HP) detector.

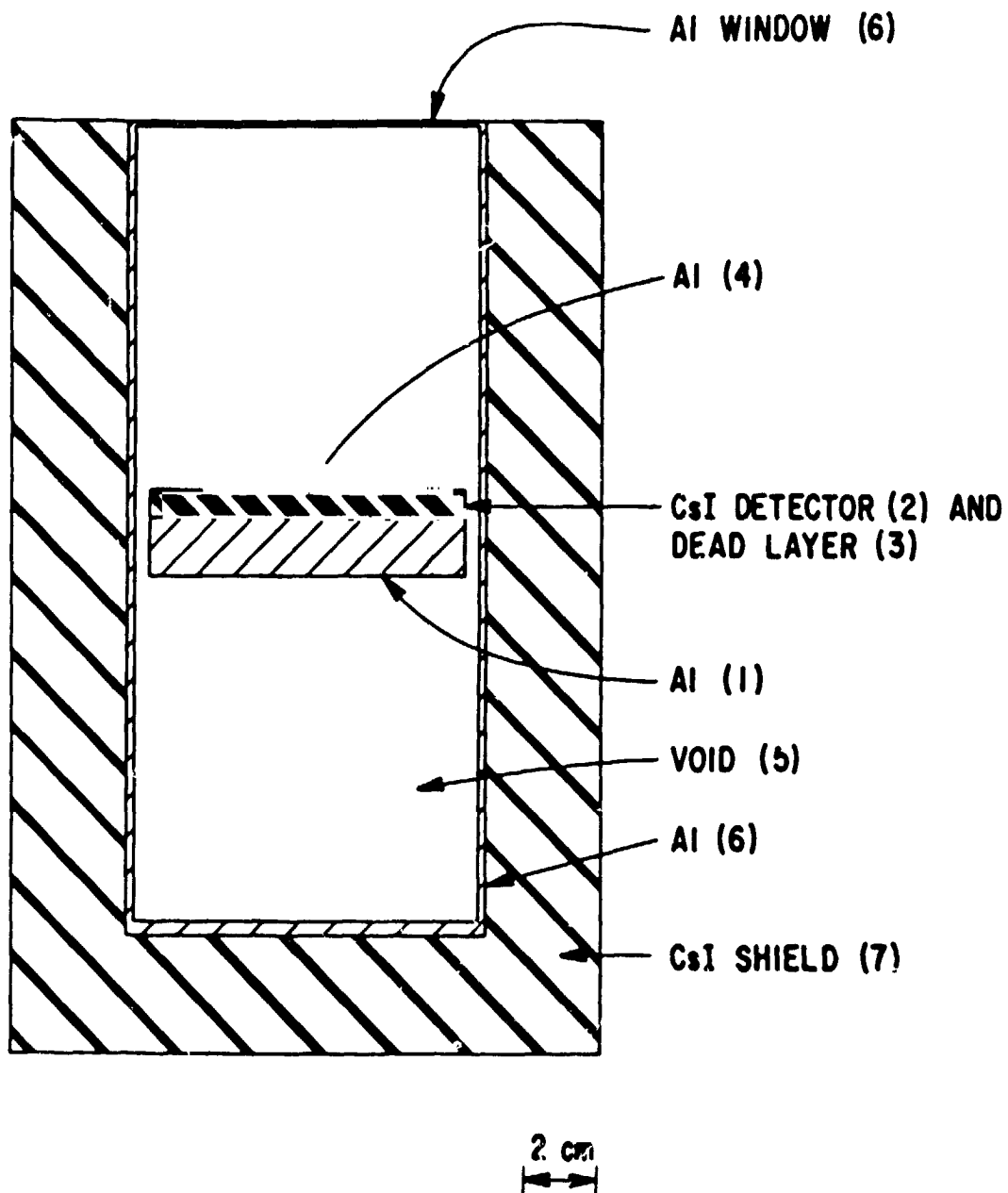
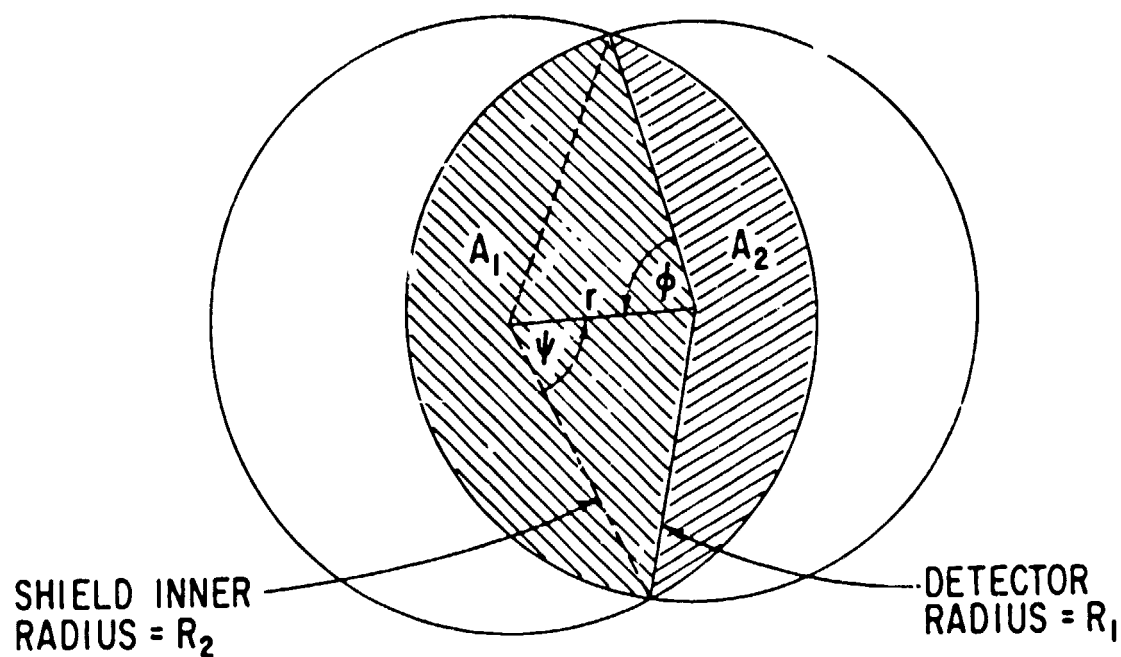


Fig. 3.4. Schematic of simulated arrangement for Hard X-Ray Burst Spectrometer detector and shield.



FOR $r > R_2 - R_1$

$$A_{\text{EFF}} = (A_1 + A_2) \cos \theta = (\phi R_1^2 + \psi R_2^2 - r R_2 \sin \psi) \cos \theta$$

Fig. 3.5. Geometry of HXRBS aperture. θ is the angle of incidence relative to the instrument optical axis. $r = h \times \tan(\theta)$, where h is the distance from aperture to detector, 9.9 cm.

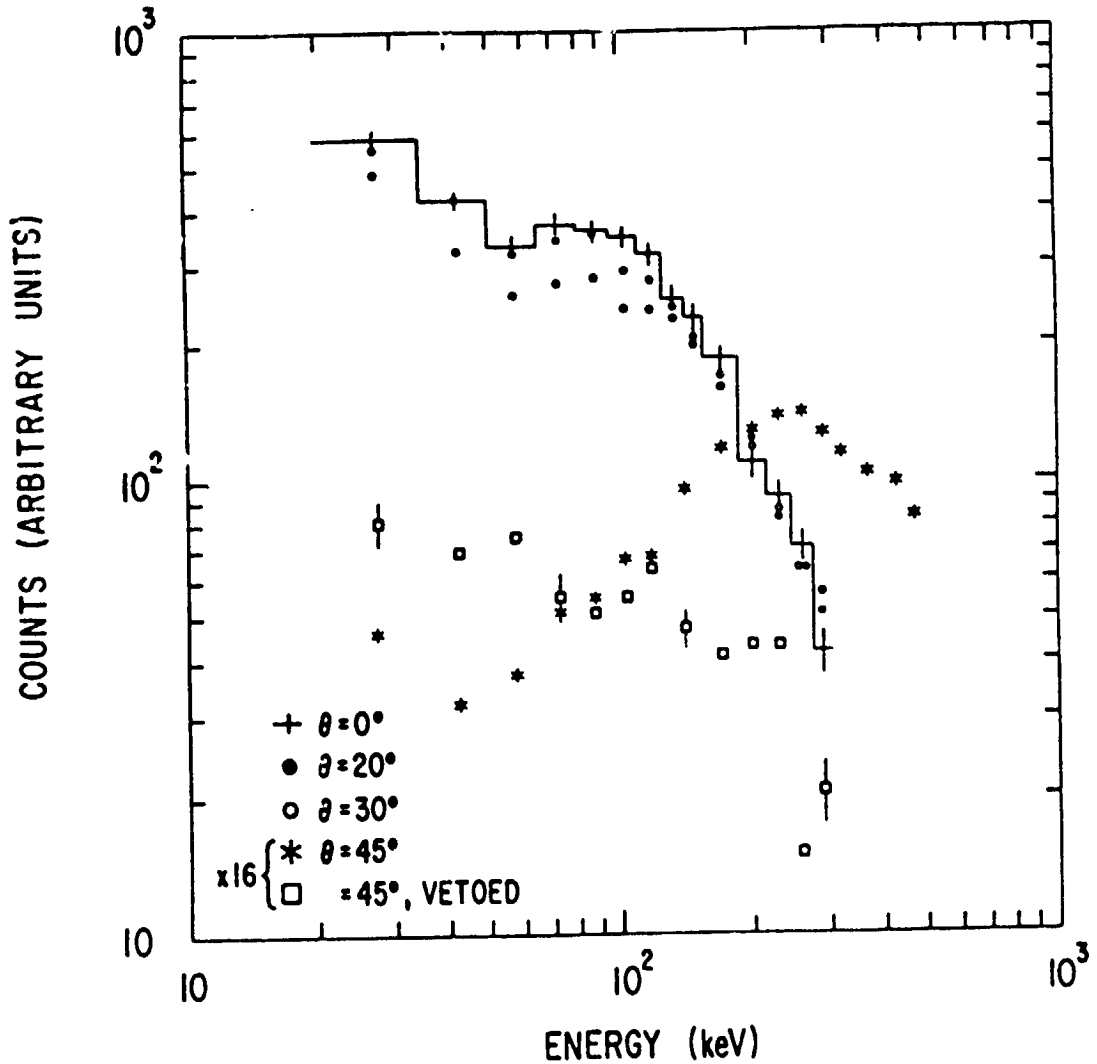


Fig. 3.6. Monte Carlo simulation of dependence of HXRBS detected spectra on angle of incidence for $\theta = 0^\circ$, 20° , 30° , and 45° . The errors for $\theta = 20^\circ$ and 30° are comparable to those shown for $\theta = 0^\circ$. The shield-vetoed spectrum for the 45° run is also illustrated.

CHAPTER IV

ISEE-3 TIME HISTORY ANALYSIS

A. Outline

The time histories (T.H.) of γ -ray bursts detected by ISEE-3 and their analysis are presented in this chapter. The T.H.'s can be classified into three broad categories. The very narrow (~ 0.1 s) spike-like events, compact events (several seconds), exhibiting multiple pulse structures, and the longer lasting (> 30 s) extended events are discussed separately. In some of the extended bursts, the T.H.'s exhibit apparently periodic structure.

Even though no spectral data were available from the ISEE-3 detectors, it was possible to obtain a measure of the nature and evolution of the spectrum of a burst from the ratio of instantaneous counting rates of two detectors with different energy thresholds (E_{thr}). The ratio of the Ge ($E_{thr} \sim 125$ keV) to the CsI ($E_{thr} \sim 70$ keV) counting rates integrated over equal time intervals was calculated for this purpose. A tendency for the bursts to exhibit hard-to-soft spectral evolution was found.

The ratio of Ge-to-CsI peak detector counts indicates that the spike-like bursts are softer spectrally than compact bursts, confirming the KONUS result (Mazets et al. 1981f).

The ISEE-3 data base contains a much larger fraction of spike-like bursts than does any previous experiment. It is argued that the ISEE-3 data more correctly represents the true proportion of spike-like bursts.

B. Temporal Analysis

A chronological listing of all the ISEE-3 events with time of occurrence, detector identification, appropriate parameter constants, and confirmation by other spacecraft is presented in Table 4.1.

As elaborated in chapter II, ISEE-3 employed a unique method for triggering on and recording transient events. The rate data are inversely proportional to the number of clock counts with frequency FT necessary for the photon counter to overflow. Hence, the relative error associated with each accumulation interval is constant and proportional to $\sqrt{N}/N$ (N = photon counter setting).

Two peculiar effects result from the technique for photon accumulation. First, more intense intervals are recorded with higher time precision than less intense intervals. Second, all events which achieve an instantaneous rate equal to or above the threshold are detected. In contrast, most experiment trigger criteria require a set level of integrated counts above background in a given time interval; hence, among bursts with equal peak flux near a given limit of sensitivity, longer duration events are preferentially detected.

In section 1, the longer duration (compact and extended = "classical") bursts detected by ISEE-3 are discussed. A relatively large fraction of the total number of events, compared to other experiments, are short duration (< 1 s) bursts. These events, which probably constitute a separate class, are discussed in section 11.

1. Classical Bursts

The T.H.'s of all classical type ISEE-3 bursts are illustrated in Figures 4.1 through 4.32, a total of 15 events. For most events both

the CsI (TH1) and Ge (TH2) detector T.H.'s were recovered. Both are illustrated if available. Figure 4.31 is the HXRBS shield T.H. of the event 26 SEP 81, one of at least five events observed in common by both experiments. THE 19 APR 80 and 02 JUN 80 bursts, also of the classical type, were detected by both ISEE-3 and the HXRBS. The 19 APR 80 burst is extensively discussed in chapter V. The 02 JUN 80 burst was only marginally discernable in the HXRBS shield rate data and therefore the shield T.H. is not illustrated. In addition, two spike-like ISEE-3 events were seen in the HXRBS shield (see section ii).

Quite often, gaps in the ISEE-3 T.H. data occurred, sometimes during interesting portions of events. The gaps have been filled in with a rate of 10 cts/s, significantly below the background level of 60 to 100 cts/s, to indicate interjacent intervals with no data. Occasionally, the T.H. will begin or end in the middle of the event. In these cases nothing is plotted in the intervals with no data.

The CsI T.H.'s are severely modulated due to the location of the detector on the spinning spacecraft (3 s spin period) and the detector's sensitivity to soft γ -ray photons which are strongly absorbed by the spacecraft material if not incident directly upon the detector. For approximately 25% of each cycle, however, the view is 80% or more transparent (see Figure 2.5). A particularly good illustration of the effect of modulation is seen in Figure 4.9, the CsI T.H. for the long event 13 FEB 80. The Ge T.H. (Figure 4.10) does not show significant modulation. The lack of Ge detector modulation is attributable to its open view location close to the spacecraft spin axis, orientation along the spin axis, and sensitivity to hard γ -ray photons which penetrate surrounding material without significant attenuation.

Note that the CsI detector photon counter setting (N) was 64 and 128 for the 07 MAR 79 and 13 FEB 80 bursts, respectively, rather than the usual value of 32 (see Table 4.1). The effect of higher counter settings is reflected in the smoother CsI temporal profiles and smaller statistical errors in these two cases.

a. Compact Bursts

Classical γ -ray burst T.H.'s exhibit complex behavior with usually more than one main structure, or pulse. Each pulse can be seen to consist of several subpulses if observed with sufficiently fast time resolution. Upon inspection, one finds that many bursts approach intervals of local maximum intensity gradually, with small pulses generally building to larger pulses. Examples of such behavior are displayed in events 04 NOV 78 (Figures 4.1 & 4.2), 07 MAR 79 (Figures 4.6 & 4.7), 05 NOV 79 (Figure 4.12), 17 APR 80 (Figures 4.13 & 4.14), 02 JUN 80 (Figures 4.15 & 4.16), 23 JUL 80 (Figures 4.18 & 4.19), 01 AUG 81 (Figures 4.21 & 4.22) and 30 SEP 81 (Figures 4.24 & 4.25). The durations of the main portions of these events, excluding small precursors and subsiding pulses, which exist in some cases, are 12 s, 20 s, >10 s and <25 s (long data gap at end of 05 NOV 79), 15 s, 14 s, 5 s, 12 s, and 10 s, respectively. These events may be characterized as compact with profiles usually contained within one or more closely spaced quasi-triangular envelopes.

The events 19 NOV 78 (Figures 4.3 & 4.4), also compact, and 13 FEB 80 (Figures 4.9 & 4.10) rise more abruptly from the background level. Still in both cases, short (~ 0.2 s) but significant rises directly precede the first large pulses. The 19 NOV 78 event is the famous burst

whose small (5 arcmin^2) error box contains an X-ray source (Cline et al. 1981; Grindley et al. 1982) The X-ray box is consistent with the position of an optical stellar flare image discovered on a 1928 plate (Schaefer 1981).

For some of the classical type bursts it was possible to compute hardness indices from ratios of the Ge-to-CsI detector count rates as a function of time, and thereby investigate the burst spectral evolution qualitatively. Two criteria were required in order to construct the ratio for a burst. First, only bursts qualified for which the Hovestadt CsI and Ge detectors operated; the Meyer CsI detector produced data which were too noisy to be of value for such calculations (see Table 4.1 for operational detectors during each event). The second requirement was that the CsI T.H. continue for a sufficient period during which the unmodulated intervals were unambiguously discernable. These criteria obtained for five events: 07 MAR 79, 13 FEB 80, 02 JUN 80, 23 JUL 80, and 01 AUG 80. Hardness indices were computed only for intervals modulated no more than 20% by summing counts above background within equal intervals for the CsI and Ge T.H.'s and taking the Ge:CsI ratio. The sampling then necessarily occurs with the spin period of 3 s and with a duty cycle of 25%.

The hardness index versus time is illustrated in the figure following the pair of T.H.'s for an event. The index is plotted only for those intervals during which both averaged detector rates are significantly above the background level. Sometimes the most intense phases in the Ge T.H. occur during the CsI modulated phase, leaving in question the value of the index for interesting intervals.

In all five events for which the hardness index was computed, marked spectral evolution occurs, sometimes from one integration interval to the next (3 s separations). One may expect spectral hardness to vary on time scales comparable to large intensity fluctuations, which are sometimes much faster than the 3 s spin cycle. In fact, some burst spectra from the SIGNE experiment do exhibit evolution on time scales of a few $\times 10$ ms (Barat et al. 1983a).

The 07 MAR 79 burst (Figure 4.8) exhibits the hardest spectral intervals in the middle of the burst with softest spectra in the initial and final intervals. The harder intervals are correlated with the most intense portions of the burst. The same correlation is seen in the 02 JUN 80 (Figure 4.17) burst. For this burst, two sequences of hard indices correlated with intense intervals evolving to softer indices occur. For the 01 AUG 81 burst (Figure 4.23) the hardness index remains practically constant during the event except for the last interval which is softer than the preceding ones. For the 23 JUL 80 burst (Figure 4.2) the intervals for which the hardness index was computed evolve towards softer spectra. However, in this event, two short pulses in the Ge T.H. occur during modulated portions of the CsI T.H. The common feature in these four bursts is soft emission in the final stage of the event.

The 13 FEB 80 burst has a unique temporal profile. Although this burst is classified as extended, it has the appearance of two long compact events separated by about 15 s (total duration ~ 70 s). The hardness index (Figure 4.11) varies in an apparently random manner with no correlation with intensity. This burst displays a wealth of significant fast temporal variations. Perhaps the 1 s integrations for the hardness index obscure a finer pattern of evolution in this case.

For comparison, many KONUS events for which several spectra were recorded display a pattern of initially hard with subsequent evolution to softer spectra. This pattern sometimes repeated during a burst with the later occurring hard intervals correlated with intense phases of the burst (Mazets, et al. 1981d), thus resembling the 02 JUN 80 and 23 JUL 80 events.

b. Extended Bursts

In addition to 13 FEB 80, three more ISEE-3 events are categorized as extended. The events of 18 APR 79 (Figures 4.26 & 4.27), 20 MAR 82 (Figures 4.28, 4.29 & 4.30), and 26 SEP 81 (Figures 4.31, 4.32 & 4.33) are similar in other respects. All three display a predominant pulse of width (FWHM) ~ 1 to 3 s (26 SEP 81 displays two such major pulses). Small precursor pulses occur 19 s (18 APR), 54 s (20 MAR), and 34 s (26 SEP) before the predominant pulse. Additional pulses occur between precursor and predominant pulse in each case. The common pattern is increasing intensity with succeeding pulses.

For comparison, about two-thirds of the events in the KONUS catalog have T.H.'s of the compact variety, whereas about 20% of the KONUS events may be categorized as extended, displaying longer duration T.H.'s. Occasionally interruptions up to 30 or 40 s between main burst structures are observed in KONUS events, during which the count rate is virtually background level.

The T.H.'s of these extended bursts exhibit structures which suggest periodicity. In the 18 APR 79 (Figures 4.26 & 4.27) T.H., the small precursor at about 50.5 s, and the centroids of the larger pulses at 60.4 s and 70.3 s are separated by 9.9 s. In 20 MAR 82 (Figures

4.28, 4.29 & 4.30) pulses at 47.0 s, 83.0 s, and 101.0 s would form a series with a period of 18.0 s save for the missing member at 65 s. And in 26 SEP 81 (Figures 4.31, 4.32 & 4.33), precursor centroid at about 22.3 s and main pulses at 39.0 s and 55.7 s (ISEE-3 times) are separated by 16.7 s. At 29.5 s a small but significant peak appears which is $\approx 155^\circ$ out of phase with the other features.

Also in 26 SEP 81, the two main pulses in the unmodulated HXRBS shield and Ge T.H.'s are both double-peaked. The initial peaks in the first double-peaked pulse from the two T.H.'s have nearly the same separation as do the corresponding peaks in the second double-peaked pulse. The interval between the conjugate peaks forming each double peak is in each case ≈ 0.6 s, about 0.035 of the apparent pulse period. A similar periodic double-peaked pattern is apparent in the 13 JAN 79 event (a member of the series is missing in this case; see Helios-B T.H. in Figure 1.3, the ISEE-3 T.H. has a 16 s gap during the initial portion of the burst).

Two other bursts, 05 MAR 79 (Cline 1980) and 29 OCT 77 (Wood et al. 1981) exhibit damped sinusoidal structure. In contrast, the three extended bursts discussed here exhibit pulses which are narrow compared to the separations. Only three or four apparent periods are discernable above background level (compared to 22 cycles for 05 MAR 79 and 6 cycles for 29 OCT 77). In order to specify conservatively and appropriately the uncertainty in the proposed periods ($\Delta P/P$), the ratios of half-width of widest pulse (at about zero amplitude) to apparent period were calculated. In order to determine a more formal uncertainty, one would assume a functional form for a modulation envelope (e.g. sinusoidal)

and perform a fit to the data. However, the exact modulation form is camouflaged by the intrinsic burst temporal evolution.

Wood et al. (1981) show there exists a theoretical minimum to the accuracy with which a period may be specified for finite event durations. In analogy to the uncertainty principle, the theoretical minimum $\Delta P/P$ increases as the burst duration decreases,

$$\delta\omega \times D \gtrsim 1 \quad (4.1)$$

with $\omega = 2\pi/P$ and D = event duration. In Table 4.2 the theoretical minimum achievable and observed $\Delta P/P$ are listed for each event. The observed ratios are ~ 1 to 3 times the theoretical minimum achievable accuracy. Hence, this method for determining $[\Delta P/P]_{\text{obs}}$ yields values consistent with the limitation (4.1). The best period determination is for the 26 SEP 81 burst, $[\Delta P/P]_{\text{obs}} \sim [\Delta P/P]_{\text{theo}} = 0.08$, for which the event duration is 37 s.

The apparent periods manifested in the extended events discussed above and 05 MAR 79 and 13 JAN 79 are of the same order of magnitude, ranging only over a factor of three: 5.5 s, 8.0 s, 9.9 s, 16.7 s, 18.0 s. Twenty percent of the bursts detected by ISEE-3 (27% percent of the "classical" type) show some evidence of periodicity. Several KONUS bursts show evidence for quasi-periodic or periodic structure (Loznikov and Kuznetsov 1982).

The hardness indices, where produceable, of the three extended events that show evidence of periodicity, are softer than the maximum spectral hardness attained by the compact bursts and the other extended burst 13 FEB 80 (see Table 4.4). In the 20 MAR 82 burst, the precursor

pulses at 47 s and 83 s have hardness indices ~ 0.2 and ~ 0.3 , respectively. These peaks appear to be (un)modulated to the same degree as the main pulse, being in spin phase with it. There is a data gap in the last, largest pulse. For the portion of this pulse observed by both detectors the hardness index is about 0.4. In the 26 SEP 81 event, spin modulation appears to have reduced the CsI T.H. precursor pulse and first main pulse (cf. HXRBS shield T.H.). The last pulse has a hardness index of about 0.3. For the 18 APR 79 burst only part of the last pulse was seen by both detectors; the hardness index is ~ 0.6 .

11. Spike-like Bursts

Out of twenty-four events detected by ISEE-3 from September 78 to May 82, nine may be characterized as spike-like with durations less than one second (Figures 4.34 through 4.49), fast rise times, and usually no discernable substructure other than an exponential decay. The 05 MAR 79 burst is included in this category for two reasons: 1) the eight-second oscillation would not have been discernable had the intensity of the initial spike-like pulse been comparable to classical burst peak intensities, and 2) the spectrum of the initial pulse is much softer than classical burst spectra. Spike-like burst spectra tend to be characteristically soft (Mazets et al. 1981f, and Table A.2)

Six out of nine of the spike-like bursts have been confirmed to be of cosmic origin by other spacecraft. For the remaining three, 15 MAR 79, 12 MAY 79, and 08 MAR 82, the CsI T.H. was not recovered nor were the events detected by another spacecraft. The Ge detector, which did record these bursts, is not sensitive to charged particles which simulate spike-like bursts in CsI scintillator detectors. The next few

paragraphs provide justification for the reality of these three unconfirmed events.

In all three events the burst consisted of a single accumulation interval of width comparable with the confirmed events' durations. Nevertheless, the single-interval accumulations may be statistical fluctuations. Hence, the amplitude of each burst above background must be analyzed in order to determine the probability that the trigger was due to random fluctuations.

If the observed counts are distributed in time according to Poisson statistics, the probability of obtaining v counts within a given time interval τ is

$$P(v) = \frac{x^v}{v!} e^{-x} \quad (4.2)$$

where $x = R\tau$ and R is the background rate level. To find the probability of occurrence of v counts in an interval shorter than or equal to τ , one integrates,

$$\begin{aligned} P(v)_{\Delta t \leq \tau} &= \int_0^x \frac{x^v}{v!} e^{-x} dx \\ &= 1 - e^{-x} \sum_{r=0}^{v-1} \frac{x^r}{r!} \end{aligned} \quad (4.3)$$

A typical background interval from a Ge T.H. was examined to determine if the distribution of count rates was indeed Poisson. For the range of rates present in the T.H., 30 to 140 cts/s, the Poisson distribution (eq. 4.2) adequately represented the actual distribution. Table 4.3 lists for the spike-like events: the peak rates, rise times, widths

(FWHM and τ , full width at about zero amplitude), background levels, probabilities of events being statistical fluctuations, and expected intervals between fluctuations equal to or greater than the peak rates observed. τ is determined by the formula Peak Rate = v/τ (in all cases $v = 32$), and the expected interval is obtained from eq. 4.3 using $T = \tau/P(v) \big|_{\Delta t < \tau}$. From the table, one sees that a statistical fluctuation as large or larger than the 08 MAY 82 peak is expected once per two years. The other two unconfirmed events have peaks which are expected to be equalled or exceeded by background fluctuations once within six or more lifetimes of the experiment. Therefore, for purposes of further discussion, the reality of the (unconfirmed) 15 MAR 79 and 12 MAY 79 bursts will be assumed.

The rise times and widths were determined from the CsI T.H. if it was recovered since it has the better statistics. Otherwise the Ge T.H. was used. The widths measured from the CsI T.H.'s, when available, agree with the Ge T.H. widths. Characteristic rise times are tens of τ s. The range in widths (FWHM) of the spike-like bursts is ~ 0.05 s to 0.36 s with an average of 0.15 s (Table 4.3). In four events, 05 MAR 79, 22 MAR 80, 31 DEC 81, and 19 MAY 82, short decays are present. In the CsI T.H. for 06 AUG 80 a build up and decay are present. The total event durations range from 0.2 s to ~ 1 s.

A qualification is necessary concerning measurement of short durations with finite statistics from the ISEE-3 T.H.'s. Since the count rate data are generated by counting clock pulses necessary for N photons to be detected, for a given detector area the observed width is a function of N , the burst intensity, and the intrinsic burst width. Lower N , higher intensity or larger area result in recording the burst

with better time resolution (and, of course, lower N results in worse statistics). Hence, the observed FWHM and rise times are probably somewhat larger than the intrinsic widths, especially for the events in which the burst is recorded in only one or two time intervals.

For comparison, the FWHM and FWZA for the short duration, soft spectra KONUS events are listed in Table A.2. The KONUS experiment records the initial stage of a burst with $1/64$ s (16 ms) time resolution. The rise time is usually faster than the 16 ms time resolution (Mazets et al. 1981f). The average width is 0.09 s. Because of the qualification on ISEE-3 resolution mentioned above, the KONUS average width, 40% lower than the ISEE-3 mean, is probably more representative of intrinsic burst widths. For the KONUS soft, spike-like bursts, a decay is usually observed with characteristic duration ~ 0.1 s to 0.3 s. Hence, taking into account the ISEE-3 qualification on resolution, the temporal characteristics of ISEE-3 and KONUS spike-like events are comparable.

Both T.H.'s were recovered for five ISEE-3 spike-like events. For four of these bursts the ratio Ge:CsI peak counts above background was calculated to produce peak hardness indices (see Table 4.4). In the remaining case, (05 DEC 80), the CsI T.H. peak is obviously diminished by spin modulation. The hardness index for 05 MAR 79 is 0.49. This serves as a fiducial for spike-like events; the spectrum of the 05 MAR intense initial spike is very soft ($kT \sim 45$ keV for a thermal bremsstrahlung fit without gaunt factor, see Table A.1 for comparison with other KONUS spectra) compared to classical burst spectra. The 05 MAR index is very well determined since its ratio was calculated using the several accumulation intervals comprising the high intensity peak.

The 05 MAR CsI T.H. is not modulated since the triangulated source direction is very close to the south ecliptic pole, the satellite spin axis.

The three other spike-like events (Table 4.4) have peak hardness indices comparable to or softer than that for 05 MAR. The values range from 0.45 to 0.22. Note however, the errors are considerably larger than for 05 MAR. The peak hardness indices for spike-like events should be considered upper bounds since only one-fourth of the CsI T.H. is 80% or more unmodulated; the CsI peaks may have been reduced by modulation.

For comparison, the maximum values of the hardness index for the compact and extended bursts are also listed in Table 4.4. The index is typically ≥ 1.0 , indicative of the hard spectra which compact bursts attain. For a few additional compact events, for example 30 SEP 81, it is not clear where the modulation occurs in the CsI T.H. and hence hardness indices were not calculated. However, in these cases the overall burst hardness appears comparable to the compact burst indices which were computed. The three extended events with evidence of periodicity also exhibit hardness indices significantly less than compact bursts. A possible explanation for this behavior is introduced in section C.

In summary, the ISEE-3 spike-like events for which peak hardness ratios are produceable prove to be similar spectrally to the KONUS spike-like events. Nearly all short duration KONUS events have very soft spectra (Table A.2).

Compared to other γ -ray burst experiments, the Teegarden ISEE-3 experiment has detected a very large percentage of spike-like events, 33%. In particular, for the KONUS experiment, the corresponding

percentage is 3%. The figure is based on KONUS events for which spectra are available. All short duration (<1 s) bursts with thermal bremsstrahlung fits of $kT < 50$ keV are included (10 out of 124).

Although the ISEE-3 experiment is one of the least sensitive γ -ray burst detectors, the ISEE-3 data set is probably more representative of the true proportion of spike-like events. To show that this is the case, one must first examine the burst trigger mechanisms for both experiments. The ISEE-3 trigger has already been described; if N photons are counted by the experiment within a preselected number of clock pulses (TH) with frequency FT , the trigger threshold ($N \times FT / TH$) is exceeded and burst recording is begun. All bursts which deliver an instantaneous count rate equal to or greater than the trigger threshold are detected. Thus, if burst spectra were not correlated with durations, sources with equal instantaneous flux would be sampled without bias for duration.

The KONUS trigger mechanism is representative of conventional experiments. Counts are integrated by two rate meters with effective time constants of 0.3 s and 1.5 s and compared to a background ratemeter with a 30 s time constant. A ≥ 6 sigma rise above the background initiates recording of the burst (Mazets et al. 1979). In Figure 3 of Mazets et al. (1979), the estimated threshold sensitivity of the KONUS experiment, assuming square burst shapes, is plotted versus duration. According to this graph, threshold fluences required to trigger the recording apparatus for bursts of duration 0.1 s, 1 s, and 10 s are 1.6×10^{-7} , 4.3×10^{-7} , and 2.6×10^{-6} erg cm^{-2} , corresponding to (average) fluxes of 1.6×10^{-6} , 4.3×10^{-7} , and 2.6×10^{-7} erg $\text{cm}^{-2} \text{s}^{-1}$,

respectively. Hence, long bursts are detected at lower flux levels than short bursts.

The difference in thresholds translates into a difference in detection limits for sources of luminosity L and distance d . The ratio of threshold fluxes for 0.1 s (spike-like) and 10 s (compact) bursts is

$$\frac{F_{0.1}}{F_{10}} = \frac{L_{0.1}}{L_{10}} \left\{ \frac{d_{10}}{d_{0.1}} \right\}^2 = 6.2 \quad (4.4)$$

If the assumption is made that the luminosities of the two types of bursts are comparable, the ratio of volumes sampled is

$$\left\{ \frac{d_{10}}{d_{0.1}} \right\}^3 = 15. \quad (4.5)$$

Another implied assumption is that the two source distributions are isotropic and homogeneous out to the distance inferred by thresholds of sensitivity and assumed luminosities, i.e., galactic structure is not a factor. Given the present understanding of γ -ray bursts, these assumptions are interdependent and not completely justifiable, and are made only for the purpose of illustrating the dependence of KONUS threshold sensitivity on duration and therefore on flux. However, the nearly isotropic distribution of burst localizations (Figure A.1) suggests isotropy of sources, indicating that observations are presently limited by experiment sensitivities rather than by the galactic source distribution geometry.

At the least, relation 4.4 obtains for the KONUS experiment, whereas

$$\frac{F_{0.1}}{F_{10}} = 1 \quad (4.6)$$

for the ISEE-3 experiment (ignoring spectral differences between classical and spike-like bursts). Hence, the ISEE-3 data set represents the proportion of spike-like events without the complication of an additional duration-dependent sensitivity factor (besides the unknown factors, source distributions, and ratio of characteristic luminosities).

The ISEE-3 sample is considerably smaller than the KONUS catalog. Therefore, one must question, is the percentage of spike-like events detected by ISEE-3 actually significantly greater than the KONUS spike-like percentage? The binomial distribution is appropriate for the small sample of ISEE-3 events. Assume the KONUS sample is truly representative of the parent populations of spike-like and classical bursts; the probability of occurrence of a spike-like event is then $p = 10/124 = 0.08$. The probability of observing x or more spike-like events from a sample of n is

$$P_b(>x, n, p) = \sum_{i=x}^n \frac{n!}{i!(n-i)!} p^i (1-p)^{n-i} \quad (4.7)$$

The probability of observing eight or more spike-like events out of twenty-four is 4×10^{-4} . If only the six confirmed ISEE-3 spike-like events are considered, the probability is still only 1×10^{-2} . These low probabilities and the argument presented above concerning trigger

criteria are strong evidence that previous burst experiments have under-represented the true proportion of spike-like bursts.

C. Discussion

The phenomenological division into two classes of bursts, one with soft spectra, short durations, and one with hard spectra and longer durations, is not clear cut. Two short duration KONUS events have thermal bremsstrahlung temperatures above 50 keV, the events of 06 APR 79 and 13 JUN 79. The 06 APR 79 event has an unusually hard spectrum even for classical type bursts. There is an inconsistency in the spectra reported for the 13 JUN 79 event by the KONUS and SIGNE investigators. The KONUS spectrum exhibits a temperature of ~ 87 keV (Table A.2), whereas the SIGNE spectrum is ~ 660 keV (Barat et al. 1983b). The difference in the reported spectra may be attributed to a possible anisotropic response of the KONUS detector system. This is suggested by a correlation of Venera spacecraft positions with burst localizations, spectral hardness, and fluence (Laros et al. 1982).

Nevertheless, the solitary short pulses and soft spectra of most spike-like bursts compared to the protracted multiple-pulse profiles and hard spectra of compact bursts suggest that fundamentally different physical mechanisms are operating in the two categories of bursts. This is suggested by Figure A.4, a histogram of the thermal synchrotron fits for the KONUS spectra listed in Table A.1 (multiple spectra for a given event in some cases). There is a definite separate peak at $\epsilon_c \sim 0.6$ (ϵ_c is the critical energy, which characterizes the spectral hardness in the thermal synchrotron model; see chapter V). This peak is accounted for entirely by the spectra of spike-like events and the spectra of later

stages of classical bursts. The classical bursts tend to soften as the event progresses. Seven of these spectra are from the two repeating sources, the 5 MAR 79 source and B1900 +14, discovered by the KONUS investigators (Mazets et al. 1981f).

The sparse number of localizations for spike-like bursts are insufficient to form a picture of a source distribution (see Figure A.1) which might differ from that of classical bursts.

Extended burst and compact burst profiles differ in two respects: 1) extended bursts are longer with gaps of duration comparable to or longer than major pulse structures, and 2) structure suggestive of (quasi-) periodicity is evident mostly in extended bursts. However, extended and compact bursts are probably produced by the same kind of process. In the following discussion, a scenario is outlined to explain the dearth of observed periodicities in bursts. This possibility is expanded in chapter VI in a general discussion of burst characteristics.

The apparent observed periodicities in bursts are longer than radio pulsar periods (cutoff period ~ 1 s, Manchester and Taylor 1977) but comparable to the shorter periods (~ 10 s) of X-ray binary pulsars (White 1982). Wood et al. (1981) have shown that the convolution of a period distribution like that of X-ray binary pulsars (peaked at several tens of seconds) with the distribution of γ -ray burst durations (peaked at about 10 s) yields a small fraction of detectable γ -ray bursts with periodicities, consistent with existing γ -ray burst observations.

Then if γ -ray bursts come from objects with a period distribution like that of the X-ray pulsars, the geometry and degree of beaming of radiation and the period modulate individual source temporal profiles. For example, consider the 13 FEB 80 extended burst (Figures 4.9 &

4.10). The temporal profile may be explained by invoking an emission region covering approximately half of the star; the region rotates into view twice before the burst subsides.

The compact bursts may come from the more slowly rotating objects corresponding to the upper end of a period distribution like that of X-ray pulsars. The burst is observed when, during a burst episode, the emission region rotates into view. Yet no rotation period is detected because the period is longer than the event duration.

The three extended bursts with long gaps, presumably due to rotation, and narrow pulses, due to beaming, have softer spectral indices than the compact bursts and 13 FEB 80. The KONUS observations indicate that the hardest portions of bursts usually come in the initial phases; when hard intervals do recur during a burst, their durations are relatively short. It may be that during the long gaps in the extended bursts discussed here, the hard portions of these bursts were missed while the source was beaming in another direction.

The X-ray binary pulsar hypothesis requires a scenario which places the γ -ray burst source objects at $\sim \text{few} \times 100 \text{ pc}$ but renders the steady-state X-ray accretion undetectable (see chapter I). However, detected X-ray binary pulsars are concentrated at several kpc distances at low galactic latitudes towards the galactic center, whereas γ -ray burst localizations appear isotropically distributed. To explain the difference, Ventura (1982) has postulated a sequence in which a binary system consisting of a rapidly rotating neutron star and initially $0.1 M_{\odot}$ companion evolve through mass exchange. The neutron star's rotation is slowed by accretion torque and the system may eventually become

unbound. The resulting γ -ray burst system may lie at a distance of ~ 300 pc and X-rays from low accretion rates remain undetected.

Alternatively, and with less contrivance, the γ -ray burst sources may be old extinguished radio pulsars with rotation periods greater than ~ 5 s, or there may be neutron stars which are born with long periods. The galactic scale height for radio pulsars, determined from observations, is ~ 230 pc (Manchester and Taylor 1977) or ~ 380 pc (Gailly et al. 1979). The scale height for "dead" pulsars, given the estimated z velocity of 150 km s^{-1} (Manchester and Taylor), is then somewhat larger. If these are the γ -ray burst sources, then accretion from a companion star and interstellar accretion are improbable explanations of γ -ray bursts.

Table 4.1
ISEE-3 Cosmic Gamma-Ray Bursts

Date Dy/Mon/Yr	Trigger U.T.C.	N1 N2	FT1 FT2	TS1 TS2	TH1 TH2	Comments	Other Spacecraft
04/NOV/78	16:17:54	32 32	2048 4096	MEH Ge	4095 190		P7 V11 V12 PVO Velas
19/NOV/78	09:26:58	32 32	4096 2048	MEH Ge	4095 110		P7 V11 V12 PVO H-B Velas
13/JAN/79	07:35:59	32 32	1024 1024	HOH Ge	4095 110	CsI T.H. Not Aval.	P7 V11 V12 PVO H-B Velas
05/MAR/79	15:52:05	128 32	1024 1024	HOH Ge	4095 95		P7 V11 V12 PVO H-B Velas
07/MAR/79	22:18:52	64 32	1024 1024	HOH Ge	4095 95		P7 V11 V12 PVO
15/MAR/79	18:52:15	64 32	1024 1024	HOH Ge	4095 95	CsI T.H. Not Aval.	Unconfirmed
18/APR/79	07:41:09	32 32	1024 1024	HOH Ge	4095 95		P7 V11 V12 PVO
12/MAY/79	21:28:25	1 32	1024 1024	MEH Ge	4095 95	CsI T.H. Not Aval.	Unconfirmed
05/NOV/79	23:47:11	4 32	1024 1024	MEH Ge	4095 95	CsI T.H. Not Aval.	V11 V12 PVO H-B

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Table 4.1 — continued

<u>Date</u> <u>Dy/Mon/Yr</u>	<u>Trigger</u> <u>U.T.C.</u>	<u>N1</u> <u>N2</u>	<u>FT1</u> <u>FT2</u>	<u>TS1</u> <u>TS2</u>	<u>TH1</u> <u>TH2</u>	<u>Comments</u>	<u>Other Spacecraft</u>
13/FEB/80	07:29:12	128 32	1024 1024	HOH Ge	4095 95		PVO
22/MAR/80	07:21:59	32 32	1024 1024	HOH Ge	4095 95	CsI T.H. Not Aval.	PVO
17/APR/80	12:10:13	32 32	1024 1024	HOH Ge	4095 95		PVO
19/APR/80	01:19:44	32 32	1024 1024	HOH Ge	4095 95		PVO SMM
02/JUN/80	13:20:23	32 32	1024 1024	HOH Ge	4095 95		PVO SMM
23/JUL/80	13:47:28	32 32	1024 1024	HOH Ge	4095 95		PVO SMM
06/AUG/80	22:03:31	32 32	1024 1024	HOH Ge	4095 95		PVO SMM
05/DEC/80	09:41:36	32 32	1024 1024	HOH Ge	4095 95		PVO SMM
01/AUG/81	17:18:58	32 32	1024 1024	HOH Ge	4095 128		PVO SMM
26/SEP/81	18:3 39	32 32	1024 1024	HOH Ge	4095 128		PVO SMM

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Table 4.1 — continued

<u>Date</u> <u>Dy/Mon/Yr</u>	<u>Trigger</u> <u>U.T.C.</u>	<u>N1</u> <u>N2</u>	<u>FT1</u> <u>FT2</u>	<u>TS1</u> <u>TS2</u>	<u>TH1</u> <u>TH2</u>	<u>Comments</u>	<u>Other Spacecraft</u>
30/SEP/81	17:43:36	32	1024	HOH	4095		PVO
		32	1024	Ge	128		
31/DEC/81	07:58:28	32	1024	HOH	4095		PVO V13 V14
		32	1024	Ge	128		
20/MAR/82	13:10:41	32	1024	HOH	4095		PVO SMM V13 V14
		32	1024	Ge	128		
08/MAY/82	21:49:55	32	1024	HOH	4095	CsI T.H. Not Aval.	Unconfirmed
		32	1024	Ge	128		
19/MAY/82	11:01:10	32	1024	HOH	4095		PVO V13
		32	1024	Ge	128		

Legend. TS1 and TS2 are the operational detectors at the event time: Ge denotes the Teegarden germanium spectrometer; HOH, the Hovestadt CsI detector; MEH, the Meyer CsI detector. The N and FT values are the photon counter overflow and clock frequency settings (Hz), respectively, for detectors TS1 and TS2. TH1 and TH2 indicate the respective threshold settings (in Hz for N1 and N2 photons) for both detectors; a value of 4095 corresponds to infinity. Abbreviations for other spacecraft are: P7 = Prognoz 7; V11, V12, V13, and 14 = Venera 11 - 14; PVC = Pioneer Venus Orbiter; Velas = one or more Vela satellites; H-B = Helios B; SMM = Solar Maximum Mission.

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Table 4.2

Periodicities in Extended Events

Event Dy/Mon/Yr	Apparent Per (s)	Duration (s)	$\delta\omega$ (rad s ⁻¹)	$\{\Delta P/P\}_{\text{theo}}$ min	$\{\Delta P/P\}_{\text{obs}}$
18/APR/79	9.9	23	0.044	0.07	0.13
26/SEP/81	16.7	37	0.027	0.07	0.08
20/MAR/82	18.0	61	0.016	0.05	0.17

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Table 4.3

Attributes of ISEE-3 Spike-Like Events

Event Dy/Mon/Yr	Ge Peak (cts/s)	Backgnd (cts/s)	Est Rise (s)	FWHM (s)	FWZA (s)	$P(v)$ $\Delta t \leq \tau$	Fluctuation Interval (yr)
05/MAR/79	32500	105	< 0.0002	0.12	0.30	< 10^{-10}	> 27
15/MAR/79	520	83	0.03	0.06	0.06	< 10^{-10}	> 27
12/MAY/79	420	80	0.04	0.08	0.08	10^{-10}	24
22/MAR/80	360	70	0.05	0.36	1.1	10^{-10}	28
06/AUG/80	431	72	0.18	0.17	0.44	< 10^{-10}	> 27
05/DEC/80	607	53	0.04	0.05	0.19	< 10^{-10}	> 27
31/DEC/81	262	50	0.02	0.30	0.30	< 10^{-10}	> 27
08/MAY/82	278	82	0.06	0.12	0.12	1.7×10^{-9}	2
19/MAY/82	910	80	0.01	0.07	0.40	< 10^{-10}	> 27

$P(v)I_{\Delta t \leq \tau}$ is the probability of obtaining v counts in an interval shorter than or equal to τ , where $\tau = v/(R)$, R = peak count rate above background. The fluctuation interval $T = \tau/P(v)I_{\Delta t \leq \tau}$.

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Table 4.4

Peak Hardness Index
Event Ge Peak/CsI Peak

Spike-Like Type

05/MAR/79	0.49 ± 0.01
06/AUG/80	0.22 ± 0.05
31/DEC/81	0.38 ± 0.10
19/MAY/82	0.45 ± 0.11

Event Max Hardness Index

Compact Type

07/MAR/79	1.11 ± 0.16
02/JUN/80	0.18 ± 0.10
23/JUL/80	0.54 ± 0.05
01/AUG/81	1.37 ± 0.17

Extended Type

18/APR/79	0.57 ± 0.14
13/FEB/80	1.31 ± 0.19
26/SEP/81 *	0.31 ± 0.08
20/MAR/82 #	0.38 ± 0.10

* Last Pulse

Middle Pulse

Figures 4.1 - 4.49. Time histories of ISEE-3 gamma-ray bursts.

The time axis refers to Coordinated Universal Time. The suffixes to the event names represent the following:

TH1 = CsI time histories

TH2 = Ge time histories

SHD = HXRBS shield time histories for events observed in common
with ISEE-3

RAT = ratio of detector counts, Ge/CsI, for the 80% or more
unmodulated portions of the CsI time histories.

The shield plots have been shifted $\pm \lesssim 4.5$ s (light travel time,
ISEE-3 - SMM) to line up with the ISEE-3 plots.

The HXRBS shield accumulation interval is 64 ms.

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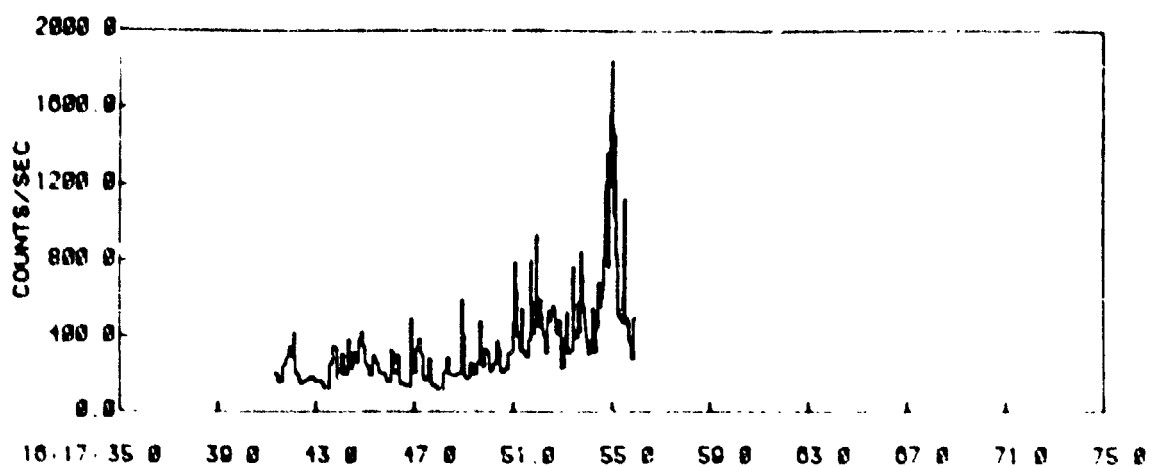


FIG 4 1 NV0478 TH1

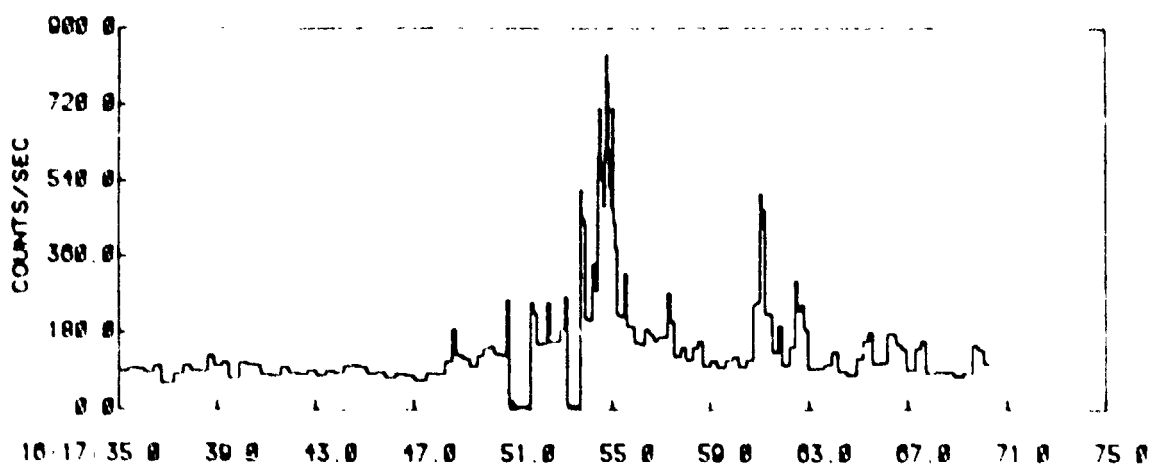


FIG 4 2 NV0478 TH2

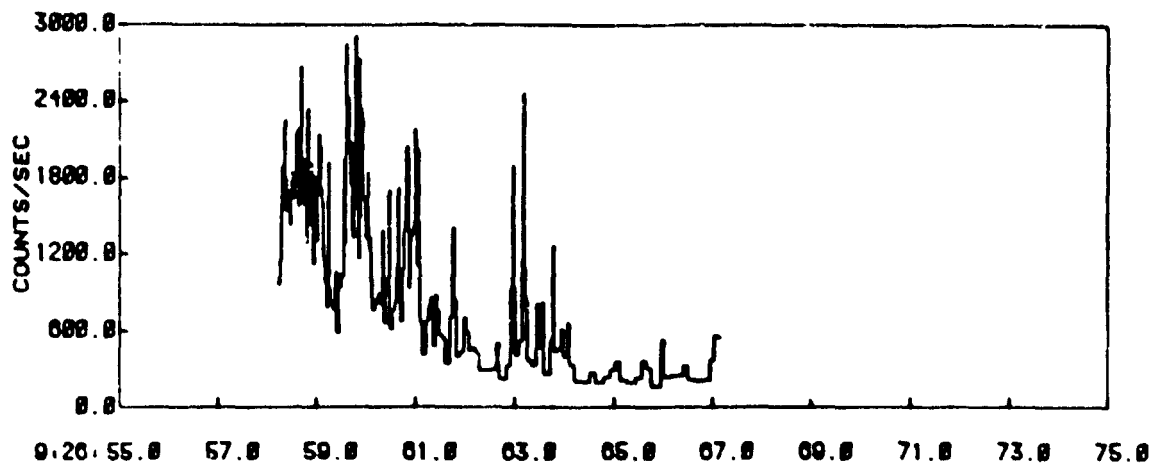


FIG. 4.3 NV1978.TH1

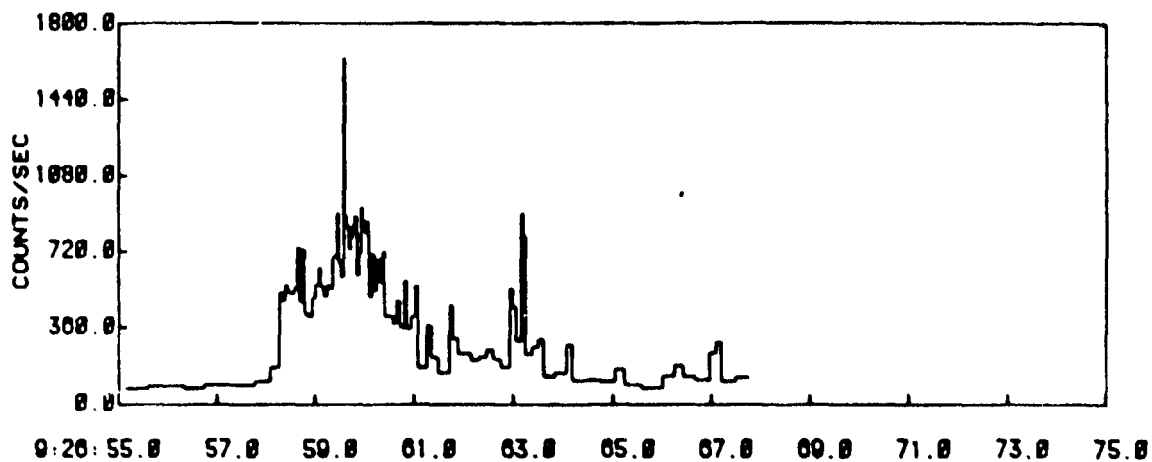


FIG. 4.4 NV1978.TH2

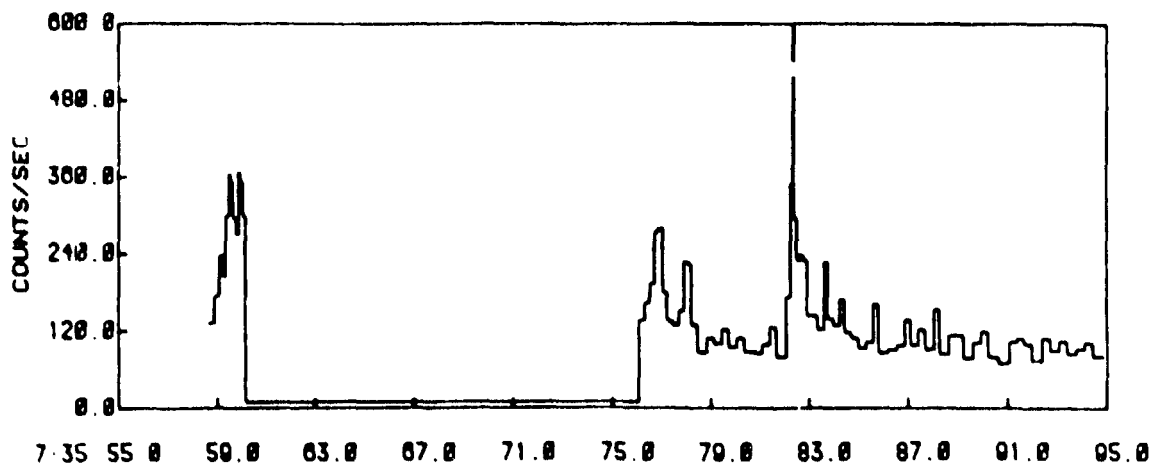
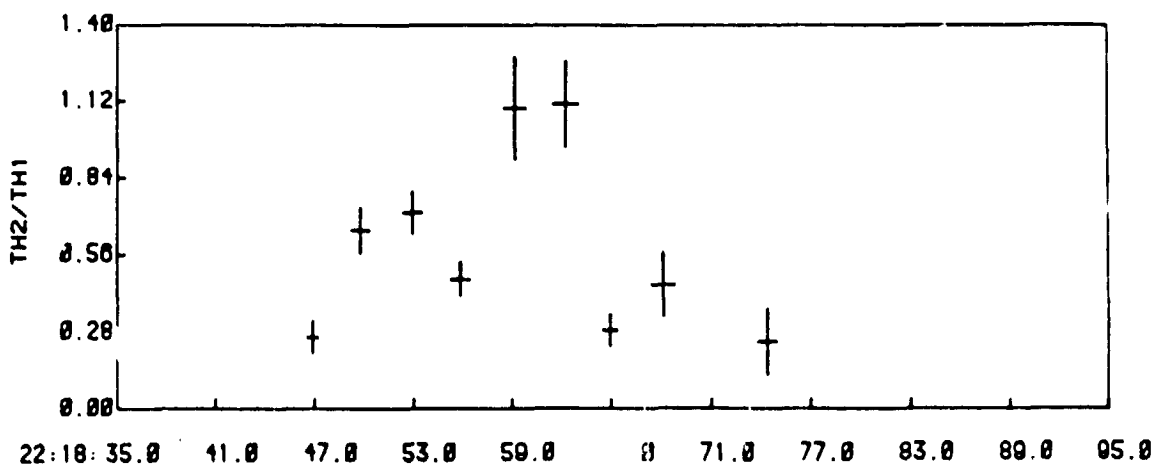
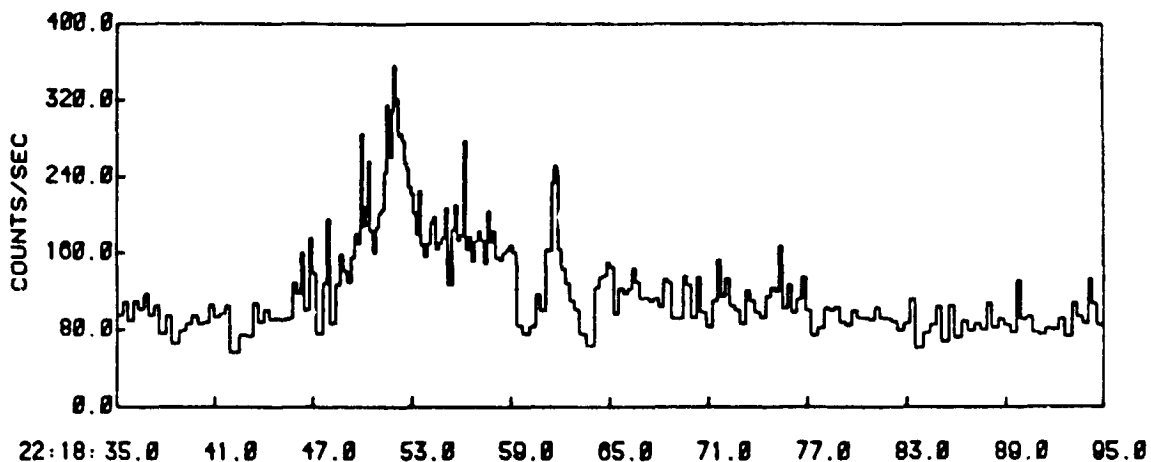
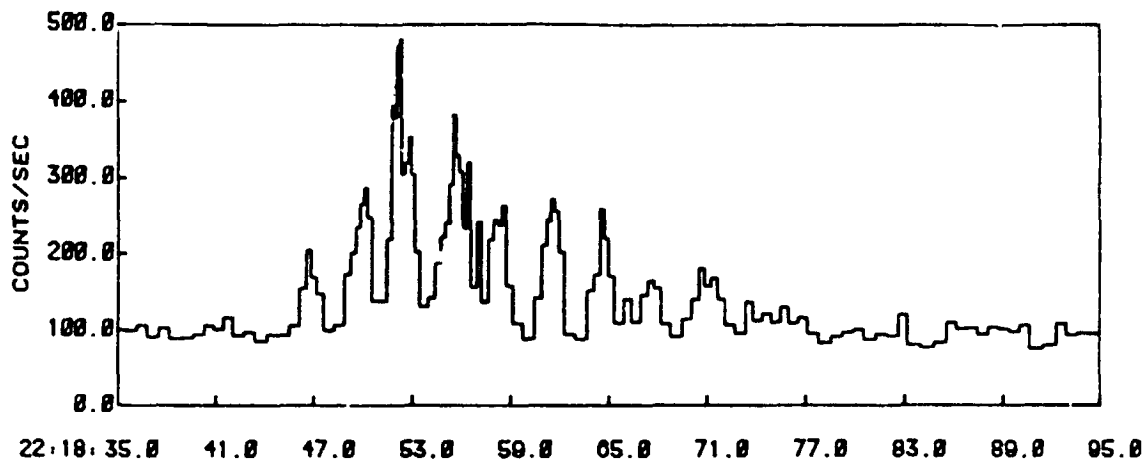
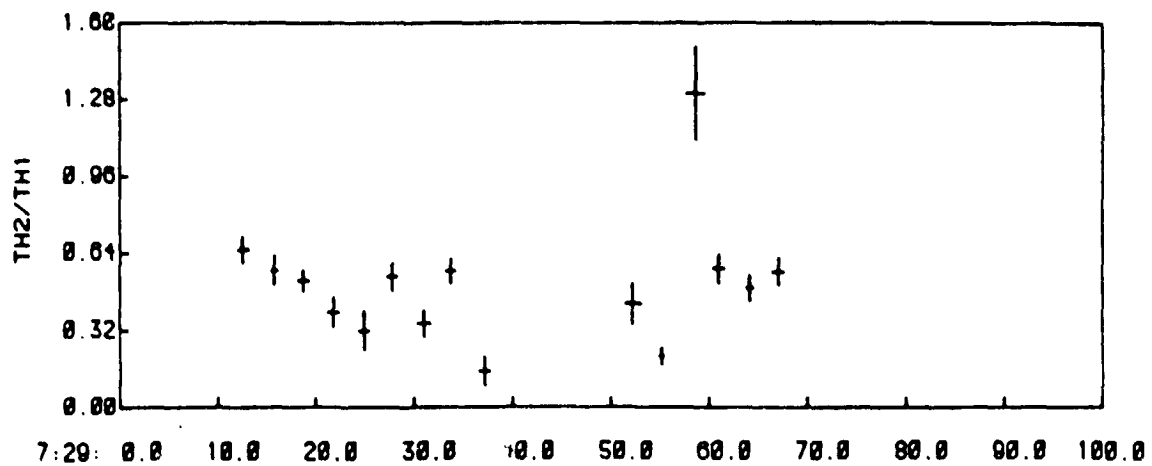
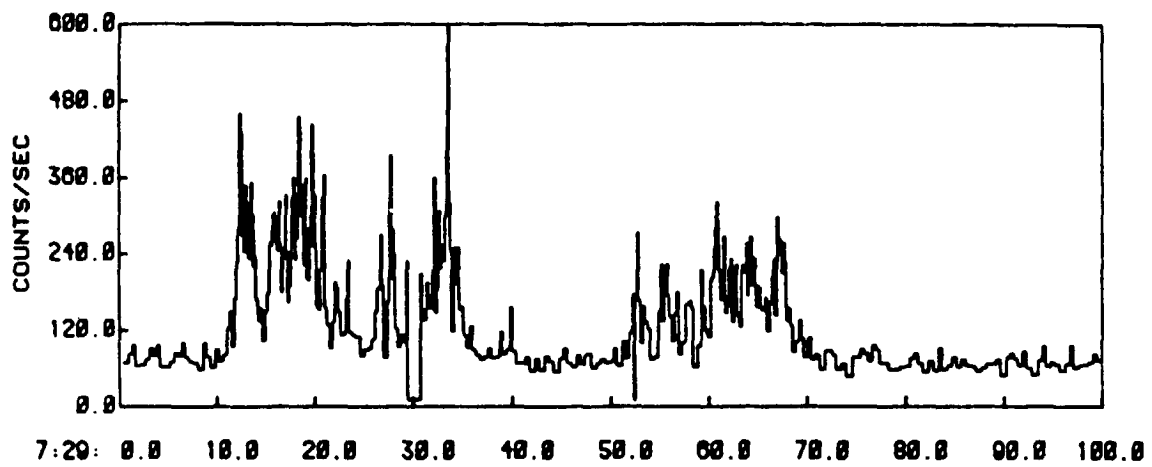
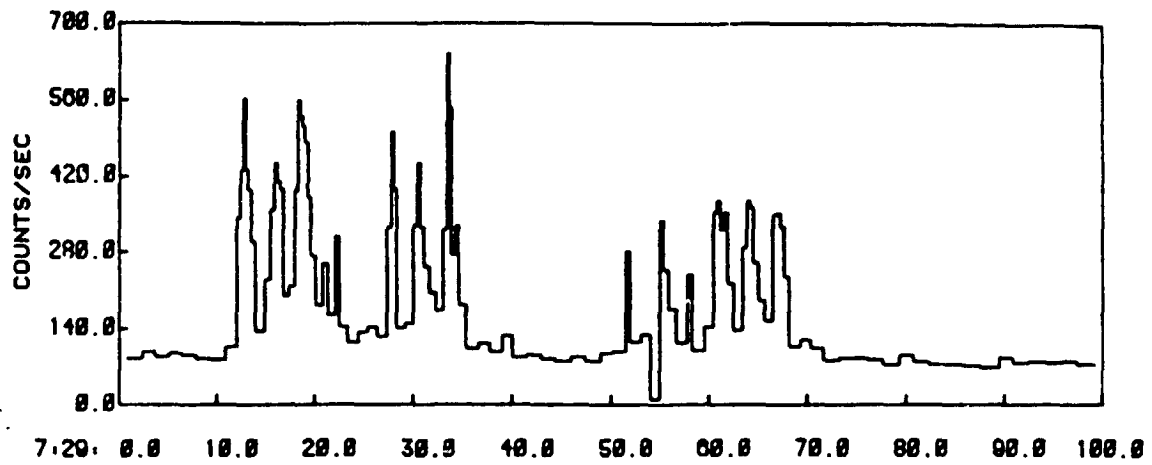


FIG. 4.5 JA1379.TH2





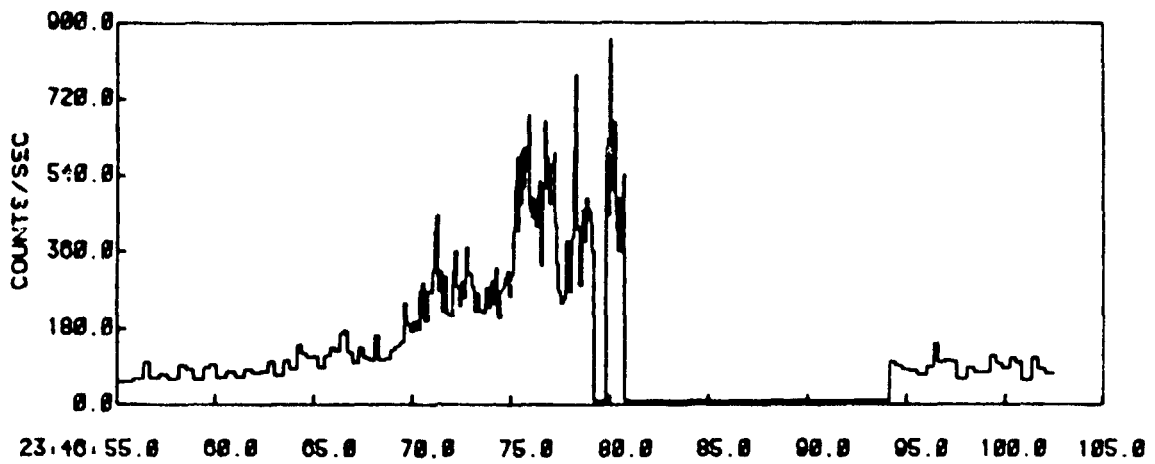


FIG. 4.12 NV0579.TH2

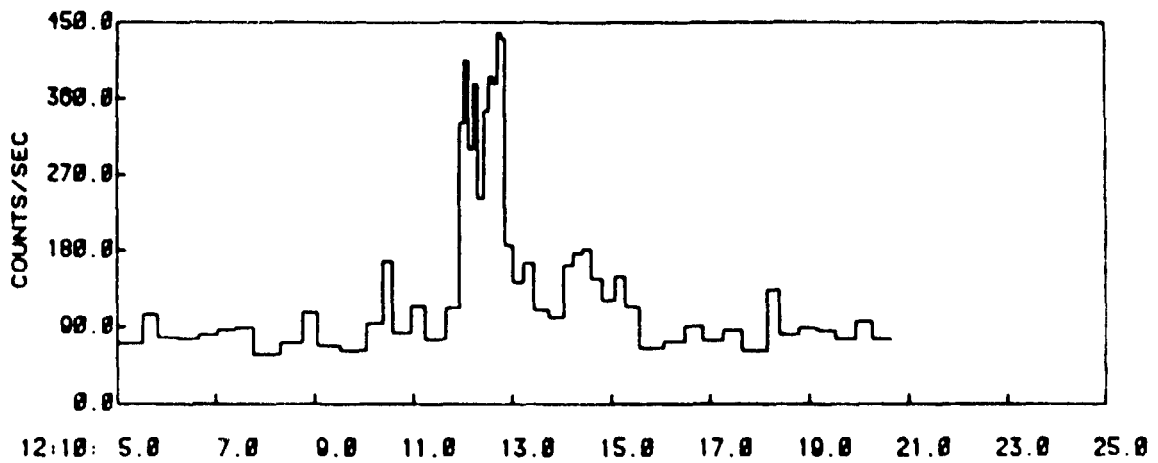


FIG. 4.13 AP1780.TH1

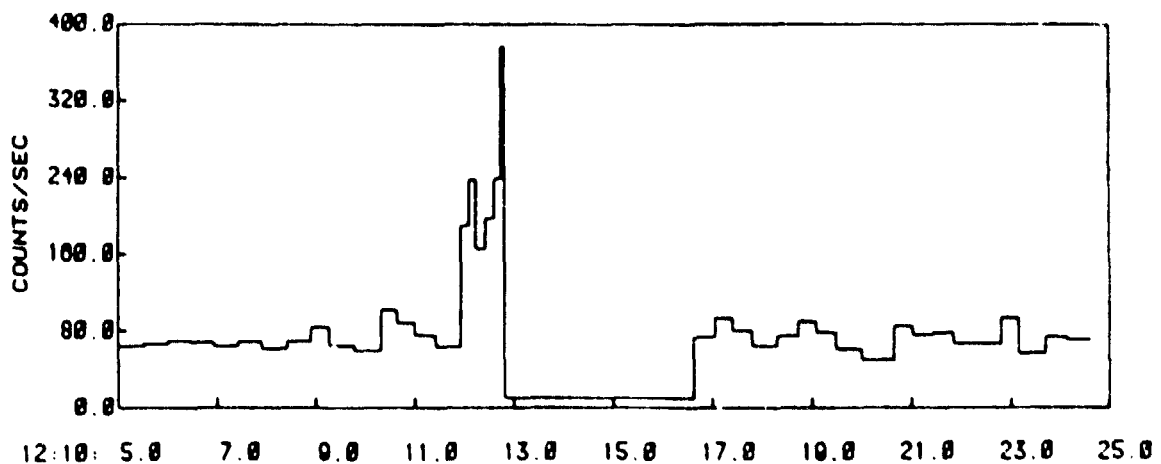


FIG. 4.14 AP1780.TH2

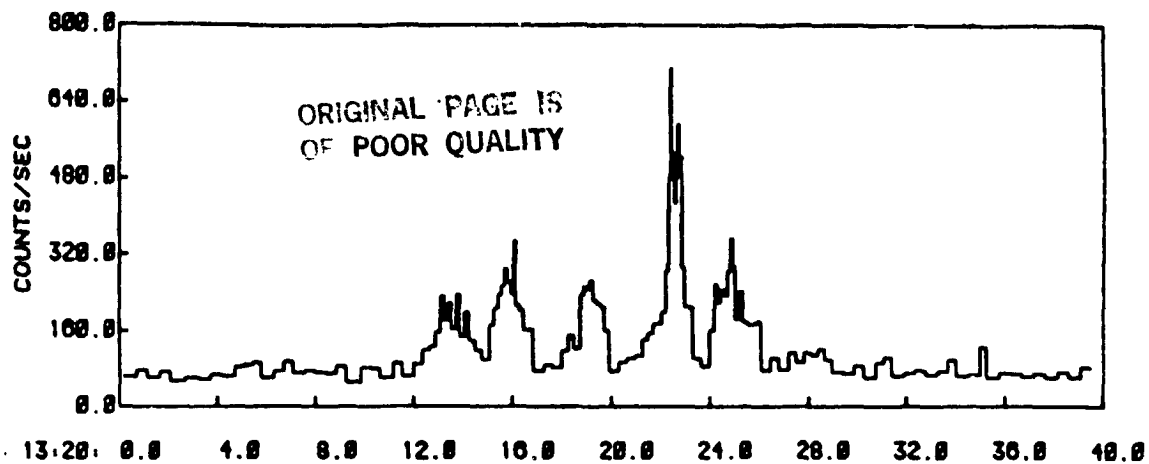


FIG. 4.15 JN0280.TH1

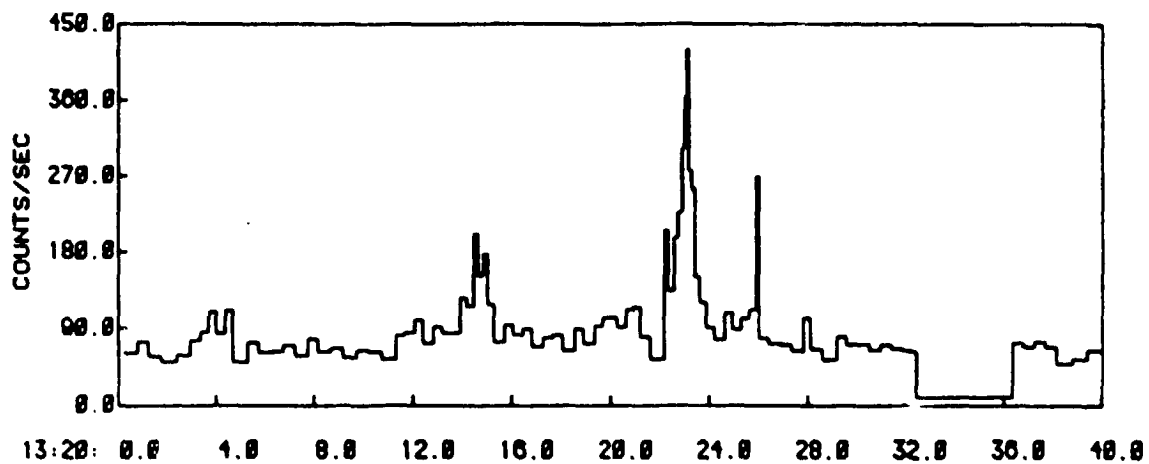


FIG. 4.16 JN0280.TH2

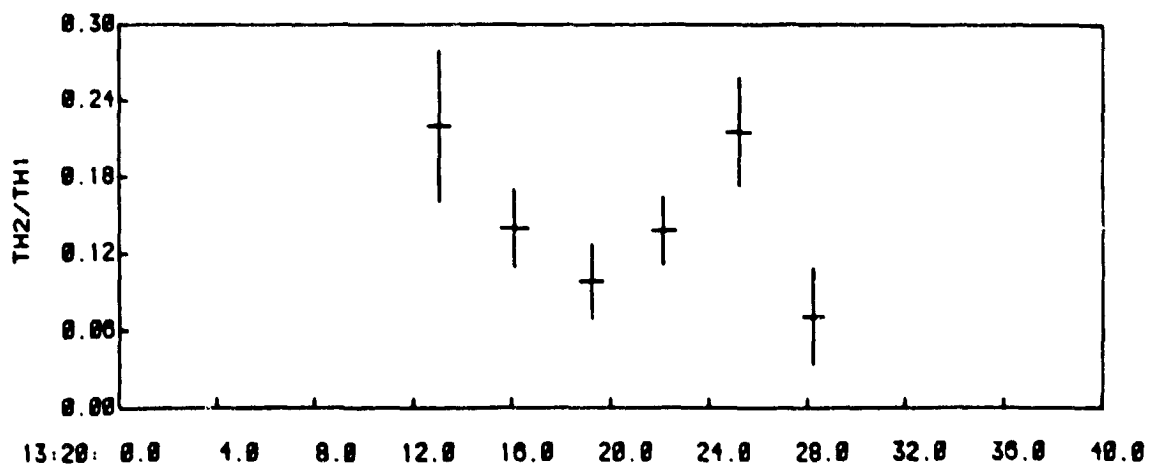
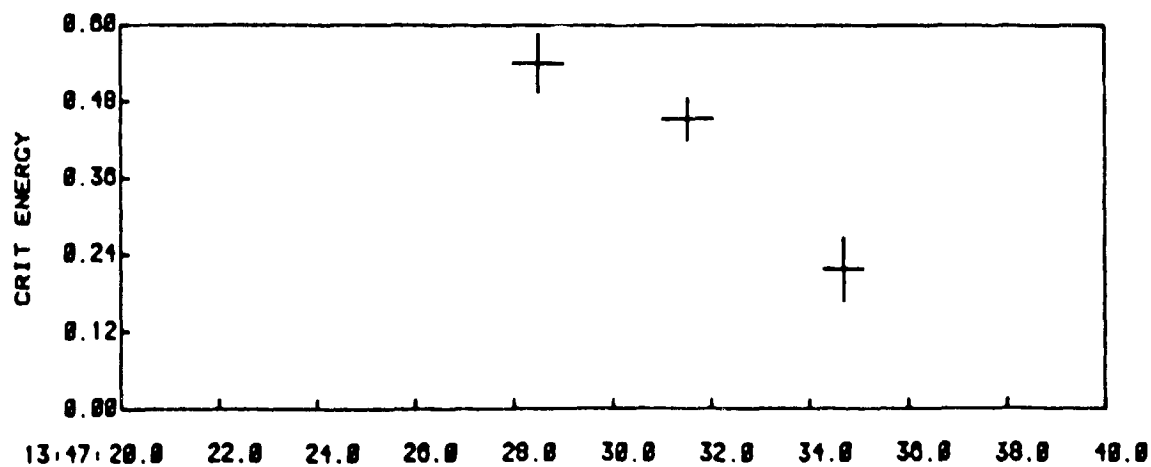
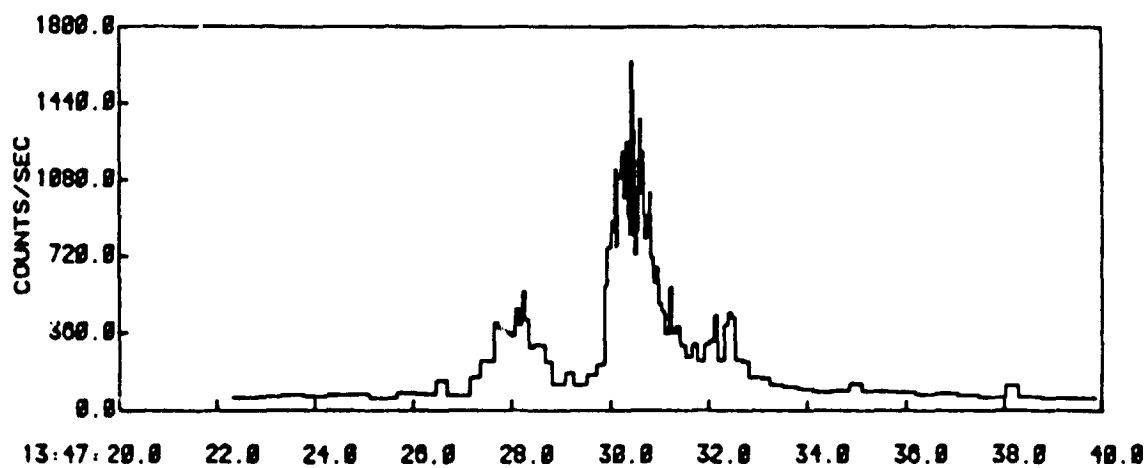
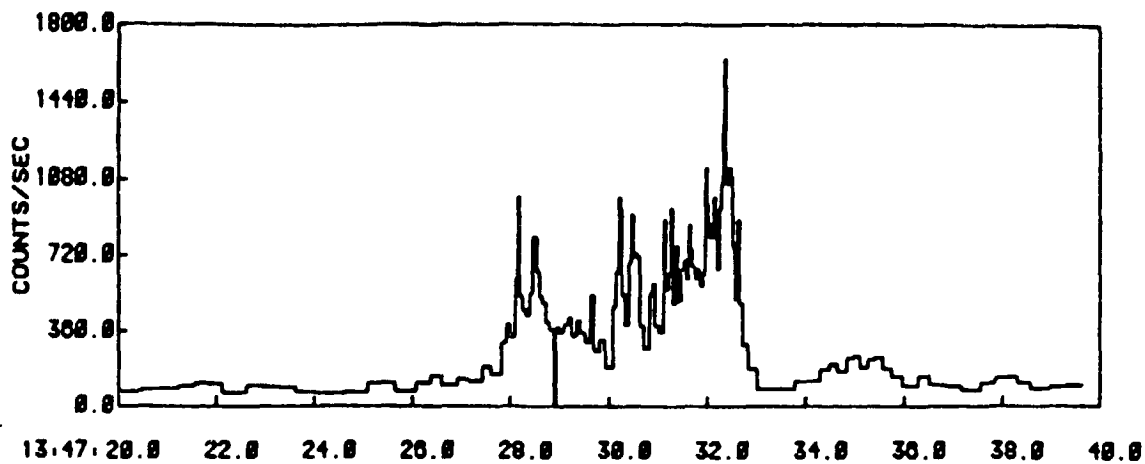
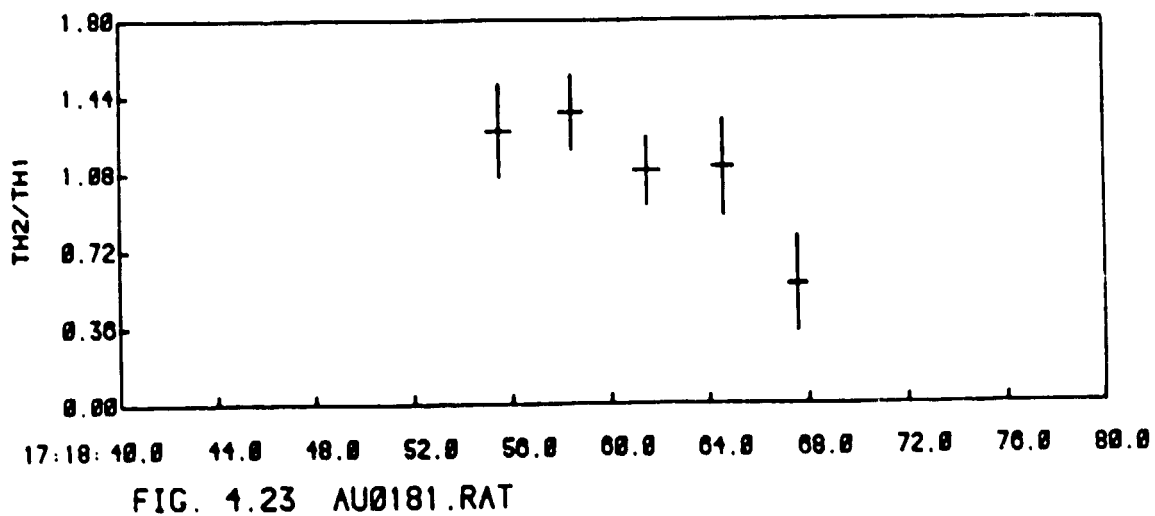
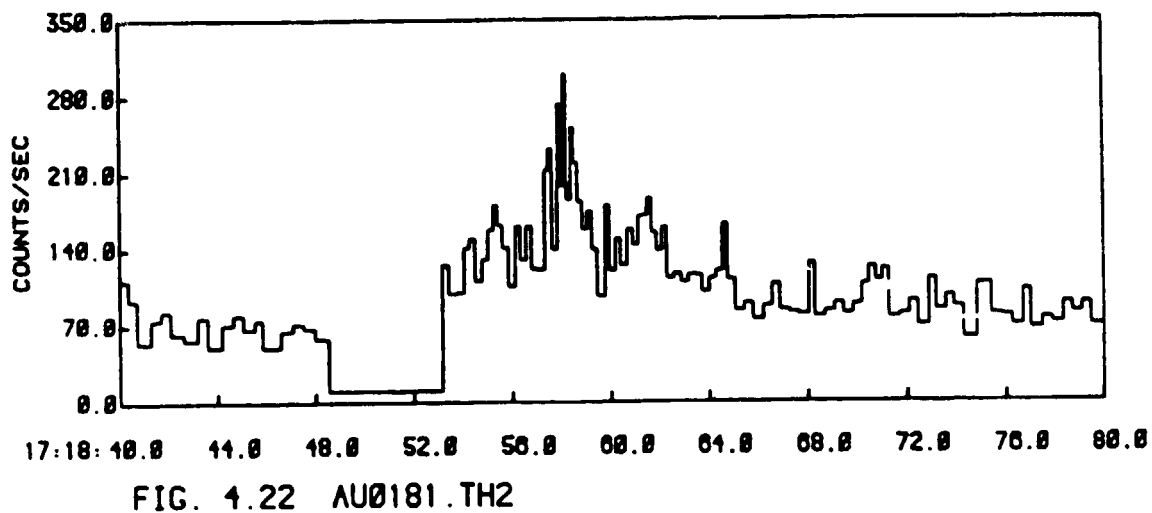
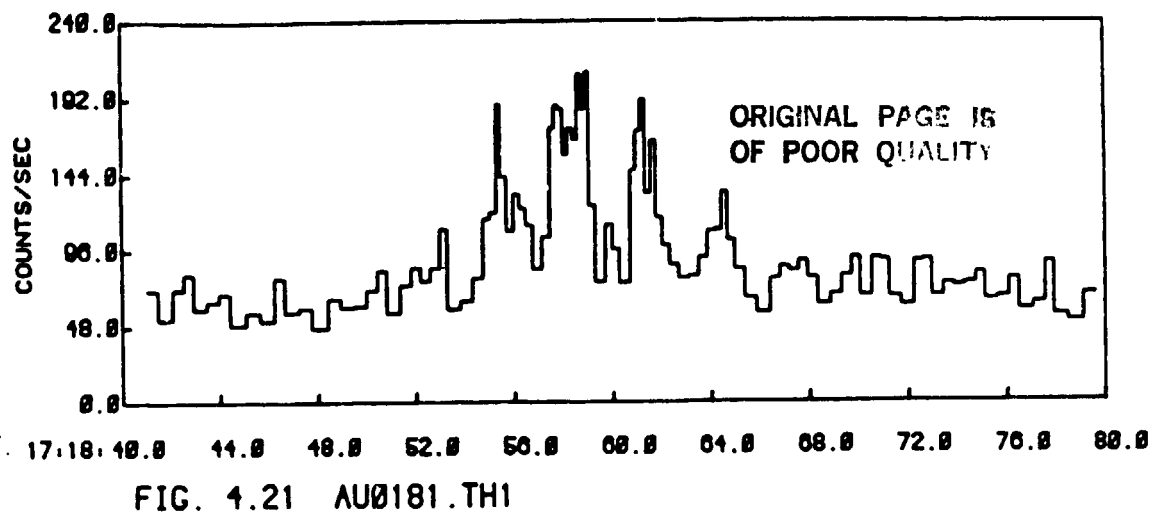


FIG. 4.17 JN0280.RAT





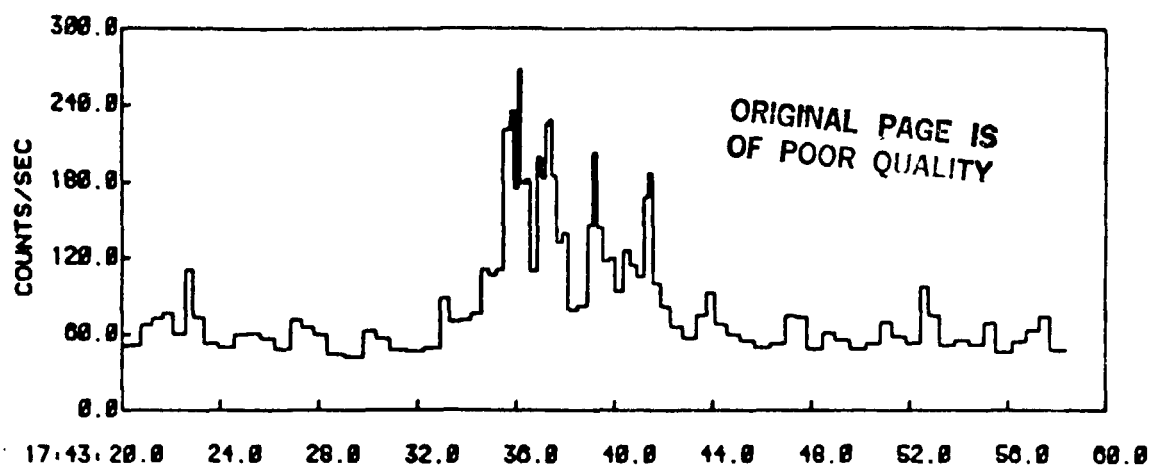


FIG. 4.24 SP3081.TH1

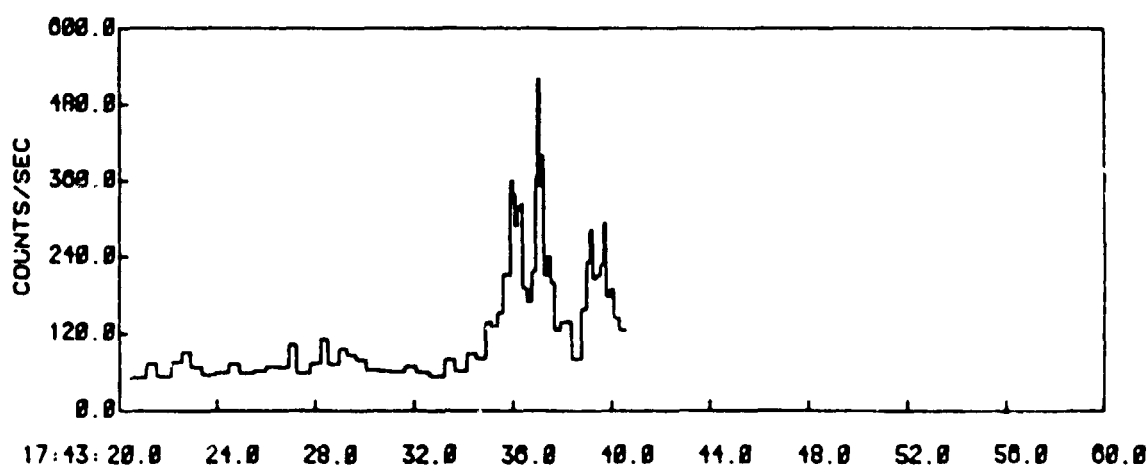


FIG. 4.25 SP3081.TH2

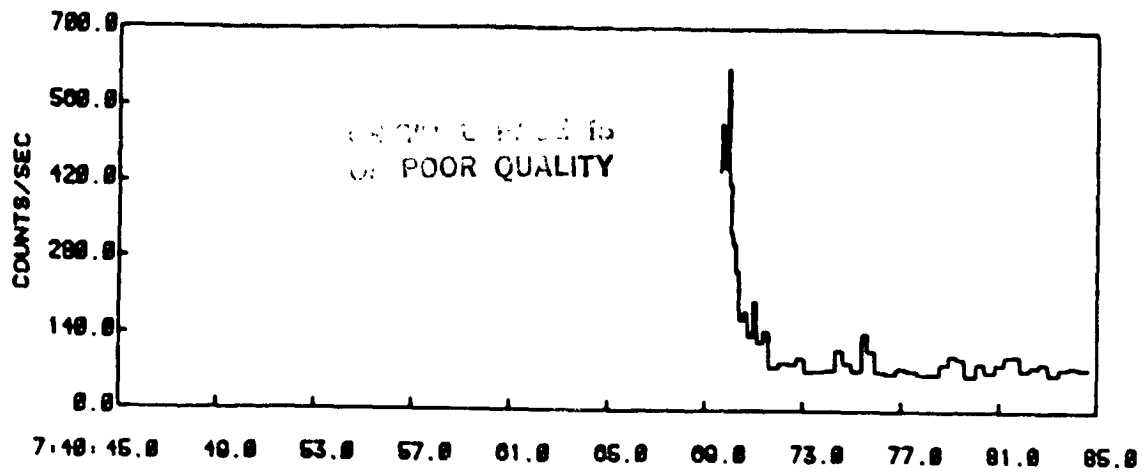


FIG. 4.26 AP1879.TH1

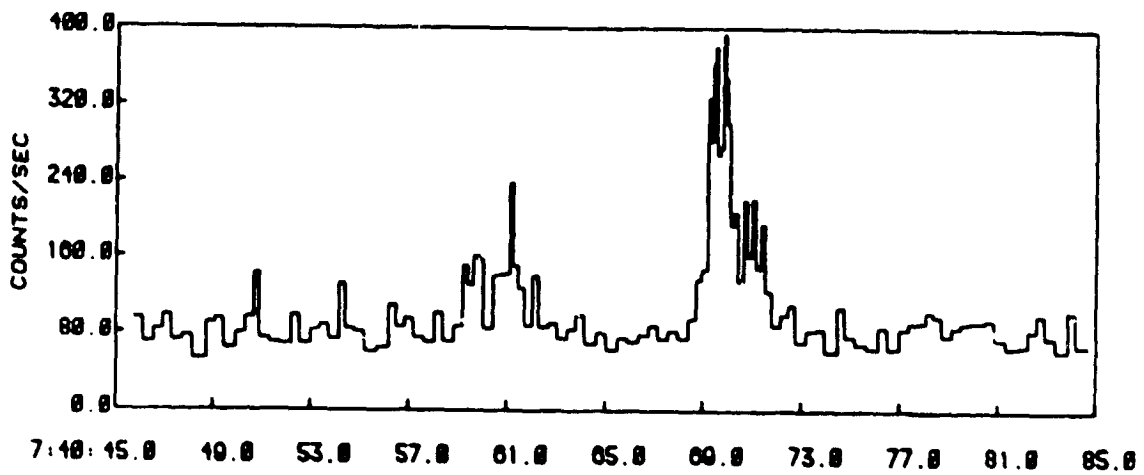


FIG. 4.27 AP1879.TH2

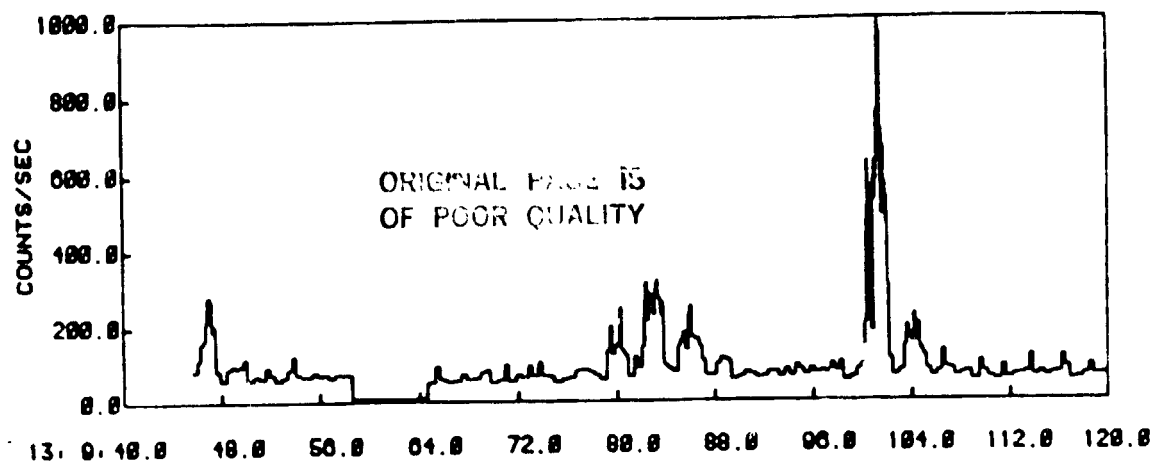


FIG. 4.28 MR2082.TH1

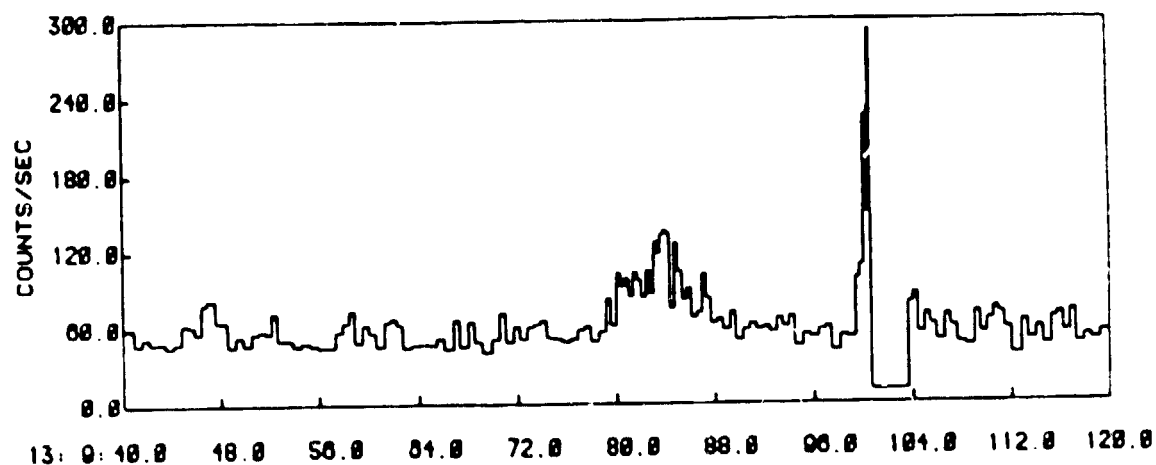


FIG. 4.29 MR2082.TH2

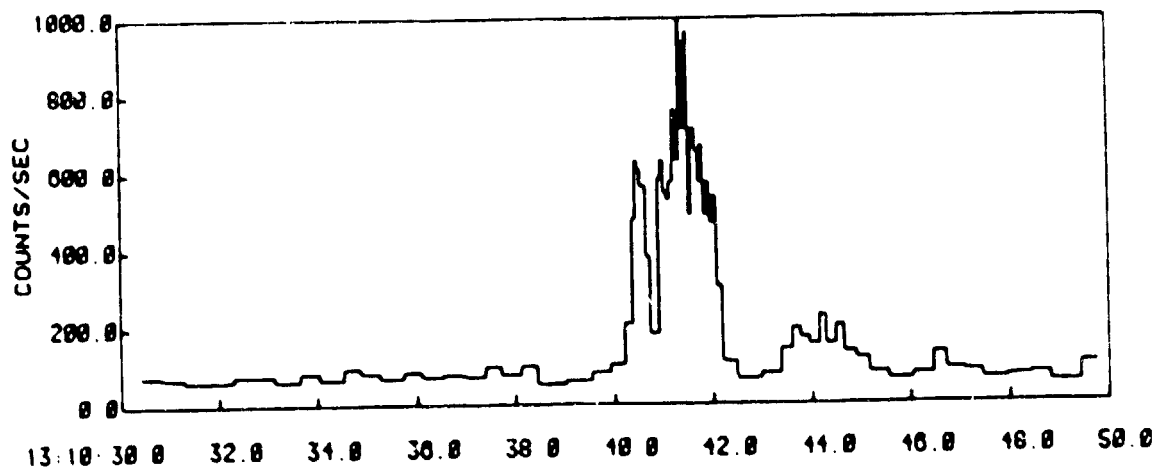


FIG. 4.30 MR2082.TH1

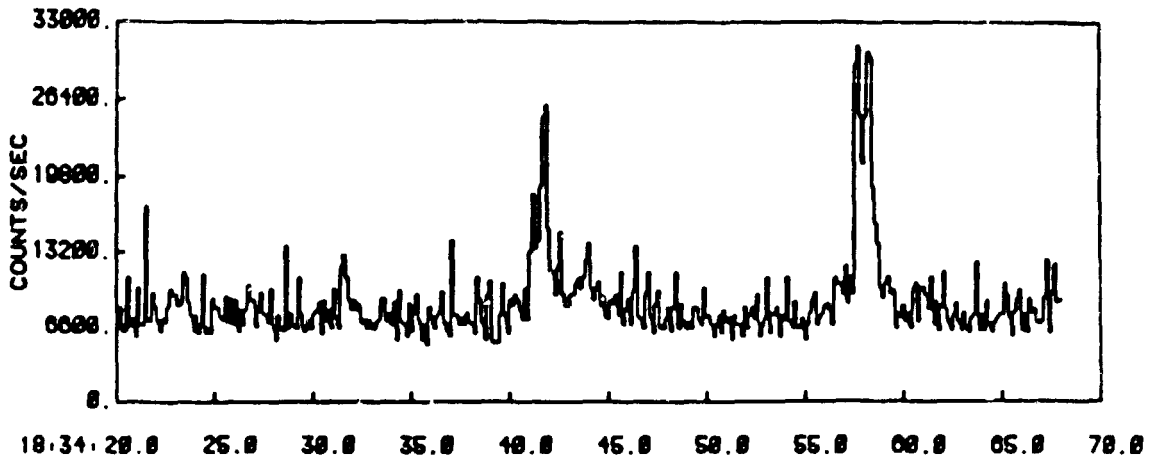


FIG. 4.31 SP2681.SHD

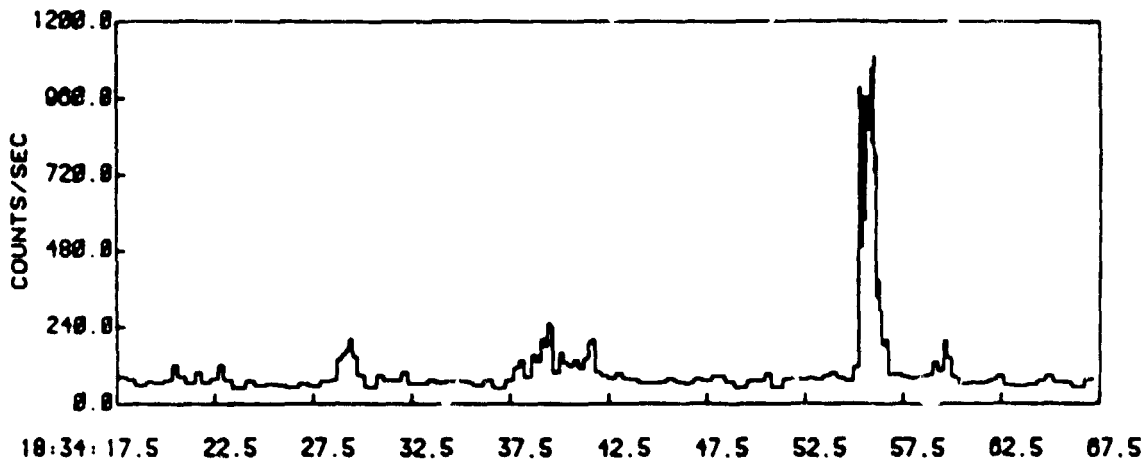


FIG. 4.32 SP2681.TH1

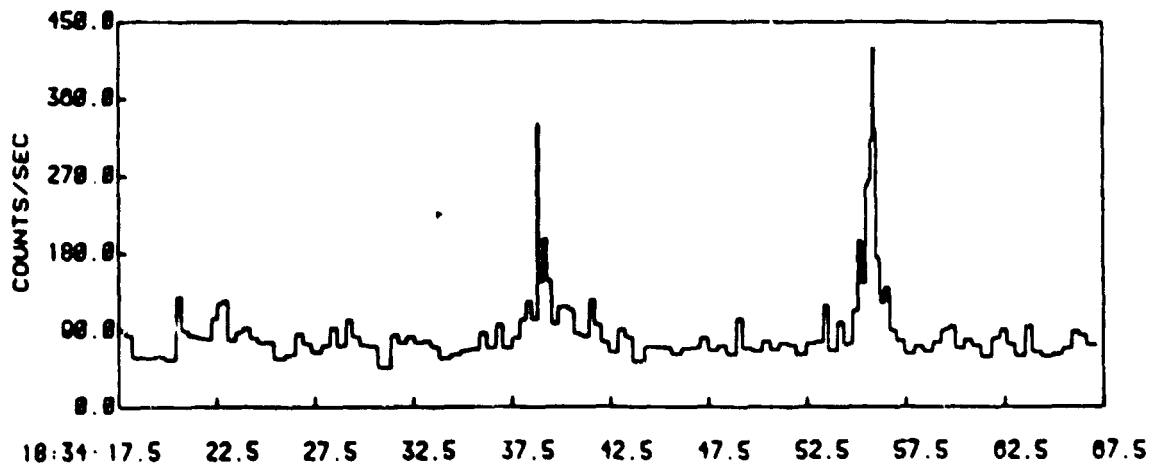


FIG. 4.33 SP2681 TH2

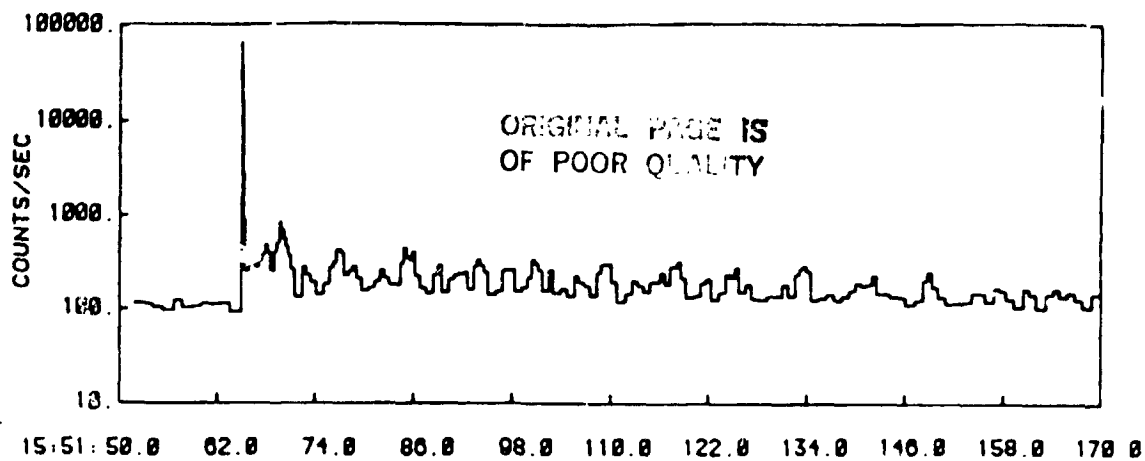


FIG. 4.34 MR0579.TH1

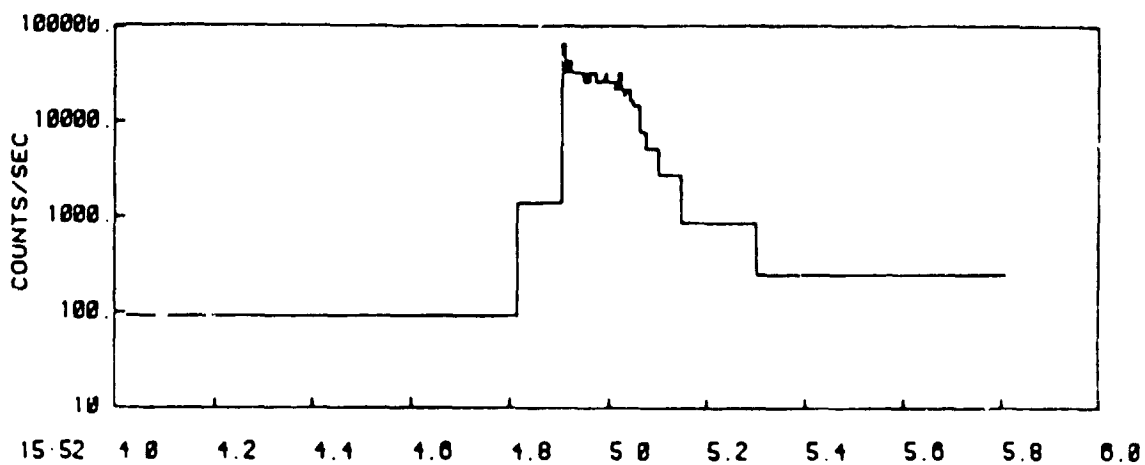


FIG. 4.35 MR0579.TH1

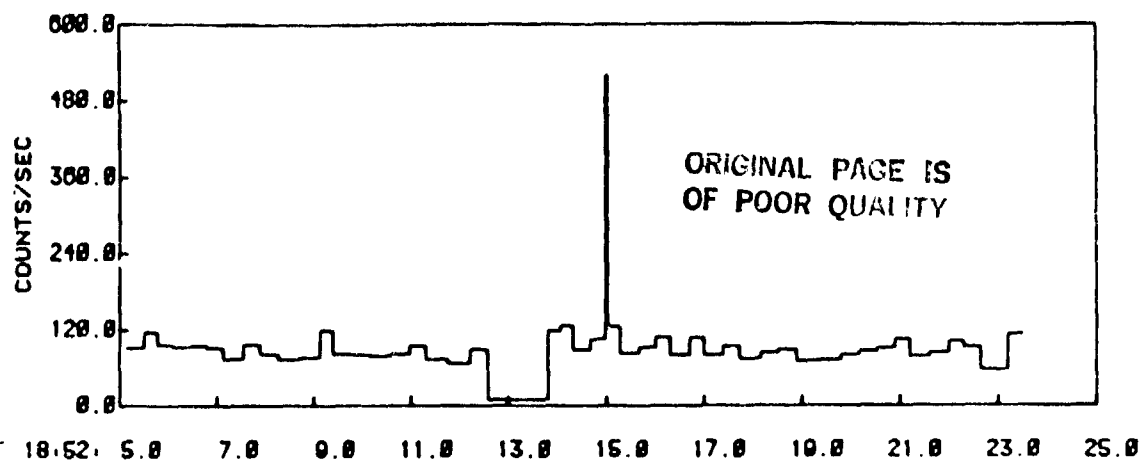


FIG. 4.36 MR1579.TH2

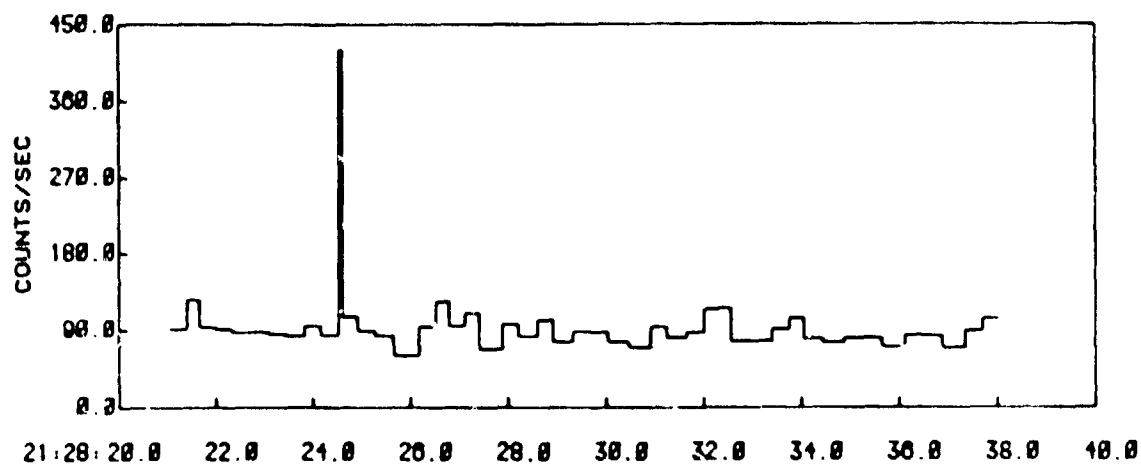


FIG. 4.37 MY1279.TH2

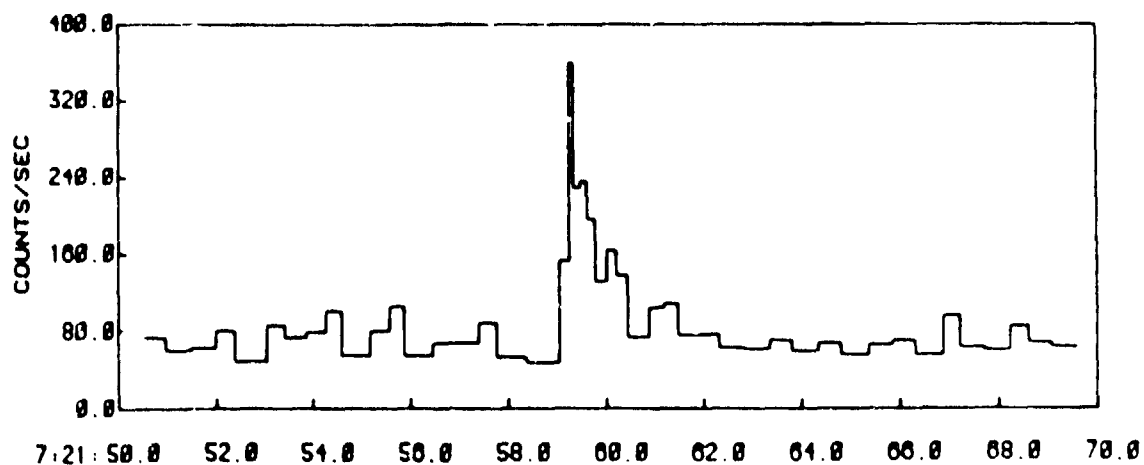


FIG. 4.38 MR2280.TH2

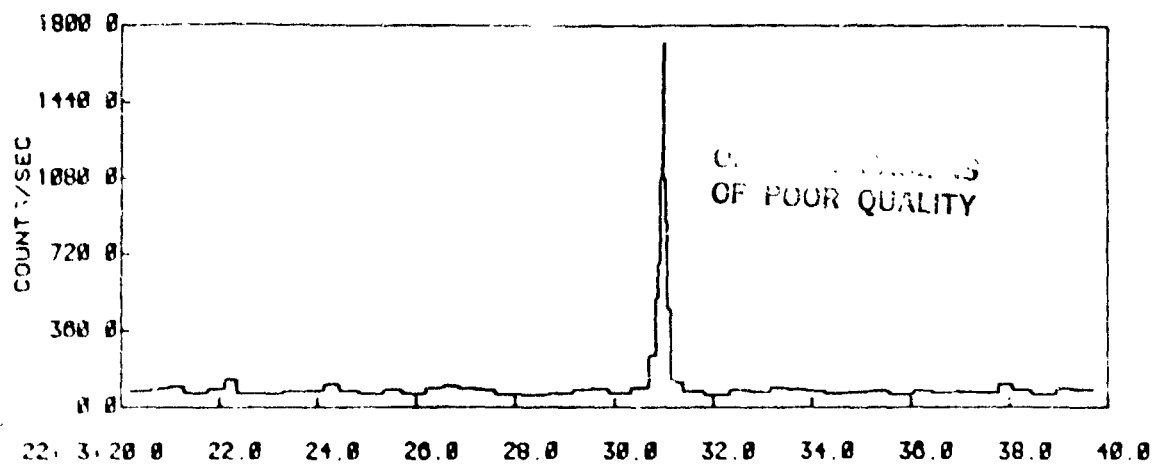


FIG. 4.39 AU0680.TH1

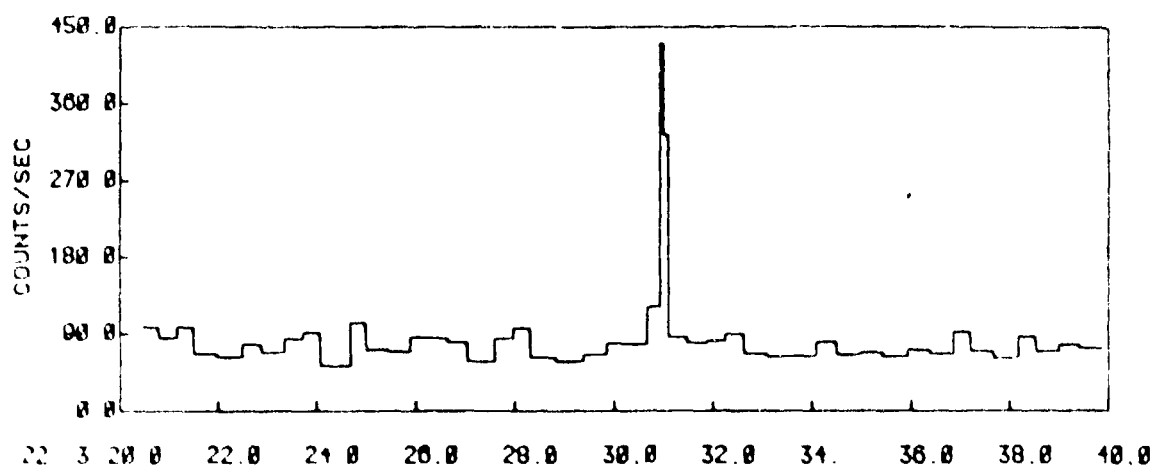


FIG. 4.40 AU0680.TH2

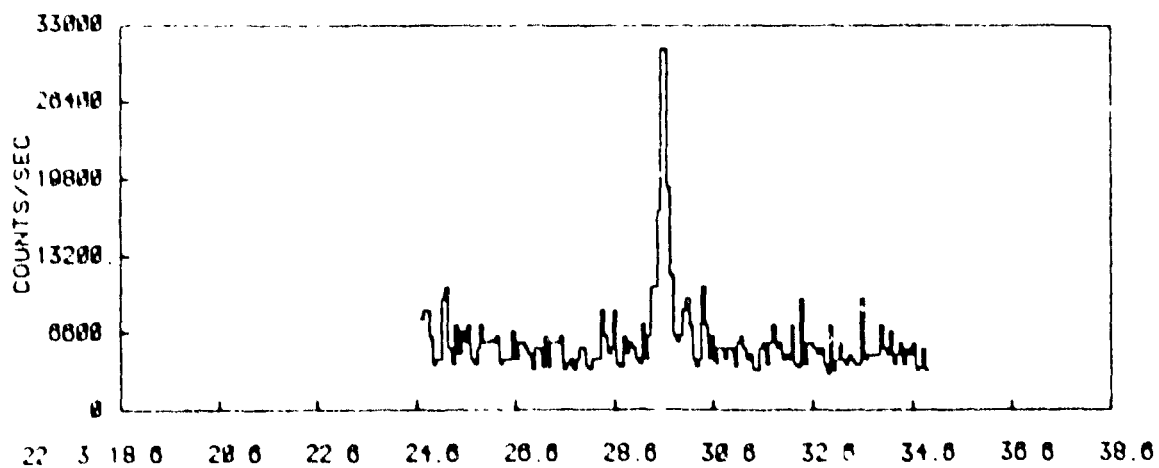
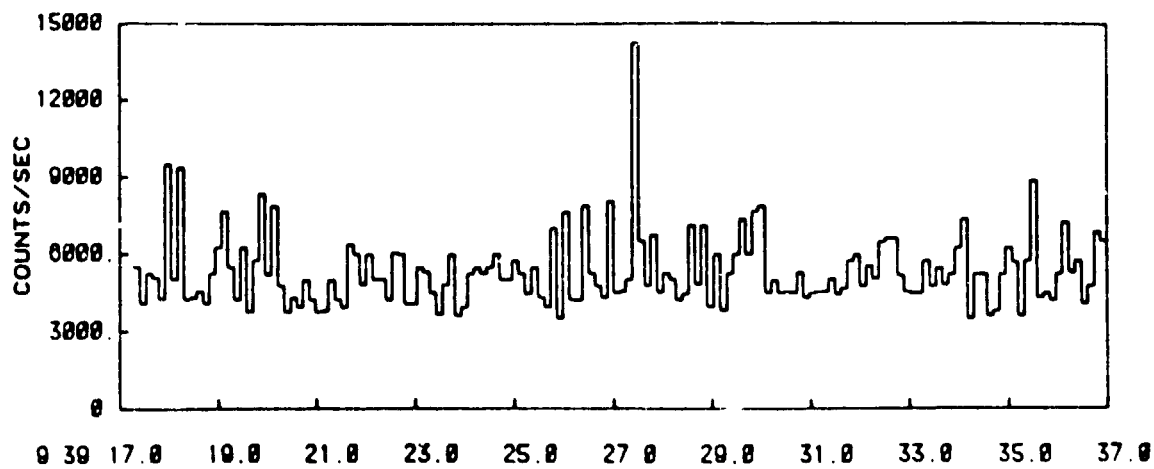
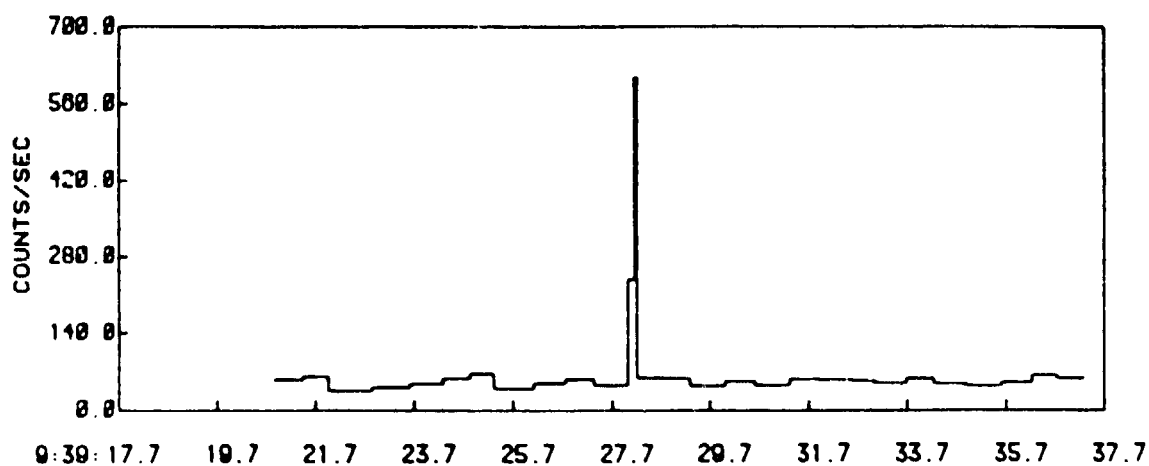
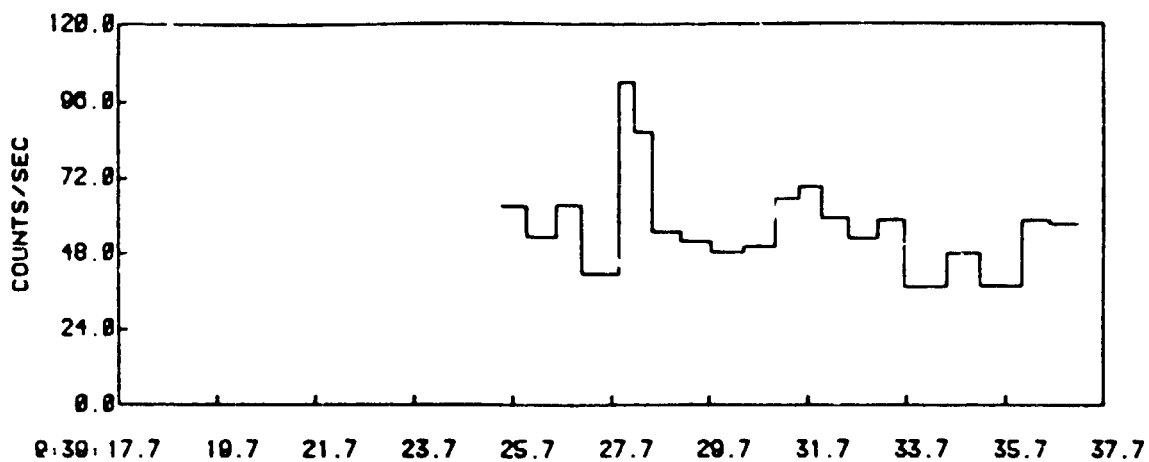


FIG. 4.41 AU0680.SH0



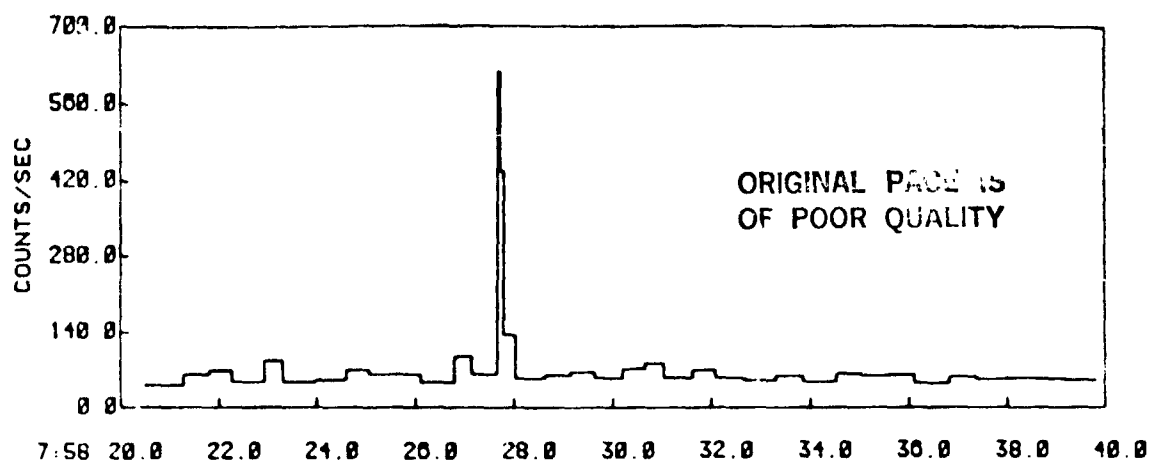


FIG. 4.45 DC3181.TH1

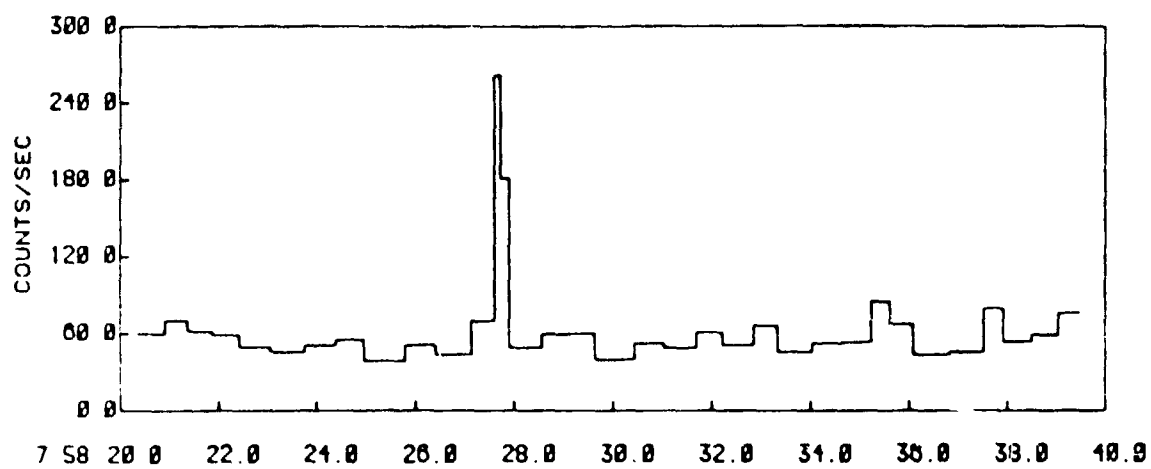
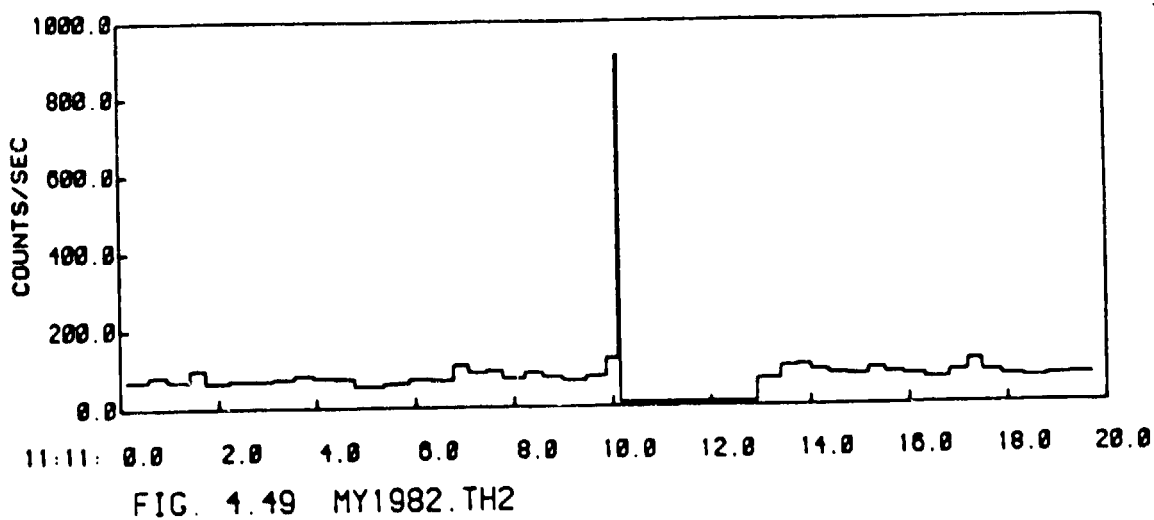
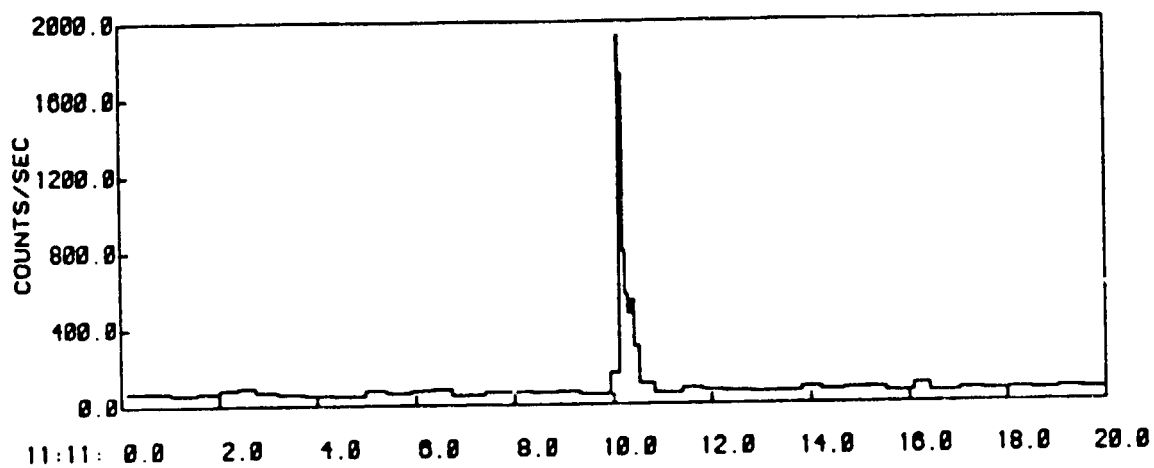
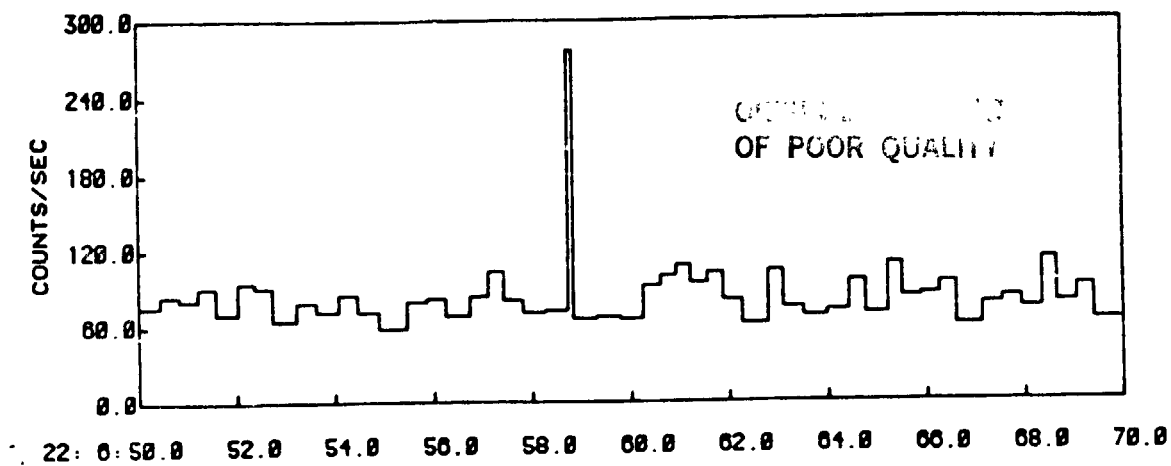


FIG. 4.46 DC3181.TH2



CHAPTER V

HXRBS SPECTRAL ANALYSIS

A. Introduction

In this chapter the γ -ray burst PHA spectra from the HXRBS experiment are analyzed to derive the photon energy spectra. The source photon spectrum for a given observed PHA spectrum is not unique, but depends on the form of the assumed incident model. The response of the shield-collimated detector of the HXRBS is dependent upon the burst arrival direction with respect to the collimator aperture. Detailed discussion of the photon energy spectra is presented only for those events whose direction of arrival fell within the detector field-of-view (f.o.v.). A significant feature of this experiment is the very fine time ($\approx 1/8$ s) resolution which enabled the study of burst spectral evolution.

The energy spectra of some events within the detector f.o.v. reveal features or depressions at energies below 100 keV which are statistically significant (see chapter I, section D; chapter III sections G and H). The energy range and strength of these features vary with time for a given event. The time variability as well as the Monte Carlo simulation of the detector response has established the intrinsic character of the features, ruling out the possibility that they are instrumental or data-reduction spectral artifacts.

Three candidate models relevant to possible physical mechanisms generating the γ -ray bursts were used to fit the spectral data. Thin thermal bremsstrahlung (TTB), thin thermal synchrotron (TTS), with and without absorption features, and power-law with exponential cutoff (PLE)

were considered. The power-law portion of the PLE model was adequate to fit the low-energy channels, supplanting the inclusion of absorption features. In many cases equally good fits were obtained for a given spectrum with more than one model. A simple power-law model was also considered. However, this model did not provide an acceptable fit to any of the HXRBS spectra.

Evaluation of those model fits which could explain the nature of the low-energy depressions has been emphasized. During some portions of the events of 19 APR 80 and 21 APR 80, a significant depression below a TTB or TTS continuum at low energies results if only the channels above ~ 100 keV are fit. In these cases, if a TTB or TTS fit is attempted to all channels, the reduced chisquare parameter, χ^2/ν , is relatively large, indicating a poor fit. Inclusion of a broad absorption feature at ~ 40 to 60 keV facilitates fitting both the depression and the higher channels; the continuum parameters are free to adjust to fit the high channels, and a significantly better fit is attained. In one case only, for an interval in the 19 APR 80 event, a "narrow" absorption line is required to fit the data (see section E.11).

The success of a particular model in giving a good fit to the data does not imply its validity. This is evident since for most of the spectra analyzed, all three models give, on the average, comparable and acceptable chisquares. Similarly, the success of an absorption line in the TTB and TTS models for fitting the low-energy channels does not imply an intrinsic spectral line. Other explanations for the depressions, such as averaging of rapidly time-varying spectra with low-energy turnovers may also satisfactorily explain the observations. In chapter VI, these alternative possibilities are discussed in detail and

it is concluded that the depressions are probably due to temporal averaging rather than absorption lines.

B. Determination of Events in Detector Field-of-View

In chapter III it was shown that the spectra of bursts observed within 20° of the HXRBS center of f.o.v. are not significantly altered by the shield-processed contribution (see Figure 3.6). The 19 APR 80 event is the only one for which a source direction was independently established by triangulation with detectors on various spacecraft. The direction of this event was determined to be $\sim 18^\circ$ from the sun, the HXRBS center of f.o.v. (Fenimore et al. 1982b). [In the case of the April 21, 1980 event, timing information from the Pioneer Venus Orbiter indicates 1) that the direction of arrival is not inconsistent with being within the f.o.v., and 2) that the event is non-solar (Klebesadel, private comm.).]

The 19 APR 80 detector-to-shield counts ratio thus serves to establish the relative orientation of source direction with respect to the f.o.v. of the detector. Events which have detector-to-shield count ratios equal to or greater than that of 19 APR 80 are considered to be within 20° of the HXRBS center of f.o.v. In Table 5.1, HXRBS events which were discernable in the detector are listed with average counts above background for both the detector and shield, the associated errors, and the ratio of detector-to-shield average counts. The error for shield counts was always the dominant contribution to the total error. The shield data is very noisy; hence the shield background level for any given interval has a large associated error.

Five events out of the thirteen in Table 5.1 have detector-to-shield ratios comparable to or greater than that of 19 APR 80, indicating the positions are within 20° of the center of f.o.v.: 07 MAR 80, 21 APR 80, 01 MAR 81, 17 MAR 81. The 05 JUN 80 event is borderline, considering the size of the error. The remaining events have very low ratios, indicating that the events were not observed in the f.o.v. The fraction of events in the f.o.v. is much larger than the ratio of solid angle of the detector FWHM to 4π ($\sim 1:33$). This is explained by the method used to search for solar flares and bursts; the detector rate data is usually examined rather than the shield data.

In Figure 5.1 the detector PHA spectrum of a burst observed through the shield (26 SEP 81) is illustrated to show the effect of preferential absorption of low energy photons by the shield (cf. Figure 3.6, 45° spectrum).

C. HXRBS Time Histories

Time histories of events observed in the central detector are illustrated in Figures 5.2 to 5.22. The smallest accumulation interval is 128 ms except in the cases of events with low intensity, 05 JUN 81 (512 ms) and 07 MAR 80 (1.024 s). Note the ordinate is plotted in cts/s. Hence, for events with accumulation interval of 128 ms, the actual number of counts per interval is $\approx 1/8$ of the value plotted. The time histories of these HXRBS events are all of the classical type.

For three of these events, sufficient counts were obtained to warrant dividing the bursts into several intervals for the purpose of studying the spectral evolution of the burst (see section E below).

Figures 5.2a and 5.3a show two reasonable groupings of intervals for spectral analysis for the event of 19 APR 80. Intervals containing the onset, peaks, and subsidence of the burst are shown in Figure 5.2a. The rising and decaying portions of two peaks and valleys in between are separated in Figure 5.3a. The gross division into rising and decaying intervals ignores any faster time variations.

Figures 5.4, 5.5 and 5.6 show the low energy (26 to 100 keV), medium energy (100 to 210 keV), and high energy (210 to 460 keV) photon time histories with the same interval divisions as shown in Figure 5.3. The 19 APR 80 event was also recorded by the ISEE-3 detectors and the shield detector of the HXRBS experiment. Figures 5.7, 5.8, and 5.9 show the time histories of the shield, the CsI (ISEE-3) detector and the Ge (ISEE-3) detector, respectively. The 19 APR 80 event exhibits three closely spaced peaks at low energy (Figure 5.4; see also the shield T.H., Figure 5.7). The ISEE-3 CsI detector does not reveal the true time history because of the spin modulation. The Ge detector, with a higher energy threshold than the HXRBS detector, does not show three distinct peaks. A smaller pulse appears at 50.5 s in the SMM data in all channels. The FWHM of the most intense pulse is narrower in the higher channels than in the lower channels. Also, the onset of this pulse (labeled RS2/DC2) appears to begin earlier (in the VL1 interval) in the medium and high energy bands than in the low energy band (see Figures 5.4, 5.5, and 5.6).

Figures 5.10a and 5.11a illustrate the groups of intervals for the 21 APR 80 event. The same two prescriptions for dividing the time history were used for 21 APR 80, i.e., division into peaks and into rising and decaying portions of peaks. Low, medium, and high channel

accumulations for the 21 APR 80 event are illustrated in Figures 5.12, 5.13, and 5.14, respectively. The spikier appearance in the higher channels could be accounted for by the statistics of low counts, or the pulses could be intrinsically narrower at high energy.

The appearance of three equally spaced peaks in the 21 APR 80 event may be due to source rotation (~ 6.5 s period), or interruption of the burst process.

Figures 5.17 through 5.20 show the temporal profile for the 01 MAR 81 event. The errors for the high channel T.H. are relatively large. The two ~ 1 s rising and decaying intervals for this event each appear to be composed of two to three pulses.

The T.H.'s of four additional HXRBS events are illustrated in Figures 5.15, 5.16, 5.21, and 5.22. The 19 NOV 80 and 07 MAR 80 bursts were too weak to divide into intervals for spectral analysis; only their total event spectra were analyzed. The 07 MAR 80 event duration (Figure 5.15) was unusually long, ~ 1 min.

The relatively intense event of 17 MAR 81 (Figure 5.21) occurred when the HXRBS was in a low gain state (i.e., high keV/channel). Consequently, the spectral data extend up to ~ 1.3 MeV, beyond the upper channels of the computed response matrix. Therefore, the spectral data for this event was not analyzed in the present study.

The 05 JUN 80 burst (Figure 5.22) was very weak. The poor statistics precluded performing a meaningful analysis.

D. Description of Spectral Analysis

Three candidate spectral models were used to fit the data: thin thermal bremsstrahlung (Gould, 1980), thin thermal synchrotron

(Petrosian, 1981), and power-law with exponential cutoff. The latter represents the spectrum resulting from an incident Planckian spectrum Compton-scattered by a weakly-relativistic Maxwellian distribution of electrons (Pozdnyakov, Sobol, and Syunyaev, 1977; Guilbert, Fabian, and Ross, 1982). For the TTB and TTS models, gaussian absorption lines were included in the incident model for those spectra exhibiting significant depression below the model continuum.

The model parameter values for the best fits to the spectral data are assembled in Table 5.2. The table is divided into parts a, b and c corresponding to the events of 19 APR 80, 21 APR 80, and all the remaining events, respectively. Within each subtable, the three model fits for the several time intervals of each event are presented. In the case of the TTB and TTS models, the fits with and without a low-energy absorption line are given, if in fact the inclusion of a line significantly improved the mathematical fit. In Table 5.2, for the TTB and TTS models there are two parameters for the continuum and an additional three parameters for an absorption line. The coefficient C_1 , in units of photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$, gives the continuum normalization of the fit. For TTB the second continuum parameter is the temperature T in keV (see eq. 3.5). For TTS this parameter is the critical energy ϵ_c in keV corresponding to the critical frequency $\nu_c = \epsilon_c/h$;

$$\epsilon_c = \frac{ehB}{2\pi m_e c} T_*^2 = 11.6 \text{ keV } B_{12} T_*^2, \quad (5.1)$$

(see eq. 3.6) where $T_* = kT_e/m_e c^2$. The TTB temperature or the TTS critical energy provide a measure of the spectral hardness.

For model fits with a gaussian absorption line, the continuum is multiplied by the factor

$$F_{abs}(E) = 1 - \frac{C_2}{\sqrt{(2\pi)\sigma}} \exp[-(E-E_0)^2/2\sigma^2] \quad (5.2)$$

where C_2 is the line equivalent width, E_0 is the central energy of the line, and the FWHM = 2.36σ , all expressed in keV.

For the PLE model there are four parameters: C_1 , the continuum normalization; α , the slope of the power-law portion of the curve; E_{cut} , the energy at which the power-law portion stops and the exponential tail begins; and E_{char} , the characteristic energy of the exponential tail. The mathematical form of the PLE model is constructed so that the power-law and exponential portions agree at E_{cut} :

$$\begin{aligned} C_1 \{ E^{-\alpha} \} & \quad E < E_{cut} \\ C_1 \{ E_{cut}^{-\alpha} \times \exp(-\frac{E_{cut} - E}{E_{char}}) \} & \quad E > E_{cut} \end{aligned} \quad (5.3)$$

In the far right column of Table 5.2, the chisquare per degrees of freedom, χ^2/ν , is listed for each fit. A value of $\chi^2/\nu \leq 1$ indicates an acceptable fit for a given model.

TTB was the first radiation process suggested to explain the burst exponential spectral shapes (Mazets et al. 1979a; Gilman et al. 1980). When relativistic corrections are included in the TTB expression (eq. 3.5), a range in temperatures from ~ 100 keV to ~ 3 MeV is required to fit the spectra (Table 5.2).

Arguments are presented in chapter VI which show that, of the three radiation processes represented by the models, thermal synchrotron

radiation is the most self-consistent and feasible radiation process for γ -ray bursts. The exponent in eq. 3.6 is proportional to $\epsilon^{-1/3}$, whereas the exponent in eq. 3.5 depends on ϵ/kT in the zeroeth approximation. Hence, bursts with a wider variation in spectral hardness can be fit with the TTS model than with the TTB model. If one fixes $B \sim 10^{12}$ G in eq. 5.1 (see chapter VI for arguments that $B \gtrsim 5 \sim 10^{11}$ G), then a much narrower range in temperatures results for the TTS model than for the TTB model. The ϵ_c values listed in Table 5.2 translate into a range in temperatures of ~ 170 keV to 800 keV for $B \sim 10^{12}$ G.

E. Spectral Analysis of Three Events

The spectra for the three events analyzed in detail, 19 APR 80, 21 APR 80, and 01 MAR 81, are illustrated in Figures 5.23 to 5.35. The spectra are of two types: detector energy-loss (PHA) spectra and deconvolved (model-dependent) photon spectra.

In the PHA spectra, the data points are plotted as crosses which represent the associated statistical errors and the channel widths. In the photon spectra, the deconvolved (model-dependent) data points as well as the candidate model curve are plotted. The spectral fitting program, which computes the deconvolved spectra, is described in chapter III, section E.

In Figure 5.23 the PHA spectra integrated over the entire events (total event spectra) are illustrated for the three events. When a TTS or TTB model is fit to the channels above ~ 100 keV, the lower energy channels fall below the model continuum. Since the exponential shape of burst spectra is observed to continue up to $\gtrsim 2$ MeV (Mazets et al.

1981d), far above the highest HXRBS channel, ~ 500 keV, it is appropriate to consider the higher channels as defining the spectral hardness of an event. From inspection of Figure 5.23 one can see the high energy portions of the total event spectra indicate that 19 APR 80 and 01 MAR 81 exhibit comparable spectral hardness, while 21 APR 80 is significantly softer.

Some PHA spectra of γ -ray bursts (including that of the 19 APR 80 event) from the SMM's Gamma Ray Spectrometer (GRS) experiment (Share et al. 1982) have a power-law shape for energies above the HXRBS energy range (> 500 keV). These observations are not necessarily inconsistent with an exponential shape at high energies for two reasons: 1) the GRS spectra are not corrected for the instrumental response, and 2) they are event-averaged spectra. However, the GRS observations do indicate that some γ -ray bursts exhibit very hard spectra that extend to 10^6 's of MeV (Share et al. 1983).

The low-energy depressions or absorption features, for example in the 19 APR 80 event, tend to flatten the spectra at low energies, making them appear harder than they would if more channels above 500 keV were present.

As described in section C, the spectral data for each of these three events were divided into intervals corresponding to structures in the temporal profiles. For almost all of the intervals, the three models gave equally good mathematical fits. Visually, the three models for a given interval vary in the closeness of the fit from channel to channel. However, the overall appearance for the three cases are usually quite similar. This is evident in Figure 5.24 where the photon spectra for the three models are illustrated for the time interval

AP1980.VL2 (spectrum of first valley in 19 APR 80 temporal profile, see Figure 5.3). No absorption line was included in the TTS or TTB model. The reduced chisquares for the three fits are comparable, ~ 0.6 to 0.7 . The same similar visible appearance for the three model fits is evident for all intervals for which an absorption feature was not included. When an absorption line is included in the TTS or TTB model spectrum, the appearance of these fits with the line are significantly different than for the PLE model. This is best illustrated in Figure 5.25, where the PLE and TTS models are shown again for the interval AP1980.RS2 (second rising interval of 19 APR 80, see Figure 5.3). This is the best example of the incapability of the TTS (or TTB) model to fit the spectra of some intervals without the inclusion of an absorption line at low energies. The TTS fit (without a line) to the upper ten channels is also illustrated to show that, indeed, the departure of the observed spectrum from the TTS fit at low energies is not due to the assumption of an absorption line in the model.

To spare the reader viewing three times as many graphs as necessary, only the photon spectra for the TTS fits are illustrated for the rest of the intervals. However, it is emphasized that the PLE model without an absorption line does afford an equally acceptable fit to all channels in most cases where the TTS or TTB models require a line.

In Figures 5.26 and 5.27 for the 19 APR 80 event, and Figures 5.30 and 5.31 for the 21 APR 80 event, the PHA spectra are illustrated for the two methods of dividing the temporal profiles. The A through E series (19 APR 80) of Figure 5.26 and the A through C series (21 APR 80) of Figure 5.30 are the spectra of the whole peaks in the temporal profiles. For 19 APR 80, A is the spectrum of the onset and E is the

spectrum of the subsidence of the burst. These spectra indicate how the burst evolves from one pulse to the next. The RS1 through VL2 series (19 APR 80 - Figure 5.27; 21 APR 80 - Figure 5.31) are the spectra of the rising and decaying portions of individual pulses and valleys between pulses. This division affords the study of the evolution of the burst spectrum within pulses.

The deconvolved photon spectra for the TTS model are illustrated for the same spectral intervals in Figures 5.28 and 5.29 (19 APR 80) and Figures 5.32 and 5.33 (21 APR 80). The PHA and photon spectra for 01 MAR 81 are shown in Figures 5.34 and 5.35, respectively.

From the discussion above on indistinguishable fits for the three models, it is evident that the nature of the continuum, and possible spectral features, cannot be determined from spectral fitting; the program almost always finds a good fit for a given model. Rather, the range of the temperature (TTB model) or critical energy (TTS model) determined from the analysis is the useful information, which when combined with additional arguments, may help determine if the model is self-consistent.

In section 1 below, the spectral evolution of the three events is discussed. The spectra are seen to evolve on time scales of $\lesssim 1$ s in two of the events. This information provides another constraint for burst models. In section 11, the analysis of the low-energy depressions, assuming a TTS or TTB continuum, is presented. These depressions are not instrumental or data-reduction artifacts. However, the analysis shows that they may not necessarily be cyclotron absorption lines, but could also be explained by fast variations of the spectra at low energies.

1. Burst Spectral Evolution

One can best follow the evolution of an event by examining and comparing the (model-independent) PHA spectra for sequential intervals (19 APR 80 - Figures 5.26 and 5.27; 21 APR 80 - Figures 5.30 and 5.31). However, for an incident exponential-shape photon spectrum, the detected PHA spectrum exhibits a "knee" at ~ 100 to 120 keV; the PHA spectra have the appearance of departing from a smooth exponential shape. The (model-dependent) photon spectra vary in appearance according to the specific model.

In this section the continuum evolution is analyzed. Only the portions of the photon spectra above ~ 80 to 100 keV reflect the continuum shape if there is a low-energy depression in the spectrum. Sometimes it is difficult to evaluate the relative spectral hardness from inspection of the figures. Therefore, in the following discussion the reader should refer to the spectral fits in Table 5.2 for the quantitative determinations.

The relevant parameter is the temperature (in k for the TTb model and the critical energy (also in keV) for the Λ S model. As mentioned above, the bremsstrahlung temperatures exhibit a wider range of variation than the synchrotron temperatures derived from the critical energy assuming a constant magnetic field strength. Yet the two parameters, T_{ttb} and ϵ_c , consistently vary in step with each other, so that either is a good indicator of spectral hardness. Since the TTS fits are illustrated in the figures, I will refer to the critical energies listed in Table 5.2 in discussing the spectral hardness of the bursts. Unless a line was not required to fit a particular interval, the model fits with an absorption line are the relevant indicator for

spectral hardness (see discussion above). The fits with lines for a given interval are always listed directly after those without lines.

No effort is spent to analyze the spectral hardness from the PLE fits. This is because two parameters, E_{cut} and E_{char} , characterize the fit to the high channels and these two parameters are relatively ill-determined.

The three events are discussed separately below. Two of them have rather short durations, 19 APR 80 $\sim$ 4 s, and 01 MAR 81 $\sim$ 2 s. The 21 APR 80 event had a much longer duration, $\sim$ 20 s. When the spectra for 19 APR and 21 APR are divided into short intervals (i.e., the rising and decaying portions), the fits are significantly different than for longer intervals (i.e., the spectra averaged over the complete peaks).

a. 19 APR 80 Event

The sequence of intervals for 19 APR 80 (Figure 5.2a), onset (A), three peaks (B through D), and subsidence (E), reveal a trend of hard-to-soft evolution (the ϵ_c values for the 19 APR and 21 APR interval sequences are included in the respective time history illustrations, i.e. Figure 5.2b, etc.). The onset, which displays a gradual rise, is the hardest interval of the burst with the critical energy (in keV) $\epsilon_c = 26.0$. The first peak is considerably softer with $\epsilon_c = 11.7$. The burst spectrum continues to soften with the middle peak ($\epsilon_c = 8.5$) and third, most intense, peak ($\epsilon_c = 10.0$). Finally, in the subsidence interval, $\epsilon_c = 7.0$. Hence, for this division of intervals, the spectra soften chronologically and the burst intensity is not correlated with hardness.

In the RS1 to VL2 sequence (Figure 5.3a), the first and third peaks have been divided into rising and decaying intervals. With division

into shorter intervals, fast evolution within the peaks can be investigated. The rise and decay intervals are only 256 to 384 ms in duration.

For the first (RS1 and DC1) and third (RS2 and DC2) peaks, the spectral hardness exhibits interesting behavior. The rise intervals in both cases are significantly harder than the decay intervals. In the first peak $\epsilon_c = 10.3$ for the rise and $\epsilon_c = 8.4$ for the decay. In the third peak $\epsilon_c = 11.5$ (rise) and $\epsilon_c = 4.7$ (decay).

The critical energies determined for the valley intervals have relatively large associated errors: for VL1, $\epsilon_c = 9.6 \pm 3.6$, and for VL2, $\epsilon_c = 9.2 \pm 3.0$.

Hence, for the 19 APR 80 event the analysis reveals a pattern of hard-to-soft evolution for the entire burst. Even on a shorter time scale, $\sim 1/4$ s, a hard-to-soft pattern is observed within individual peaks.

b. 21 APR 80 Event

The peak intervals (Figure 5.10a) for 21 APR 80 are wider (~ 5 s) than those for 19 APR 80. Wider intervals were required to obtain comparable statistics since 21 APR was $\sim 1/4$ the intensity of 19 APR. In fact the longer peak intervals appear to be comprised of several unresolved individual pulses.

The evolutionary trend of the composite peaks is from soft to hard, opposite to that of the narrower, individual peaks in the 19 APR 80 burst. The critical energies ϵ_c are 1.3, 2.3, and 3.0 for intervals A, B, and C, respectively.

When 21 APR 80 is divided into "rise" and "decay" intervals (Figure 5.11a), the interval durations range from ~ 1 s to 2.8 s, longer than the durations (~ 0.6 s) of the whole peaks in the 19 APR 80 burst. The rise and decay intervals still have the appearance of composite pulses. The ϵ_c values for these intervals do not reveal any spectral evolution from rise to decay portions. In the first peak, $\epsilon_c = 1.4$ (rise) and 1.5 (decay), and in the second peak $\epsilon_c = 2.3$ for both rise and decay. If the burst spectrum evolved significantly on a time scale comparable to the short ($1/4$ to $1/2$ s) pulses within the spectral intervals, then the ϵ_c determinations reflect the averages of spectral variations.

c. 01 MAR 81 Event

The duration of the 01 MAR 81 event is about 2.7 s. This burst has also been divided into rise and decay intervals, 1.4 s and 1.3 s, respectively. Again, these intervals are not strictly rises or decays since within both intervals two or three individual pulses are apparent. However, because of the relatively low intensity of the burst, it was not divided into shorter intervals.

For the total event spectrum, a value for ϵ_c of 13.5 was obtained. The values of ϵ_c for the rise (11.9 ± 2.6) and decay (14.5 ± 2.4) differ only slightly from each other.

ii. Spectral Features

In several of the spectral intervals the lower channels depart from an exponential shape, giving the appearance of a depression or broad absorption feature. Only spectra were analyzed for which the event

direction of arrival was close enough to the detector center of f.o.v. for the shield-processed contribution to be insignificant. Also, careful attention was given to the Monte Carlo simulation of the HXRBS detector system. Therefore, the depressions are probably not instrumental or data-reduction artifacts, but are intrinsic to the burst spectra.

The option of absorption lines was included in the TTS and TTB models in order to obtain an acceptable fit to some of these spectra. However, two considerations indicate that the depressions are not necessarily absorption features.

First, in all but one case (the spectrum of the third, most intense peak of the 19 APR 80 event), the spectral fitting program tended to fit broad lines with $\text{FWHM} \geq 50$ keV. In most cases the program would have fit lines of $\text{FWHM} \sim 60$ to 70 keV. An upper limit to the width of 50 keV was set in the program because widths greater than that energy were deemed unphysical. The effect of limiting the line width on the other parameters of the fit and on χ^2/ν was insignificant. By increasing the width of the absorption line the program was creating broad shallow features, attempting to fit a flat "shelf" to the lower energy portions of the spectra. This is evident in the PLE model fits also. Absorption lines were not necessary in this model because the flat power-law part of the model readily fit the low-energy "shelf".

Second, in practically all HXRBS solar flare spectra, which are otherwise well fit by either a pure TTB or pure power-law form, channel one is (artificially) high (Larry Orwig, private communication). The reason for this instrumental effect is not clear, although it is possibly connected to the fact that channel one is only ~ 4.5 keV wide

whereas the remaining channels are ~ 30 keV wide (channel 15 is ~ 100 keV wide). If channel one were plotted at lower (correct) values, the depressions in some of the spectra might have more the appearance of low-energy turnovers rather than an absorption feature or flattening of the spectrum.

If channel one were as wide as the other low-energy channels it would be expected to dominate the spectral fits. Channel one would have the smallest errors since the spectra are monotonically decreasing. However, channel one is only about 1/7 as wide as the other channels, and in fact, the errors are larger than those for the other low-energy channels.

To determine the effect of channel one on the fits, the analysis was performed on the spectra with channel one excluded. The values for the fit parameters and the χ^2/ν parameter, with and without channel one, were nearly uniformly equivalent. For the TTS and TTB models, the computed parameter values were significantly different for only three spectra. A comparison of the 14 and 15 channel TTS fits is shown in Table 5.3 for the three cases. Only for the interval AP1980.DC2 was a substantial difference found. The line energies were determined to be 46 keV (15 ch) and 55 keV (14 ch). The reason for the lower line energy in the 15 channel case is that channel one was low rather than high (see Figure 5.27b); the program attempted a broad line fit over the energy range of channels one through three (see Figure 5.29b). In the other two cases, intervals C and RS1 of 21 APR 80, the same effect is apparent, although not as pronounced. Channel one is somewhat lower than it is for the other intervals of 21 APR 80 (see Figures 5.30 and 5.31a), and the program fit slightly higher line energies when channel

one was excluded. In all three cases the program fit somewhat softer continuum parameters (kT and ϵ_c) since the spectrum appears higher at low energies when the low point, channel one, is excluded. For the PLE model, all the parameter values for the 14- and 15- channel spectral fits agreed to within the computed errors for every spectrum. Hence, in general, the problem of the calibration of channel one did not significantly affect the analysis and interpretation of the low-energy portion of the spectra.

Whereas the depressions can be fit by broad absorption lines, this does not imply that there are absorption features in the burst spectra. The depressions may be the high end of low-energy turnovers. The low end where the spectrum is actually turned over would then be below the HXRBS spectral range. Another possibility is that the depressions are the result of integrating the burst spectrum over intervals of rapid spectral evolution. From the discussion above on continuum evolution, it was concluded that spectral variations are present on time scales ≤ 1 s. Examination of the 19 APR 80 and 21 APR 80 events reveals that evolution of the depressions occurs on short time scales also.

a. 19 APR 80 Event

There is a conspicuous evolution of the low-energy portion of the spectrum of the 19 APR 80 event, which can be seen in the PHA spectra, Figures 5.26 and 5.27. However, because of the characteristic shape of the detected spectra, with a "knee" at ~ 100 to 120 keV, it is difficult to visually appreciate from the PHA spectra the degree of departure of the low-energy portion from a TTS or TTB shape. This effect is more

easily seen in the illustrations of the photon spectra, Figures 5.28 and 5.29. In these figures the models with absorption lines are shown. The same fits (i.e. same continuum) without lines are extrapolated to low energies to show the departure from the model continuum.

For the spectra of the first (intervals B, RS1 and DC1) and third (intervals D, RS2 and DC2) peaks, the best-fit model included an absorption line. A significant improvement in χ^2/ν is obtained for these intervals for models with lines compared to those without lines (see Table 5.2a). The improvement is most impressive for the D and RS2 (rise of D) intervals. For the D interval χ^2/ν decreases from ≈ 3.6 to 0.6 (TTB) or ≈ 1.7 to 0.9 (TTS). For the RS2 interval χ^2/ν decreases from ≈ 3.2 to 1.2 (TTB) or ≈ 1.8 to 1.3 (TTS). Generally, the TTS model continuum provided a closer fit to the low-energy channels than did the TTB continuum. Hence, the improvement in χ^2/ν when a line was included was not as marked in the TTS fits.

The D and RS2 intervals are the only ones for which the program tended to fit "narrow" lines. For these intervals the line width tended to decrease to ~ 10 keV. However, as the widths decreased below ~ 30 keV, the changes in χ^2/ν and the other parameters of the fit were insignificant. Therefore, a lower limit for the width, 33 keV equal to the instrumental resolution at 50 keV, was set in the program.

The program also gave better fits for models with lines for interval DC2 and the intervals comprising the first peak. However, the improvement in χ^2/ν over the models without lines was not as significant in these cases.

The central line energies determined by the program were model dependent, ranging from ~ 35 to 55 keV for the TTB fits, and from ~ 42

to 70 keV for the TTS fits. For a given interval the TTS line energies were always 5 to 10 keV higher than the TTB energies. Since the detector resolution at 50 keV is 33 keV and the FWHM of the lines was usually ≥ 50 keV, the evidence for the position of the depression changing is marginal.

In conclusion, there are three important aspects of the spectral behavior at low energies for this event. First, the depressions evolve on a time scale ≤ 1 s. Second, the depressions appear only in the spectra of the first and third peaks, and are most prominent in the rising portions of the peaks. Third, a "narrow" line is determined for the spectrum of the third, most intense peak.

b. 21 APR 80 Event

From Table 5.2b one can see from the χ^2/ν values that the peak intervals A, B, and C of the 21 APR 80 event are better fit by a TTB or TTS model with line than a model without. This can also be seen in the photon spectra (Figure 5.32).

When the first two peaks are divided in rising and decaying intervals and valleys (Figure 5.33), the depressions appear most significant in the rising intervals and VL2 (Figure 5.33a, b, and c). This is reflected in the substantial improvement in χ^2/ν when a line is included in the fits for these intervals: 4.2 to 2.0 for RS1; 5.7 to 2.7 for RS2; and 1.0 to 0.3 for VL2.

The presence of the depressions in all three peaks, over a duration of ~ 15 s, is contrary to most observations of the KONUS experiment (Mazets et al. 1981e). Low-energy depressions or absorption features were observed in the KONUS spectra usually only in the first 4 s

interval of the burst. Infrequently, the depressions persisted for three or four 4 s intervals.

Since the 21 APR burst exhibited a higher detector-to-shield ratio than the 19 APR burst, 0.38 compared to 0.10 (Table 5.1), it is very unlikely that the 21 APR detector spectrum was significantly contaminated by the shield-processed flux. Hence, the departure of the spectrum from a TTB or TTS continuum is probably an intrinsic feature of the burst spectrum in this case.

F. Discussion

In summary, several points emerge from the spectral analysis. Significant spectral evolution occurs on time scales $\lesssim 1/2$ s in some events. The 19 APR 80 burst exhibits hard-to-soft evolution within two $\sim 1/2$ s wide peaks. The 21 APR 80 burst, when the peaks are decomposed into shorter intervals, also exhibits significant evolution on a time scale $\lesssim 2$ s.

Fast evolution of the depressions is observed in the 19 APR 80 event. Rapid continuum evolution and (apparent) evolving low-energy turnovers or absorption features at energies as high as 200 to 300 keV are also seen on time scales of tens of ms to 250 ms in some spectra from the SIGNE experiment (Barat et al. 1983a; Barat 1983).

The low-energy depressions evident in some spectral intervals are intrinsic to the burst spectrum, but are not necessarily absorption features. Averaging of rapidly-varying spectra with low-energy turnovers may create the appearance of absorption features. An example of such a spectral artifact is illustrated in Figure 5.36. Two simulated spectra with different ϵ_c 's and the sum of these spectra are

plotted. The turnover energies, due to the synchrotron cutoff [$\epsilon_h B / (2\pi mc) = 11.6 B_{12}$ keV], and the ϵ_c 's correspond to magnetic field strengths of 4.4×10^{12} G and 1.4×10^{12} G and plasma temperatures of 200 keV and 100 keV, respectively. The turnover (~ 16 keV) in the softer spectrum is below the lowest channel plotted. The sum of these two spectra gives the appearance of an absorption feature at ~ 40 keV.

In fact, many KONUS spectra (Mazets et al. 1981e) which are claimed to display absorption features merely depart from a TTB continuum in the lowest one or two energy channels; the continuum is higher than the feature only on the high energy side.

If the features are due to averaging of spectra with rapidly time-varying cutoffs, the cutoff energy, proportional to the magnetic field strength, is not necessarily correlated with the critical energy, which depends upon the additional parameter, the temperature (see eq. 5.1).

There is a tendency in the KONUS data for bursts with absorption lines to exhibit hard spectra. From Table A.1 the mean value for ϵ_c for the KONUS spectra is 4.1 keV [excluding six values above 20.0 keV which imply $T_* > 1$ if $B_{12} \sim 1$; Petrosian's expression (1981) for the synchrotron emissivity, eq. 3.6, is not valid for $kT \gtrsim 511$ keV]. This value is 4.4 keV if the spike-like bursts with soft spectra are excluded. The mode of the ϵ_c distribution is much lower, about 2.0 keV (Figure A.4). For the spectra which exhibit a depression or absorption feature (indicated by # in the table), the mean value for ϵ_c is much higher, about 7.0, excluding values above 20.0 from the average. The KONUS spectra exhibit the tendency to soften as the burst progresses (Mazets et al. 1981d), and absorption features are observed usually only during the first 4 s, and only in about 20% of the events (Mazets et al.

1981e). Hence, the evolving cutoff scenario described above appears to be consistent with the KONUS data. An initially high value of ϵ_c , reflecting a high magnetic field, would be required to produce a cutoff observable within the KONUS detector energy range. However, most KONUS spectra are softer than those in which absorption features are observed, and the cutoff for these spectra would be below the detector energy range.

If the absorption features are due to an evolving cutoff, then the cutoff would yield the temperature of the plasma. The cutoff energy is approximately $11.6 \times B_{12}$ keV. For a "feature" at ~ 50 keV, $B_{12} \sim 4$. For the range of critical energies derived for the KONJS spectra, 2 to 15 keV (see Figure A.4), eq. 5.1 yields a range of temperatures from 100 to 280 keV.

Table 5.1

HXRBS Detector Counts to Shield Counts Ratios

<u>Event</u> <u>Dy/Mon/Yr</u>	<u>Detector</u> <u><Cnts/s></u>	<u>Shield</u> <u><Cnts/s></u>	<u>Ratio</u> <u>Det/Shd</u>	<u>Duration</u> <u>sec</u>
07/MAR/80	38 ± 2	422 ± 41	0.091 ± 0.010	42
19/APR/80	547 ± 14	5485 ± 436	0.100 ± 0.008	4.5
21/APR/80	257 ± 5	668 ± 140	0.384 ± 0.081	22
02/JUN/80	6 ± 2	1503 ± 155	0.004 ± 0.002	15
05/JUN/80	33 ± 5	293 ± 188	0.113 ± 0.074	12
19/NOV/80	38 ± 5	1112 ± 210	0.034 ± 0.008	10
06/AUG/80				<1.0
05/DEC/80				<1.0
01/MAR/81	464 ± 19	774 ± 410	0.600 ± 0.319	2
17/MAR/81	109 ± 8	389 ± 286	0.280 ± 0.207	4
.6/SEP/81	45 ± 8	13330 ± 400	0.0034 ± 0.0006	34
25/JAN/82	98 ± 9	1540 ± 180	0.063 ± 0.009	1.7

Table 5.2a
Spectral Fits for April 19, 1980 Event
Detector Dead Layer 5.0 Mils

Spectrum	Thin Thermal Bremsstrahlung*		w/ w/o		Absorption line [§]		χ^2 / ν^e
	C_1 [#]	kT	C_2		Energy	FWHM	
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)	(keV)	
AP1980.A	0.033±0.009	4430± 125					10.3/13
.B	0.40 ± 0.12	2057± 676					30.4/13
	1.25 ± 0.05	883± 32	32.7± 3.4		50.0± 3.4	50.0±10.9	18.2/10
.C	0.90 ± 0.10	966± 108					20.6/13
.D	0.30 ± 0.06	3874± 531					47.4/13
	3.10 ± 0.27	582± 45	36.6± 5.0		50.5± 2.6	33.0±11.0	6.3/10
.E	0.48 ± 0.10	577± 121					10.2/13
Spectrum	Thin Thermal Synchrotron**		w/ w/o		Absorption Line		χ^2 / ν
	C_1	ϵ_c	C_2		Energy	FWHM	
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)	(keV)	
AP1980.A	0.18 ± 0.08	26.0±10.2					7.9/13
.B	1.68 ± 0.42	16.1± 3.7					19.7/13
	2.81 ± 0.11	11.7± 0.4	23.7± 4.1		64.9± 7.1	50.0±15.9	14.6/10
.C	3.52 ± 0.90	8.5± 1.7					16.3/13
.D	1.73 ± 0.02	22.8± 0.3					22.3/13
	5.23 ± 0.45	10.0± 0.6	24.3± 6.4		55.4± 5.4	33.0±20.0	8.7/10
.E	1.39 ± 0.28	7.0± 0.2					12.3/13

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Table 5.2a -- continued

Table 3.2a -- continued

Spectrum	Power-Law with Exponential Cutoff***				χ^2 / ν
	C_1 keV ⁻¹ cm ⁻² s ⁻¹	α (keV)	E_{cut} (keV)	E_{char} (keV)	
AP1980.A	0.36 ± 0.21	0.71±0.13	182± 116	457± 613	7.6/11
.B	2.13 ± 1.20	0.71±0.13	229± 57	125± 84	8.4/11
.C	4.74 ± 1.78	0.85±0.09	78± 43	333± 120	15.3/11
.D	1.27 ± 0.04	0.50±0.01	136± 9	337± 51	12.1/11
.E	6.03 ± 0.23	1.20±0.01	98± 76	371± 64	10.6/11

Spectrum	Thin Thermal Bremsstrahlung w/ w/o Absorption line					χ^2 / ν
	C_1 keV ⁻¹ cm ⁻² s ⁻¹	kT (keV)	C_2 (keV)	Energy (keV)	FWHM (keV)	
AP1980.RS1	0.36 ± 0.05 1.41 ± 0.03	2074± 203 709± 13				20.9/13 10.8/10
.DC1	0.32 ± 0.01 2.19 ± 0.13	2967± 61 604± 33				12.6/13 8.6/10
.VL1	0.71 ± 0.17	1090± 281				7.8/13
.RS2	0.45 ± 0.01 3.19 ± 0.05	3678± 49 781± 11				41.7/13 12.0/10
.DC2	0.87 ± 0.13 5.42 ± 0.31	1060± 169 281± 13				25.3/13 13.4/10
.VL2	0.79 ± 0.38	947± 347				9.7/13

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Table 5.2a -- continued

Spectrum	Thin Thermal Synchrotron		w/ w/o		Absorption Line		χ^2 / ν
	C_1	ϵ_c	C_2		Energy	FWHM	
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)	(keV)	
AP1980.RS1	1.41 ± 0.44 3.08 ± 0.17	17.0 ± 5.0 10.3 ± 0.4	32.2 ± 5.1		53.7 ± 5.6	50.0 ± 20.4	$12.5/13$ $9.2/10$
.DC1	2.18 ± 0.71 5.35 ± 0.31	14.4 ± 4.5 8.4 ± 0.3	34.1 ± 5.1		69.8 ± 6.3	50.0 ± 13.3	$10.1/13$ $7.1/10$
.VL1	2.66 ± 1.34	9.6 ± 3.6					$7.3/13$
.RS2	2.03 ± 0.50 6.23 ± 0.26	27.7 ± 7.6 11.5 ± 0.4	26.8 ± 3.4		51.4 ± 4.3	33.0 ± 10.1	$23.1/13$ $13.3/10$
.DC2	2.71 ± 0.15 12.68 ± 0.73	11.4 ± 0.5 4.7 ± 0.2	40.9 ± 3.7		46.4 ± 2.9	50.0 ± 23.5	$18.2/13$ $12.7/10$
.VL2	2.77 ± 1.10	9.2 ± 3.0					$8.4/13$
Spectrum	Power-Law with Exponential Cutoff						χ^2 / ν
	C_1	α	E_{cut}		E_{char}		
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)		
AP1980.RS1	1.04 ± 0.05	0.57 ± 0.01	196 ± 18		146 ± 37		$4.5/11$
.DC1	3.01 ± 1.14	0.76 ± 0.09	250 ± 90		100 ± 120		$5.6/11$
.VL1	2.40 ± 0.58	0.78 ± 0.05	338 ± 163		10 ± 130		$7.7/11$
.RS2	1.02 ± 0.04	0.37 ± 0.01	127 ± 9		387 ± 91		$16.5/11$
.DC2	0.89 ± 0.93	0.46 ± 0.24	132 ± 37		171 ± 77		$9.7/11$
.VL2	4.71 ± 8.95	0.89 ± 0.48	118 ± 111		241 ± 184		$8.1/11$

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Table 5.2b
Spectral Fits for April 21, 1980 Event
Detector Dead Layer 5.0 Mils

Spectrum	Thin Thermal Bremsstrahlung		w/ w/o		Absorption		Line		χ^2 /v
	C_1	KT	C_2		Energy		FWHM		
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)		(keV)		
AP2180.A	2.13 ± 0.19	191 ± 14							
	5.83 ± 0.91	111 ± 9	30.7 ± 4.9		44.4 ± 2.0		50.0 ± 28.3		50.3/13 16.0/10
.B	1.12 ± 0.12	288 ± 28							
	2.85 ± 0.06	166 ± 3	32.5 ± 1.5		48.3 ± 1.4		50.0 ± 9.6		50.9/13 11.9/10
.C	0.50 ± 0.09	426 ± 63							
	1.56 ± 0.12	199 ± 11	33.7 ± 3.5		45.1 ± 2.6		50.0 ± 26.4		34.7/13 7.3/10
Spectrum	Thin Thermal Synchrotron		w/ w/o		Absorption		Line		χ^2 /v
	C_1	ϵ_c	C_2		Energy		FWHM		
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)		(keV)		(keV)		
AP2180.A	7.05 ± 0.91	2.9 ± 0.2							
	49.6 ± 2.9	1.28 ± 0.04	35.8 ± 2.2		44.1 ± 1.3		50.0 ± 17.2		46.5/13 17.3/10
.B	3.00 ± 0.42	4.5 ± 0.4							
	12.49 ± 0.27	2.33 ± 0.03	36.4 ± 1.4		49.5 ± 1.2		50.0 ± 7.4		42.2/13 14.6/10
.C	1.32 ± 0.22	6.0 ± 0.7							
	5.24 ± 0.14	3.00 ± 0.04	33.9 ± 1.8		47.1 ± 1.7		50.0 ± 12.6		23.0/13 7.2/10

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Table 5.2b -- continued

Spectrum	Power-Law with Exponential Cutoff					χ^2 / ν
	C_1 keV ⁻¹ cm ⁻² s ⁻¹	α (keV)	E_{cut} (keV)	E_{char} (keV)		
AP2180.A	8.88 ± 2.64	1.17±0.09	114± 15	85± 13	17.9/11	
.B	5.81 ± 1.99	1.14±0.08	163± 25	95± 25	9.9/11	
.C	1.74 ± 0.37	0.95±0.05	130± 21	142± 32	6.3/11	

Spectrum	Thin Thermal Bremsstrahlung w/ w/o Absorption line					χ^2 / ν
	C_1 keV ⁻¹ cm ⁻² s ⁻¹	kT (keV)	C_2 (keV)	Energy (keV)	FWHM (keV)	
AP2180.RS1	2.66 ± 0.16	193± 9				54.7/13
	9.06 ± 0.23	103± 2	37.6± 1.3	45.2± 0.9	50.0±10.4	20.4/10
.DC1	3.30 ± 0.52	157± 22				10.7/13
	4.74 ± 0.19	128± 4	10.4± 2.8	41.8± 9.3	33.0±26.9	8.2/10
.VL1	1.00 ± 0.35	135± 35				5.0/13
.RS2	1.49 ± 0.60	293± 8				74.5/13
	4.32 ± 0.13	166± 4	39.6± 1.7	46.2± 1.4	50.0±12.0	27.3/10
.DC2	1.49 ± 0.28	284± 46				15.7/13
	4.54 ± 0.48	148± 10	36.6± 4.8	46.5± 2.8	50.0±29.0	6.2/10
.VL2	7.71 ± 0.16	212± 36				12.8/13
	2.18 ± 0.64	119± 20	32.3± 15.1	51.5± 4.8	39.0±31.1	3.3/10

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Table 5.2b -- continued

Spectrum	Thin Thermal Synchrotron w/		w/o Absorption		Line		χ^2 / ν
	C_1	ϵ_c	C_2	Energy	FWHM		
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)	(keV)	(keV)		
AP2180.RS1	8.46 ± 1.19 56.8 ± 4.15	3.0 ± 0.3 1.39 ± 0.04	37.1 ± 2.7	44.5 ± 1.5	50.0 ± 19.9		$51.9/13$ $22.9/10$
.DC1	12.6 ± 3.3 38.0 ± 1.5	2.4 ± 0.4 1.50 ± 0.03	17.8 ± 2.4	42.6 ± 4.5	50.0 ± 12.4		$10.6/13$ $7.3/10$
.VL1	4.88 ± 0.37	1.9 ± 0.4					$5.0/13$
.RS2	3.79 ± 0.67 18.6 ± 0.6	4.7 ± 0.5 2.34 ± 0.03	41.9 ± 1.7	47.3 ± 1.3	50.0 ± 9.9		$65.4/13$ $31.2/10$
.DC2	4.04 ± 0.91 16.1 ± 0.6	4.4 ± 0.6 2.31 ± 0.04	33.4 ± 2.4	47.9 ± 2.2	50.0 ± 16.2		$12.7/13$ $5.5/10$
.VL2	2.41 ± 0.69 13.0 ± 4.4	3.3 ± 0.6 1.57 ± 0.22	34.7 ± 12.6	50.7 ± 3.8	40.9 ± 26.7		$12.7/13$ $3.4/10$
Spectrum	Power-Law with Exponential Cutoff						χ^2 / ν
	C_1	α	E_{cut}	E_{char}			
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)	(keV)			
AP2180.RS1	8.18 ± 2.76	1.10 ± 0.10	130 ± 15	68 ± 15			$15.4/11$
.DC1	15.2 ± 4.8	1.22 ± 0.09	73 ± 28	102 ± 20			$8.8/11$
.VL1	20.1 ± 1.6	1.63 ± 0.02	58 ± 246	112 ± 54			$5.0/11$
.RS2	3.46 ± 1.50	0.95 ± 0.10	193 ± 29	63 ± 26			$15.2/11$
.DC2	5.95 ± 1.65	1.07 ± 0.07	127 ± 28	115 ± 36			$5.2/11$
.VL2	5.51 ± 1.75	1.28 ± 0.08	128 ± 38	97 ± 39			$8.0/11$

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Table 5.2c
Spectral Fits: Remaining Events
Detector Dead Layer 5.0 Mils

Spectrum	Thin Thermal Bremsstrahlung		w/ w/o		Absorption line		χ^2 / ν
	C_1 $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	kT (keV)	C_2 (keV)		Energy (keV)	FWHM (keV)	
MR0780	0.046 ± 0.001	903 ± 25					$30.9/12$
	0.14 ± 0.01	402 ± 29	37.0 ± 5.4		48.6 ± 4.1	50.0 ± 26.1	$8.8/9$
NV1980	0.046 ± 0.008	862 ± 128					$10.1/13$
MR0181.TOT	0.09 ± 0.01	1873 ± 205					$18.0/13$
MR0181.RS	0.13 ± 0.02	1623 ± 248					$14.3/13$
MR0181.DC	0.07 ± 0.04	1824 ± 756					$11.3/13$

Spectrum	Thin Thermal Synchrotron		w/ w/o		Absorption Line		χ^2 / ν
	C_1 $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	ϵ_c (keV)	C_2 (keV)		Energy (keV)	FWHM (keV)	
MR0780	0.11 ± 0.03	12.3 ± 2.3					$18.4/13$
	0.33 ± 0.03	6.1 ± 0.3	34.7 ± 6.4		51.6 ± 5.0	50.0 ± 25.8	$8.0/10$
NV1980	0.15 ± 0.05	8.8 ± 2.3					$9.9/13$
MR0181.TOT	0.41 ± 0.12	13.5 ± 2.9					$13.6/13$
MR0181.RS	0.56 ± 0.16	11.9 ± 2.6					$11.1/13$
MR0181.DC	0.30 ± 0.06	14.5 ± 2.4					$10.2/13$

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Table 5.2c -- continued

Table 5.2c -- continued		Power-Law with Exponential Cutoff					χ^2 / ν
Spectrum	C_1 $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	α (keV)	E_{cut} (keV)		E_{char} (keV)		
MR0780	0.054 ± 0.053	0.56 ± 0.25	$132 \pm$	30	$210 \pm$	73	7.6/10
NV1980	0.17 ± 0.08	0.80 ± 0.13	$82 \pm$	54	$348 \pm$	173	9.9/11
MR0181.T01	0.88 ± 0.30	0.86 ± 0.07	$197 \pm$	68	$209 \pm$	126	10.7/11
MR0181.RS	0.79 ± 0.40	0.80 ± 0.01	$188 \pm$	22	$162 \pm$	45	7.5/11
MR0181.DC	0.98 ± 0.07	0.95 ± 0.02	$220 \pm$	59	$249 \pm$	152	10.1/11

The TTB and TTS fits including absorption lines are listed directly following the fits without lines for a given interval. If the reduced chisquare parameter did not significantly improve when a line was included, the fit with line is not listed in the table. The quoted 1 sigma errors represent the increment necessary for chisquare to increase by 1.0, assuming the parameters are uncoupled, i.e., that chisquare depends quadratically on the parameters near the minimum.

- * The dependence of the TTB model on kT is described by eq. 3.5
- ** The dependence of the TTS model on ϵ is described by eq. 3.6
- *** The parameters for the PLE model are explicitly described by eq. 5.3
- # C_1 denotes the continuum normalization.
- \$ The gaussian absorption line parameters, C_2 = line equivalent width, ENERGY = central line energy, and FWHM = line full-width at half-maximum, are explicitly described by eq. 5.2.
- @ χ^2/ν is the chisquare parameter, χ^2 , divided by the number of degrees of freedom, ν . ν is the number of data points included in the spectrum minus the number of fit parameters.

Table 5.3
Spectral Fits Exhibiting Significant Differences for
Inclusion and Exclusion of Channel One

Spectrum	Thermal		Synchrotron		w/ w/o Absorption Line		Energy		FWHM	χ^2 / ν
	C_1	ϵ_c	C_2							
	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$	(keV)	(keV)			(keV)		(keV)		
AP1980										
DC2 15 ch	12.68 ± 0.73	4.7 ± 0.2	40.9 ± 3.7			46.4 ± 2.9		50.0 ± 23.5		12.7/10
14 ch	22.53 ± 3.67	3.5 ± 0.3	47.0 ± 8.7			54.6 ± 4.0		50.0 ± 21.9		7.4/ 9
AP2180										
C 15 ch	5.14 ± 0.14	3.00 ± 0.04	33.9 ± 1.8			47.1 ± 1.7		50.0 ± 12.6		7.2/10
14 ch	7.15 ± 0.20	2.59 ± 0.04	37.9 ± 1.8			49.0 ± 1.7		50.0 ± 9.2		6.1/ 9
RS1										
15 ch	56.8 ± 4.15	1.39 ± 0.04	37.1 ± 2.7			44.5 ± 1.5		50.0 ± 19.9		22.9/10
14 ch	85.1 ± 6.30	1.20 ± 0.04	42.6 ± 3.0			47.5 ± 1.4		50.0 ± 13.8		16.1/ 9

Parameter descriptions given in footnotes of Table 5.2 apply to Table 5.3 also.

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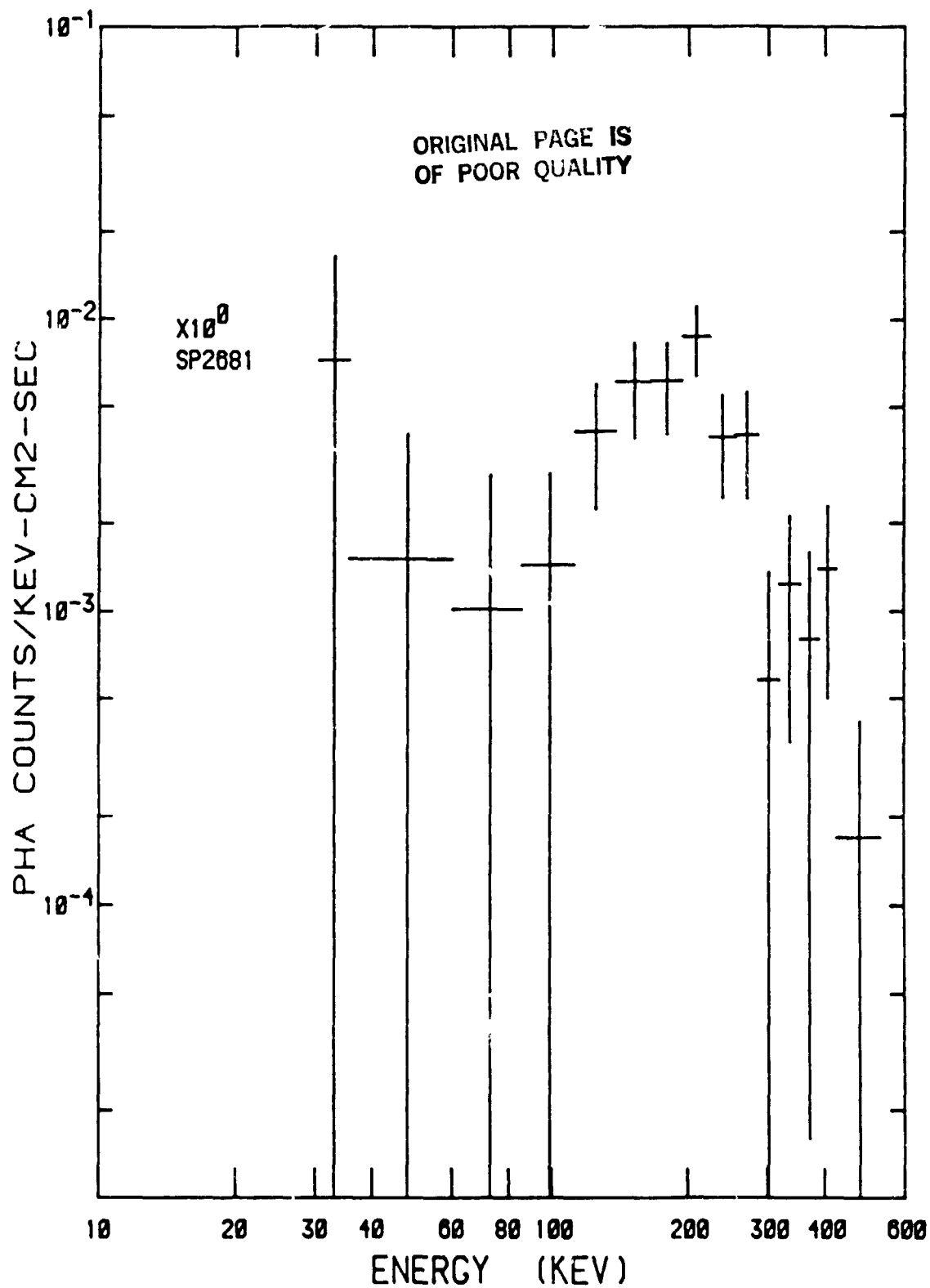


FIG 5.1 Shield-influenced PHA spectrum for 26 SEP 81 event.

Figures 5.2a - 5.22. Time histories of SMM gamma-ray bursts.

The time axis refers to Coordinated Universal Time. The suffixes to the event names represent the following:

SMM = HXRBS detector time histories

SHD = HXRBS shield time histories

EV1, EV2 = time sequences for critical energy, ϵ_c

LCH = time histories for lowest five channels

MCH = time histories for intermediate five channels

HCH = time histories for highest five channels

TH1 = ISEE-3 Cal time history

TH2 = ISEE-3 Ge time history

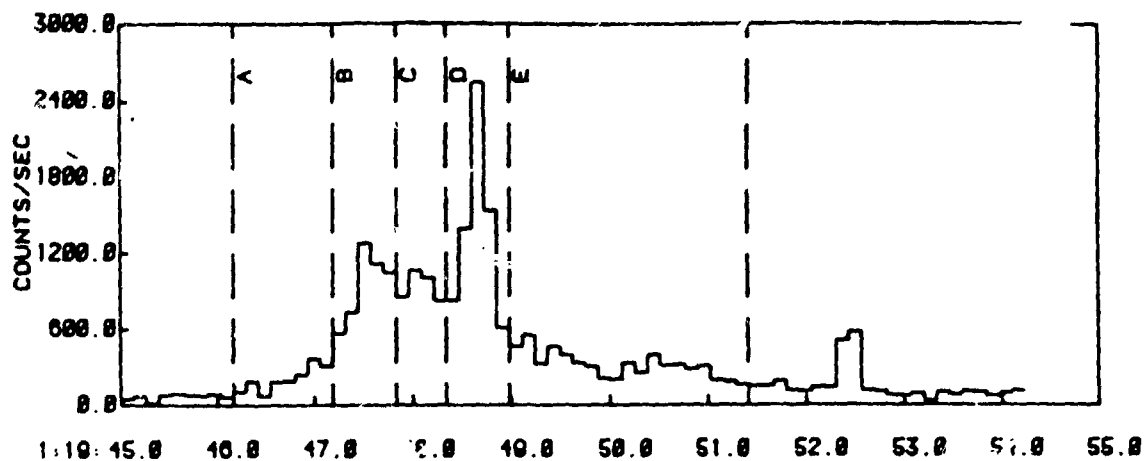


FIG. 5.2A AP1980.SMM

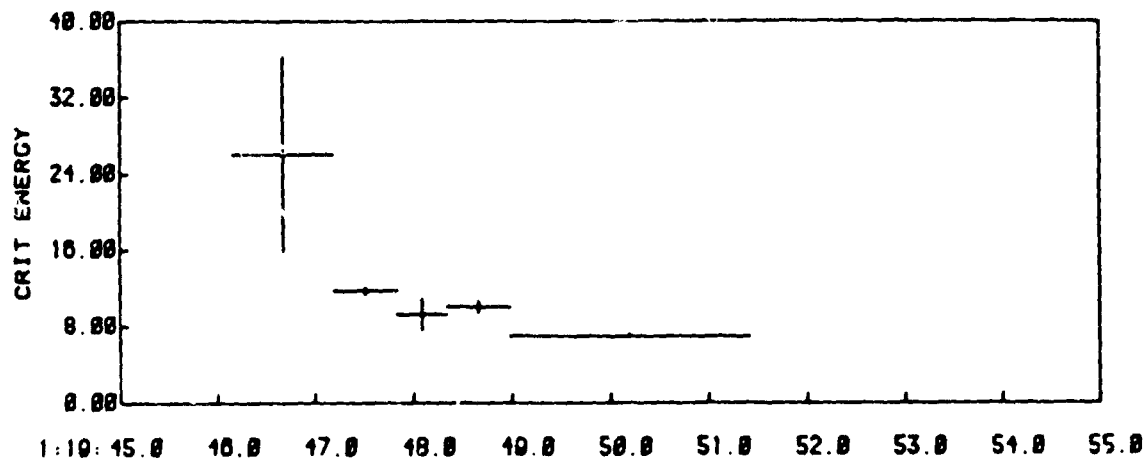
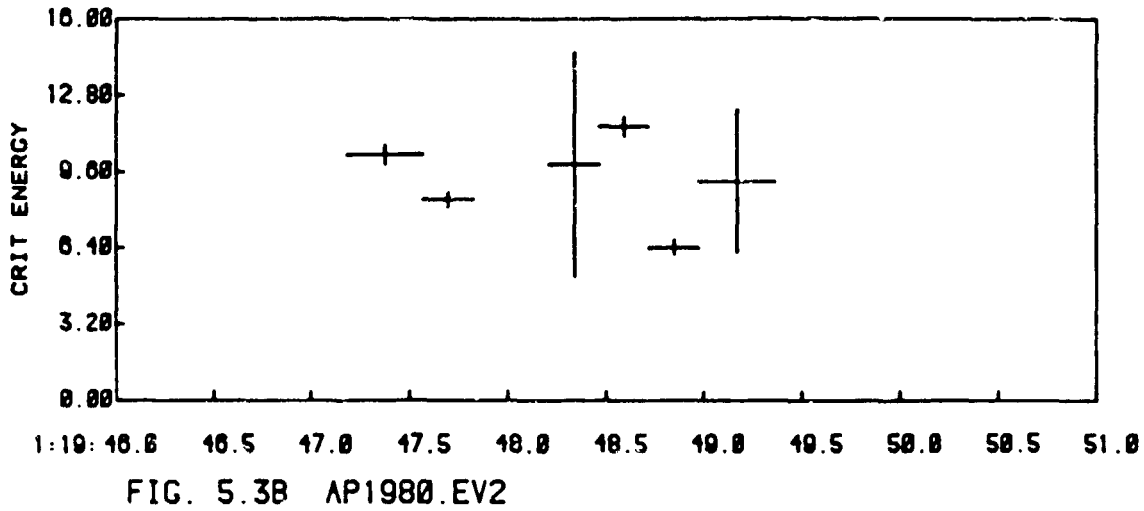
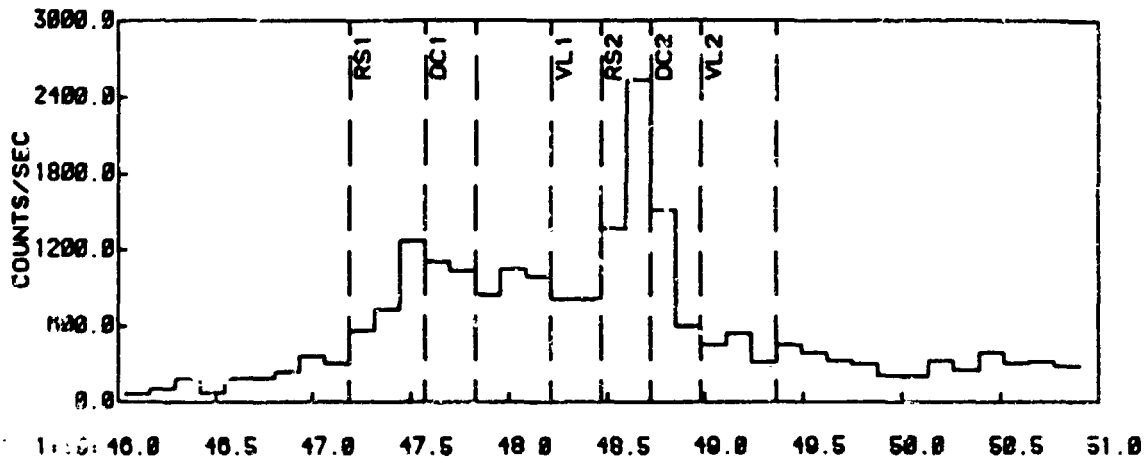
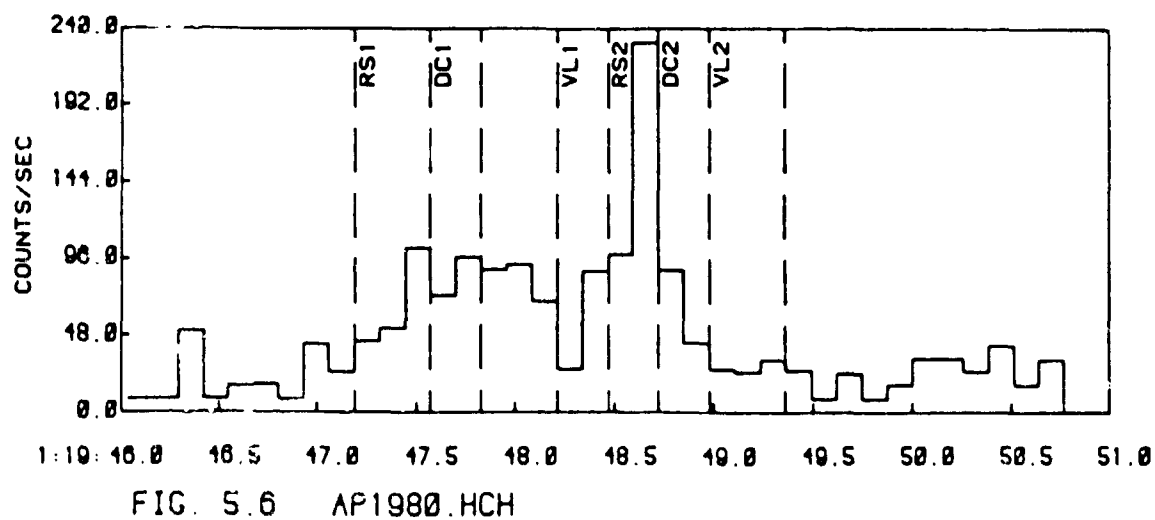
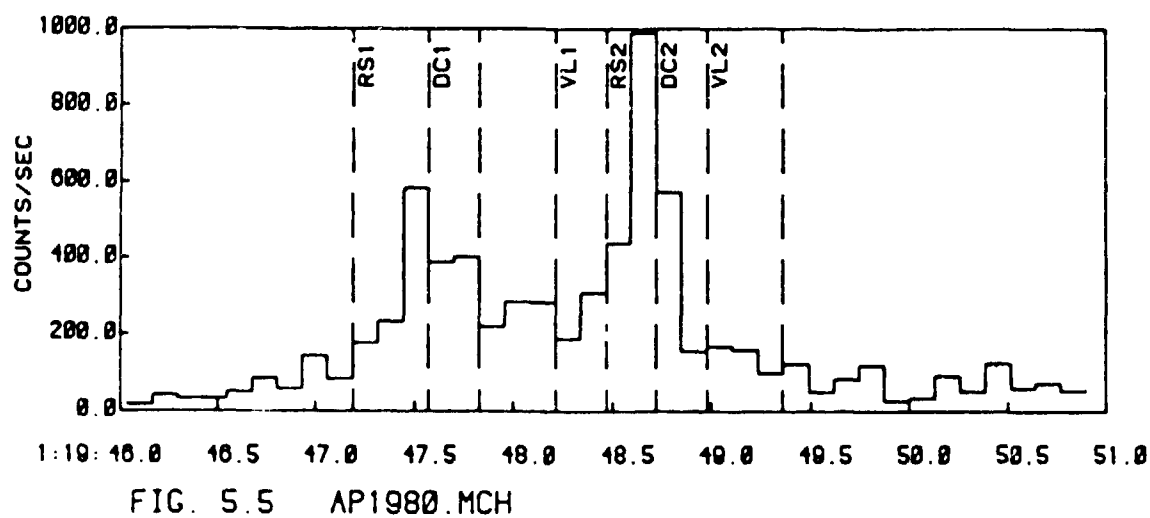
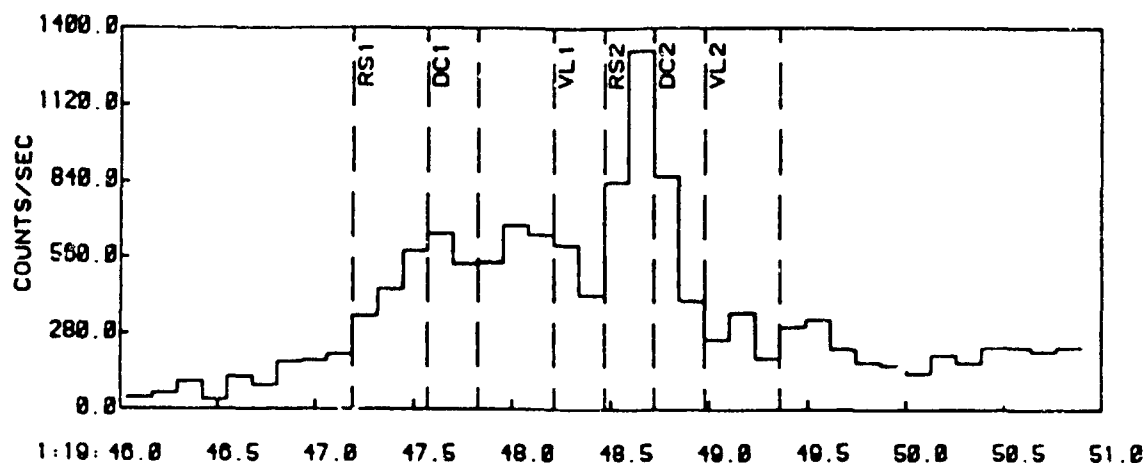


FIG. 5.2B AP1980.EVI



C-3



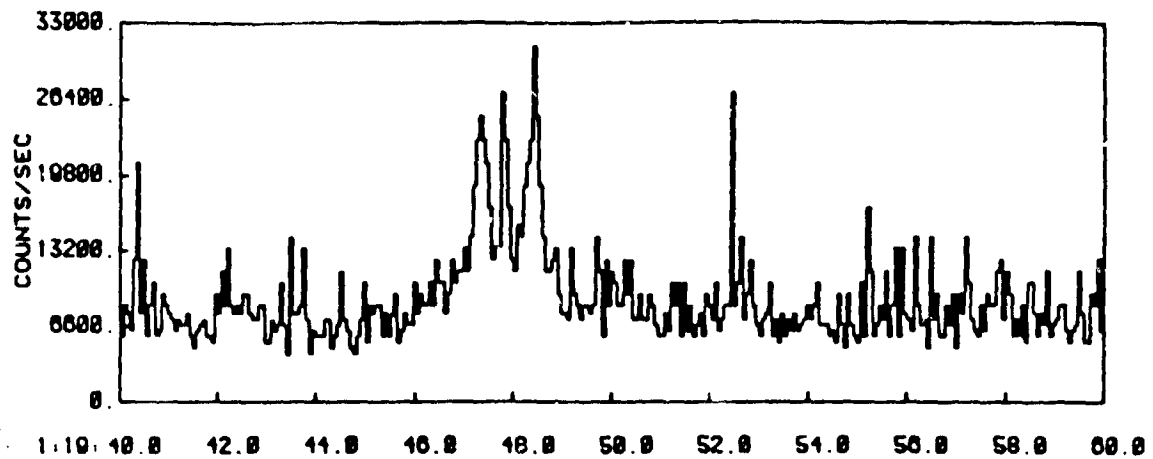


FIG. 5.7 AP1980.SH0

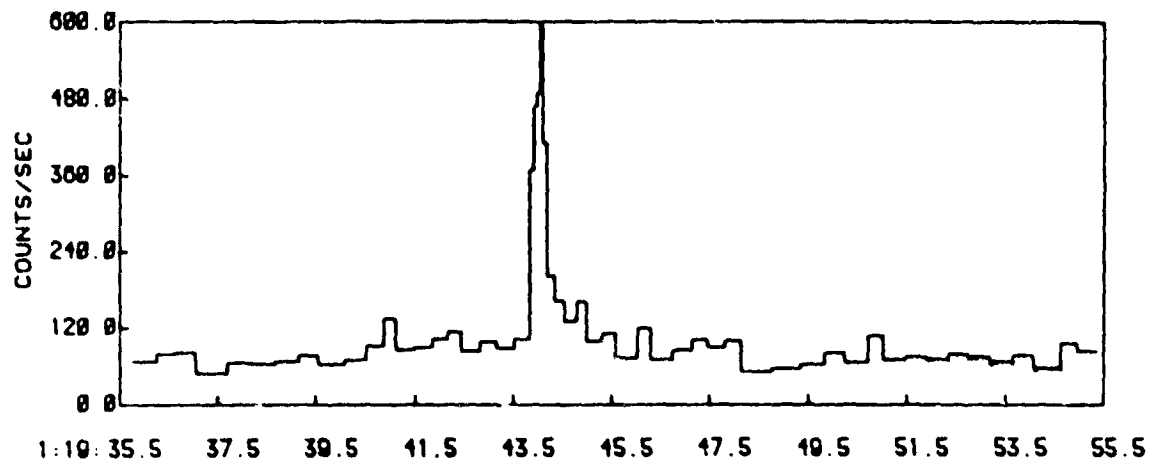


FIG. 5.8 AP1980.TH1

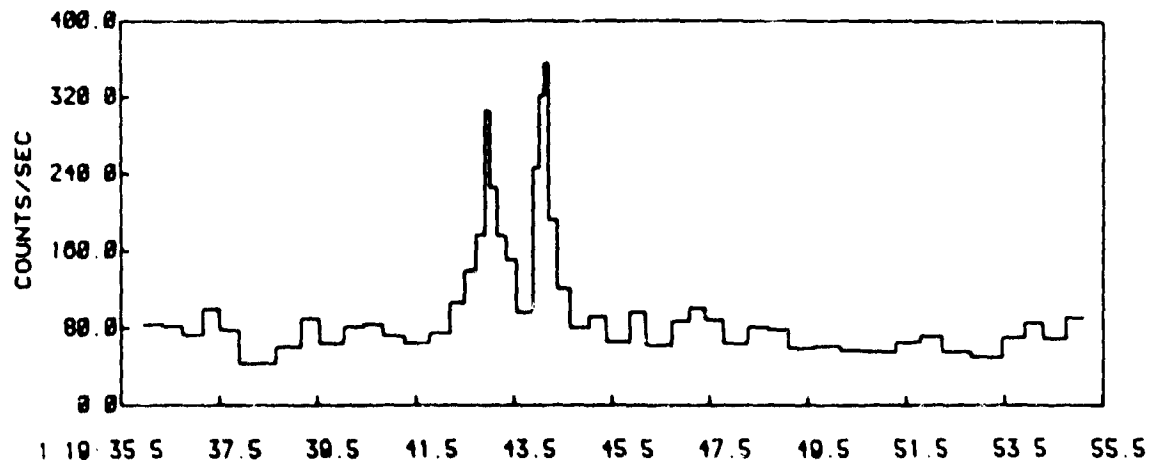
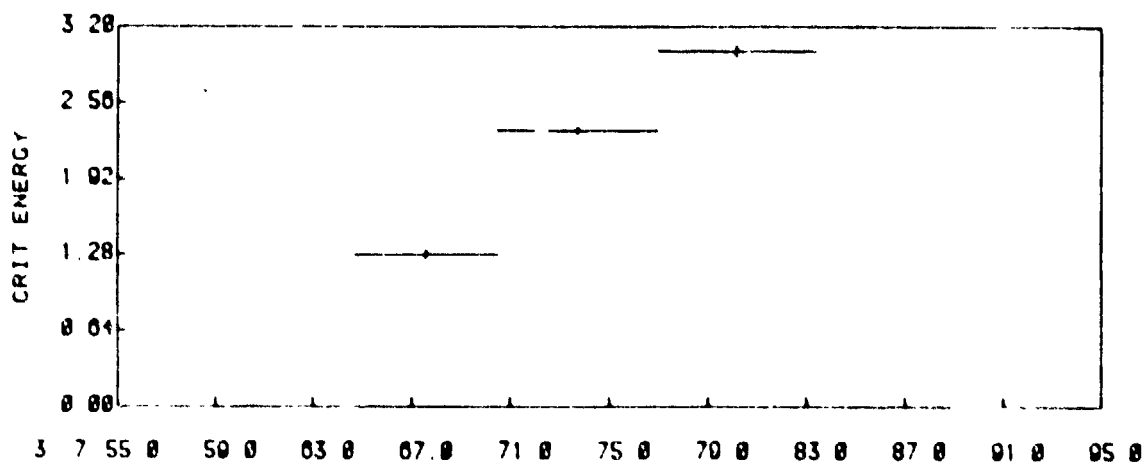
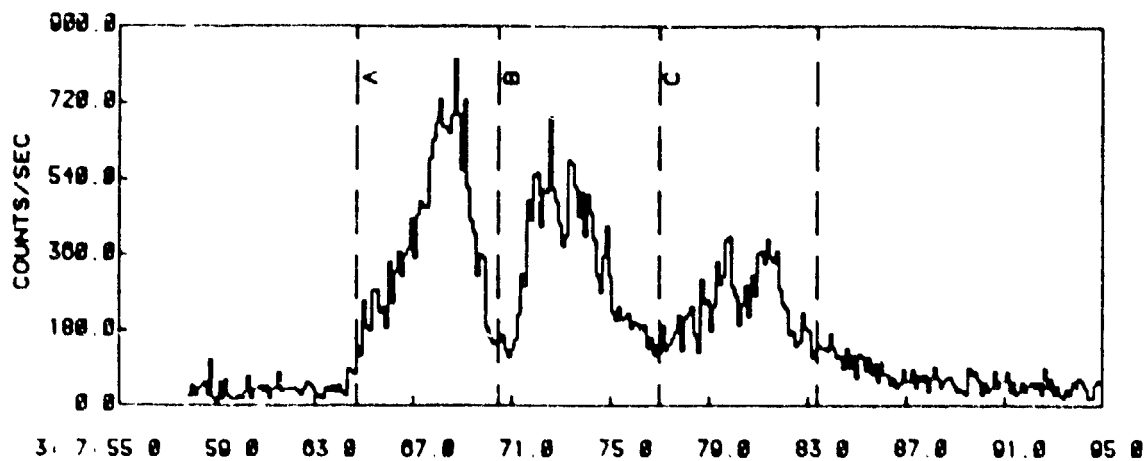
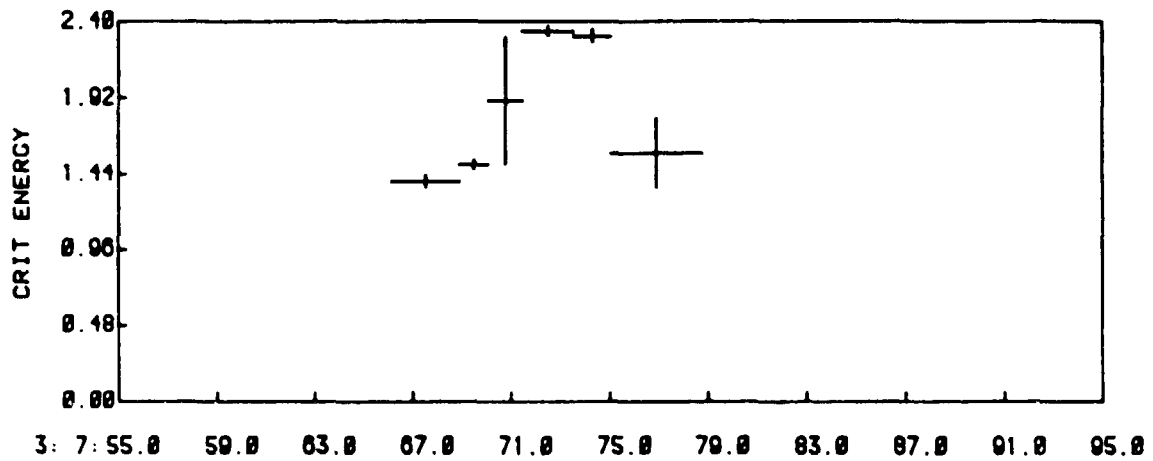
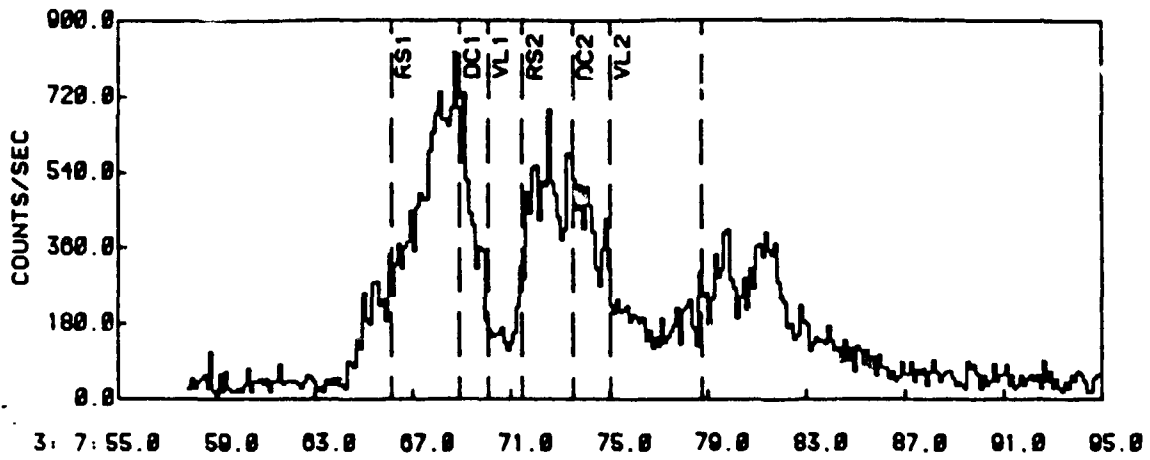
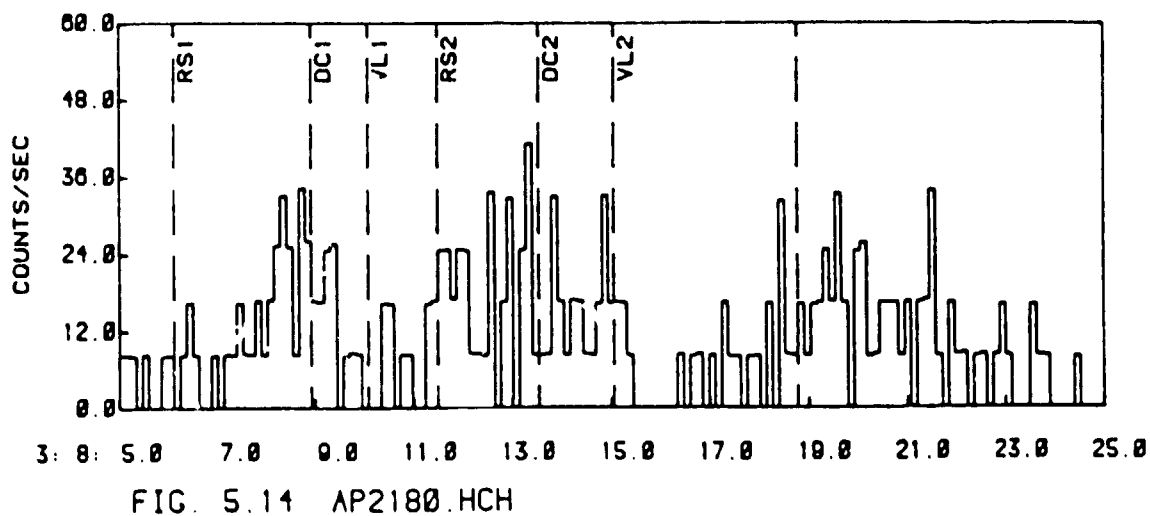
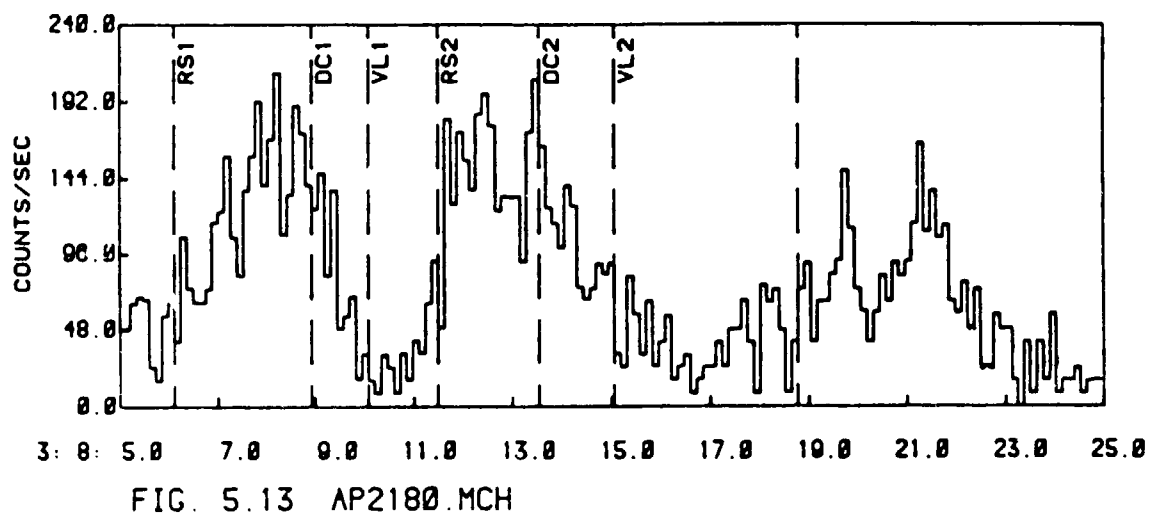
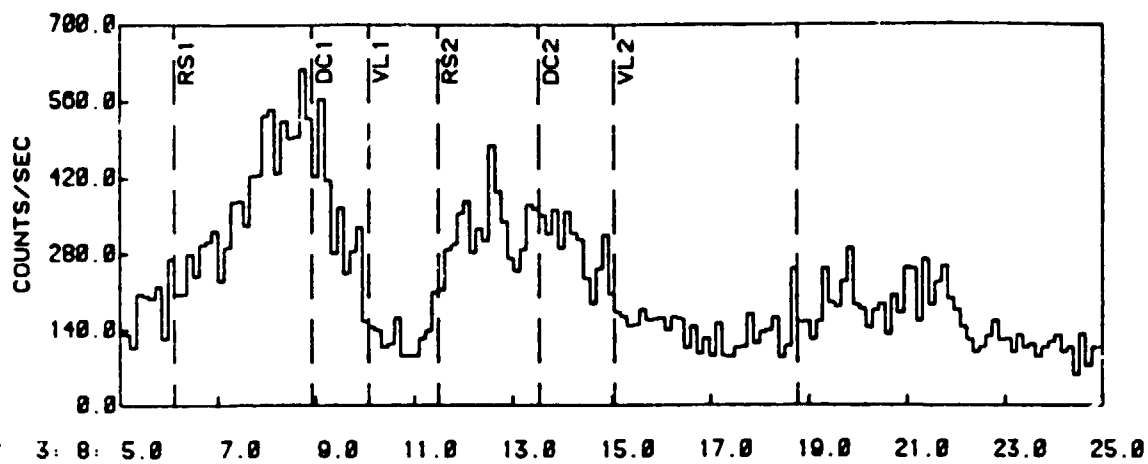


FIG. 5.9 AP1980.TH2







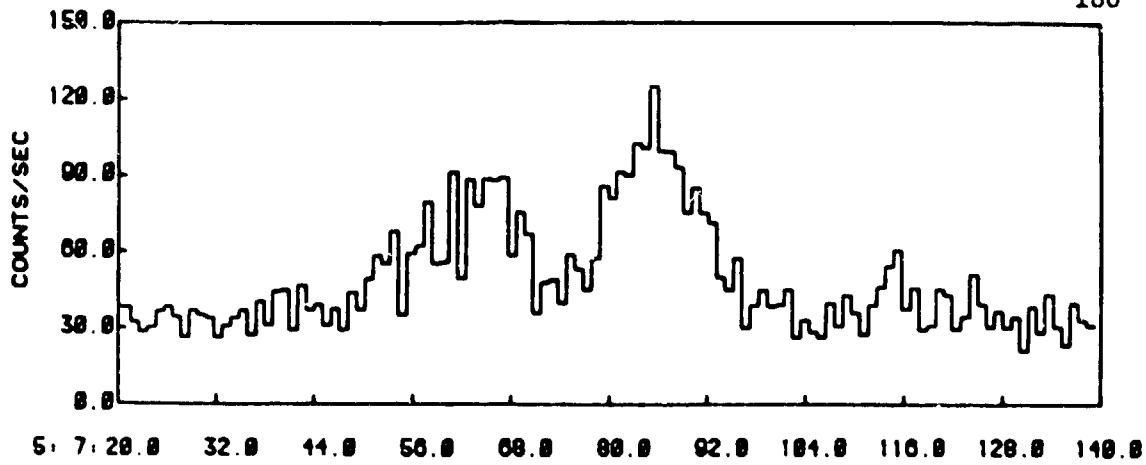


FIG. 5.15 MR0780.SMM

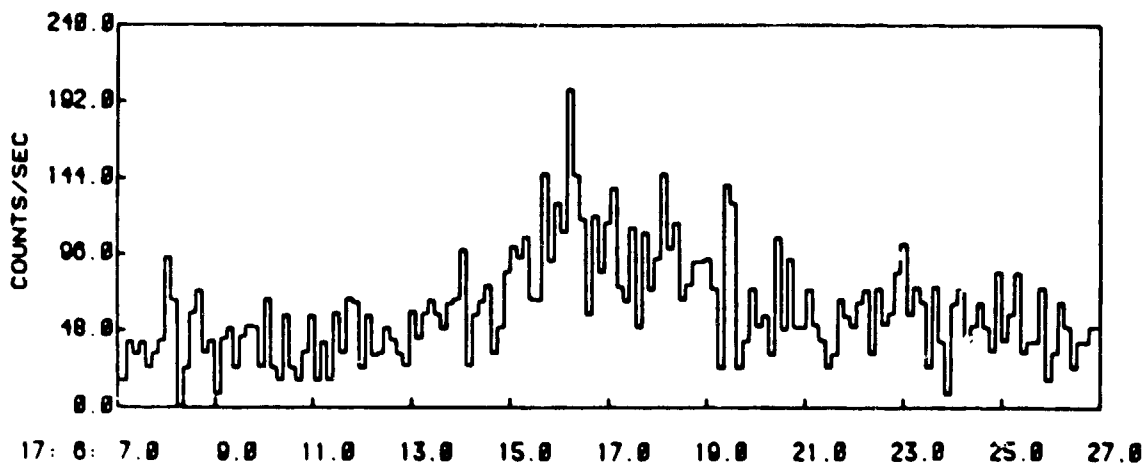


FIG. 5.16 NV1980.SMM

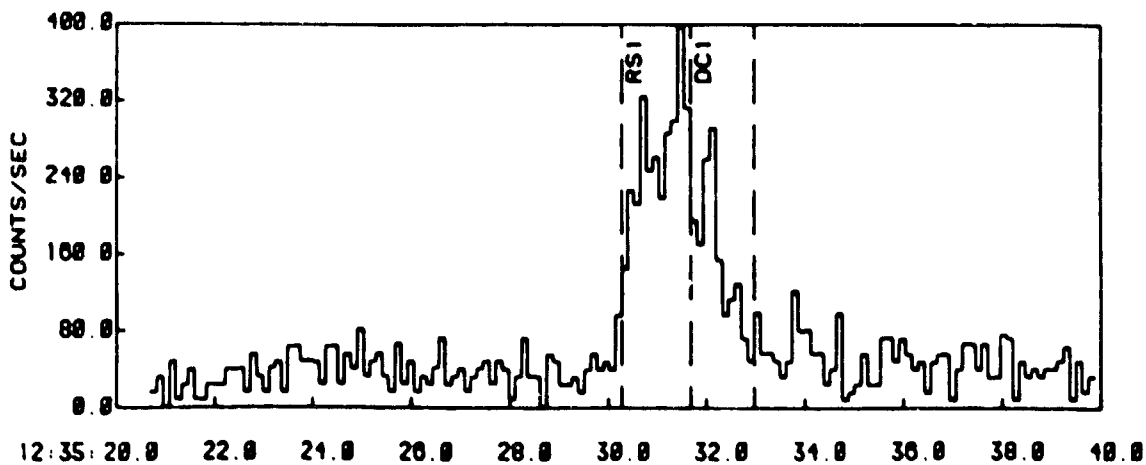
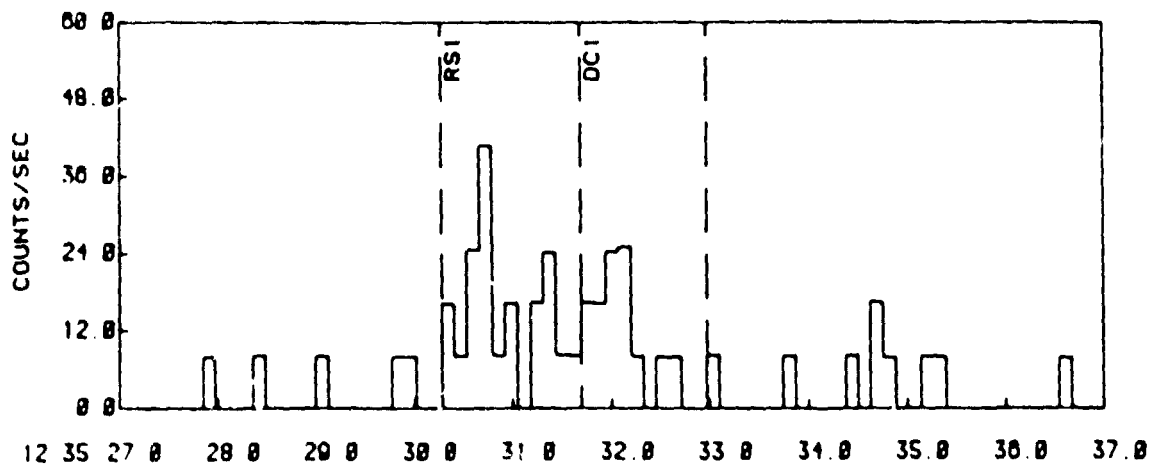
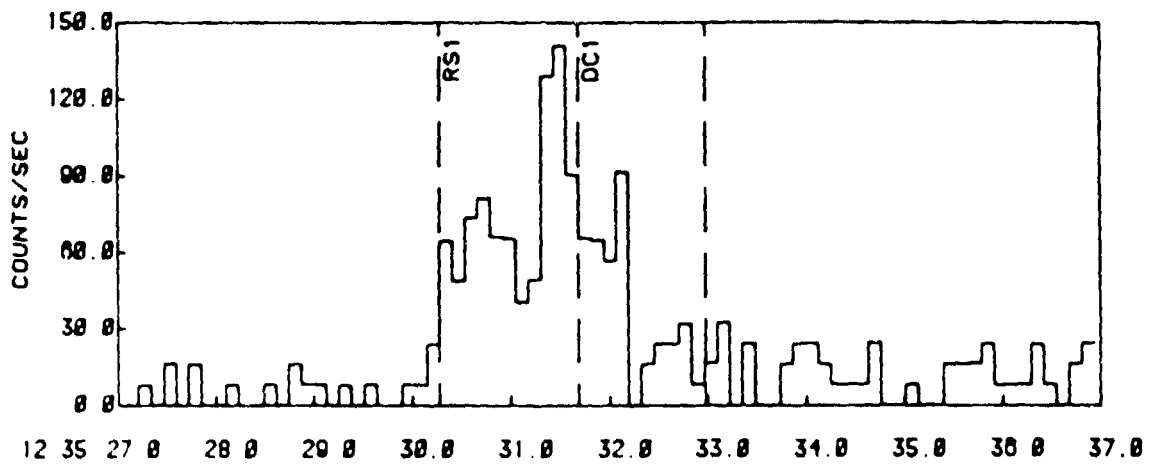
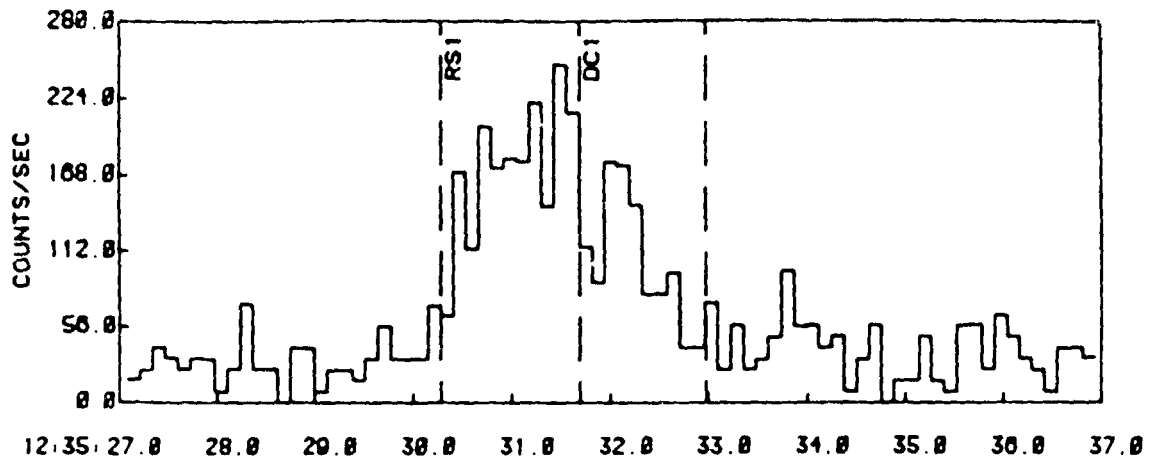


FIG. 5.17 MR0181.SMM

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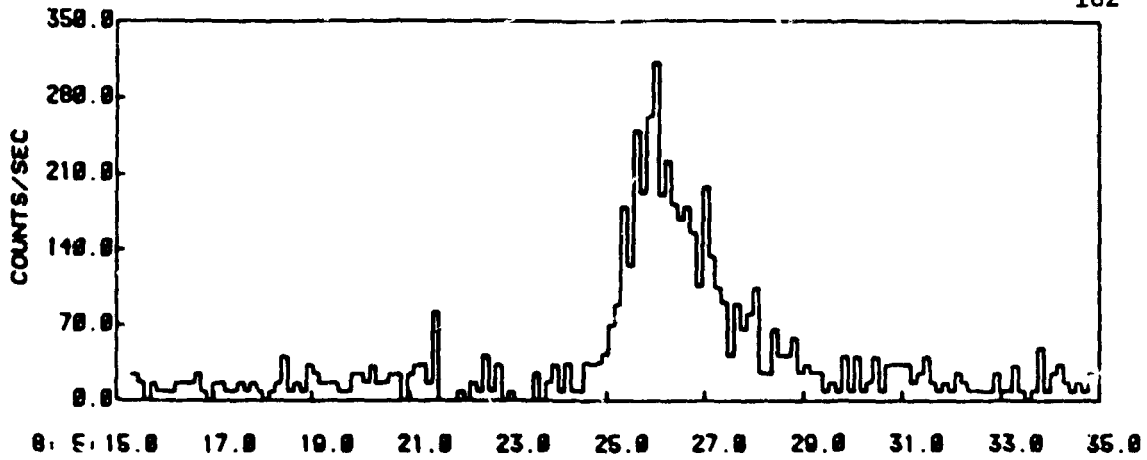


FIG. 5.21 MR1781.SMM

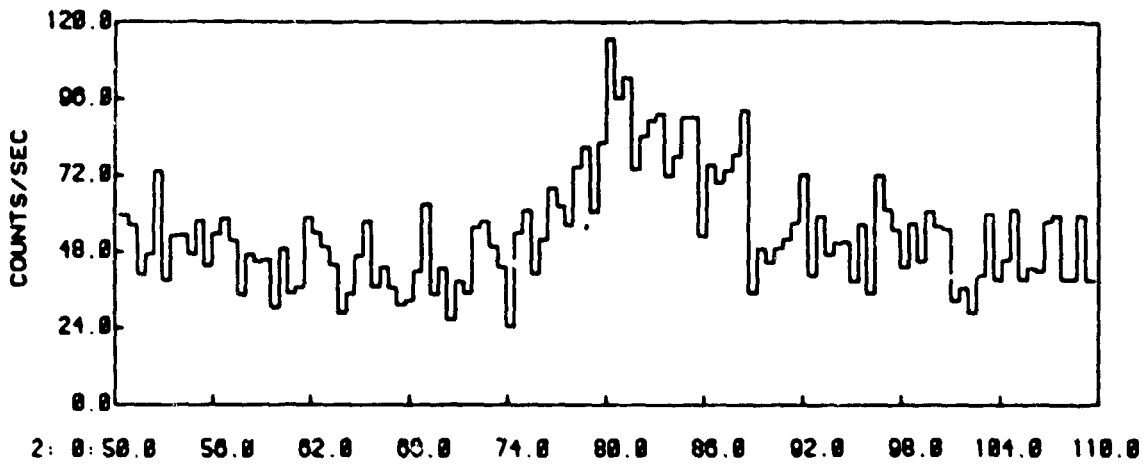


FIG. 5.22 JN0581.SMM

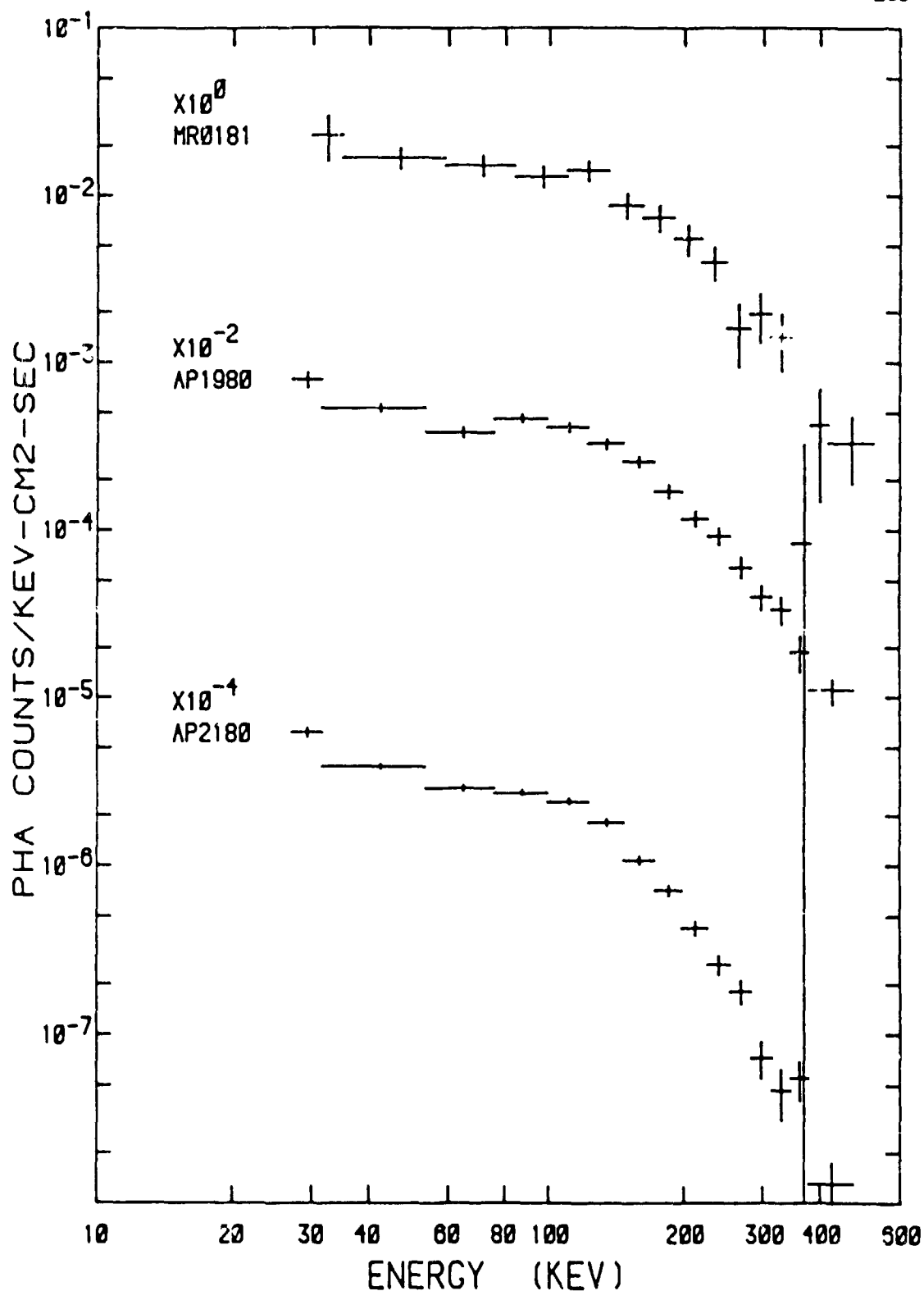


FIG 5.23 Total event spectra for 01 MAR 81, 19 APR 80,
and 21 APR 80.

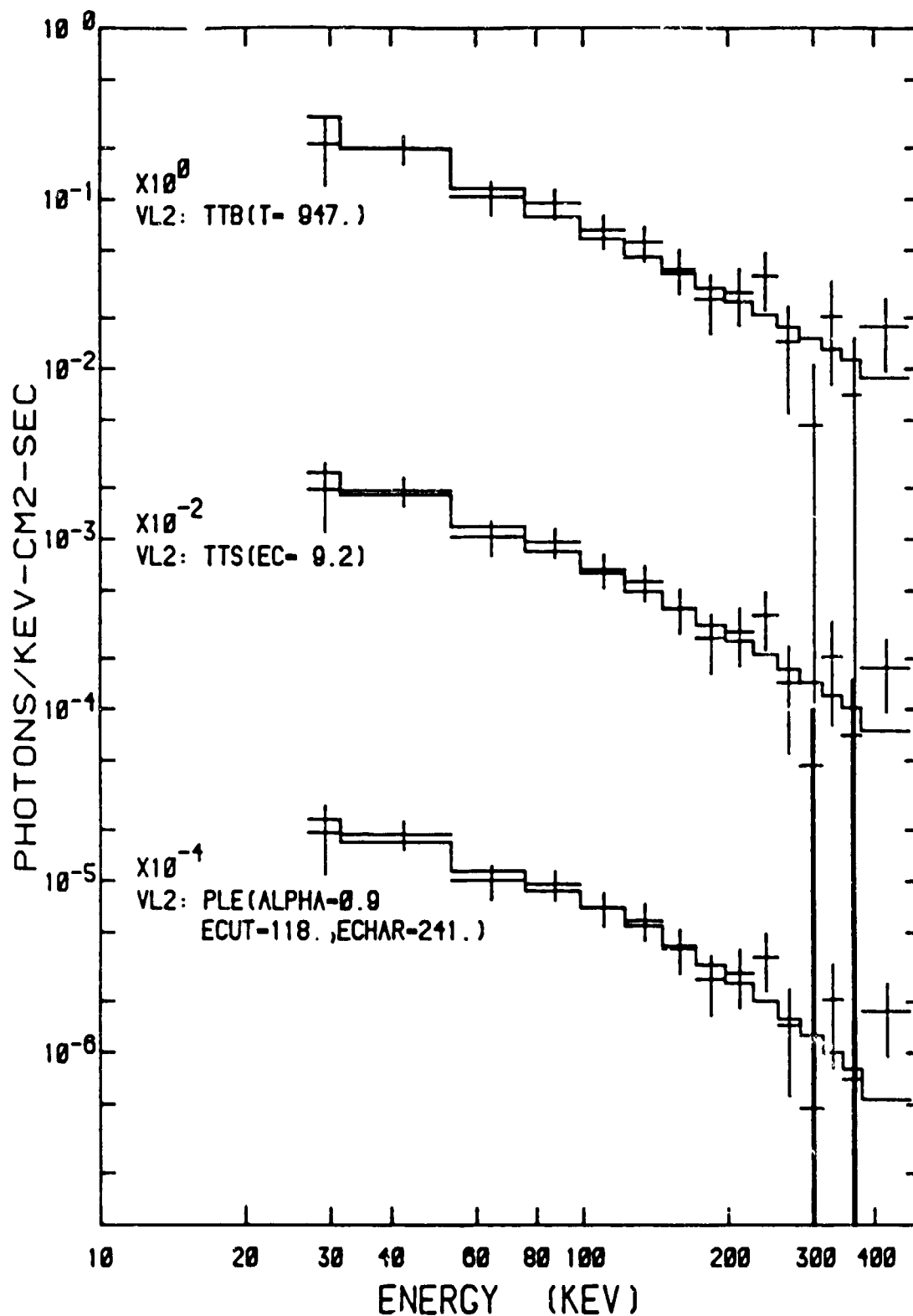


FIG 5.24 TTB, TTS, and PLE fits for Interval VL2
of 19 APR 80 event.

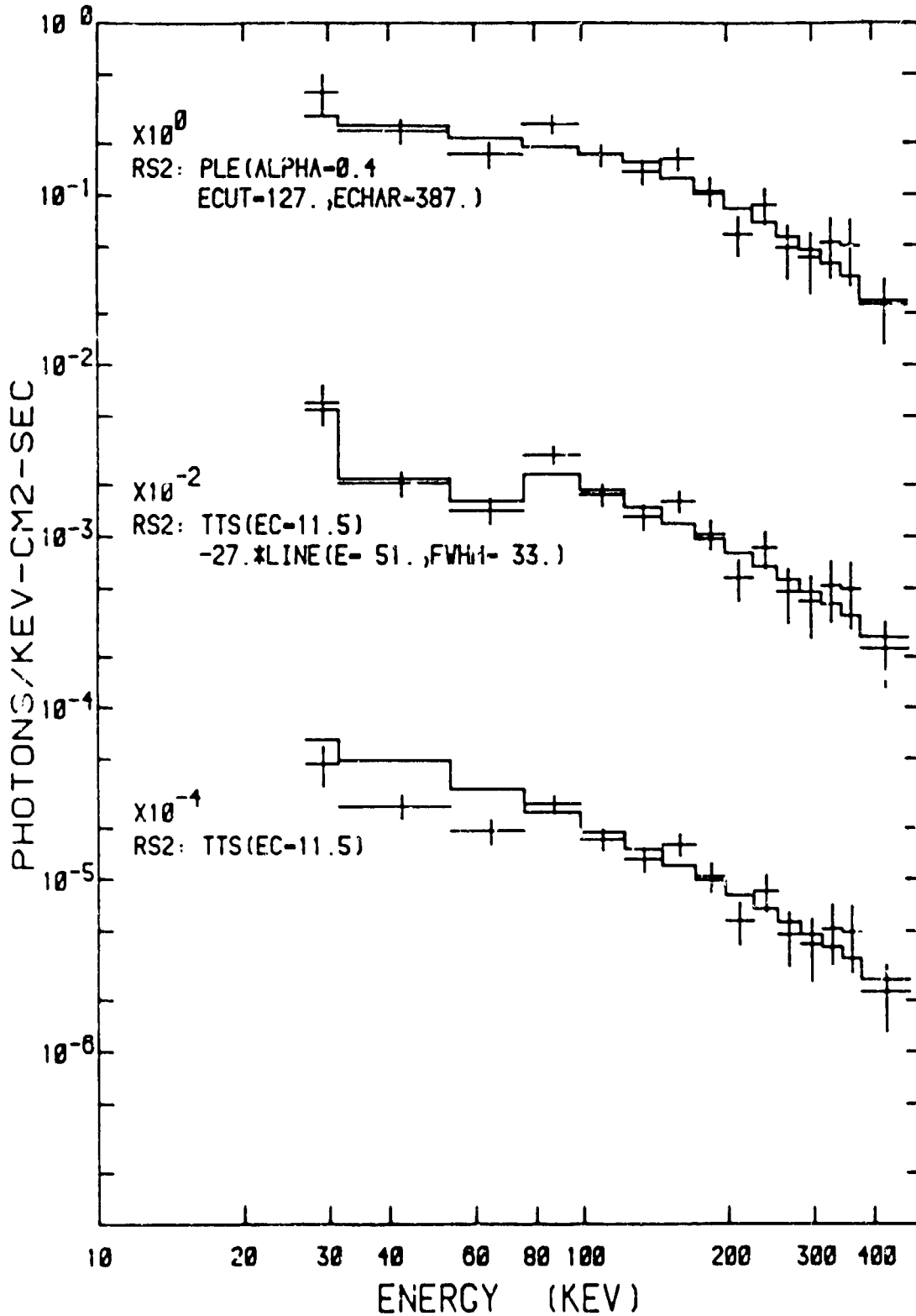


FIG 5 25 PLE and TTS fits (with line and with extrapolated continuum) for Interval RS2 of 19 APR 80 event

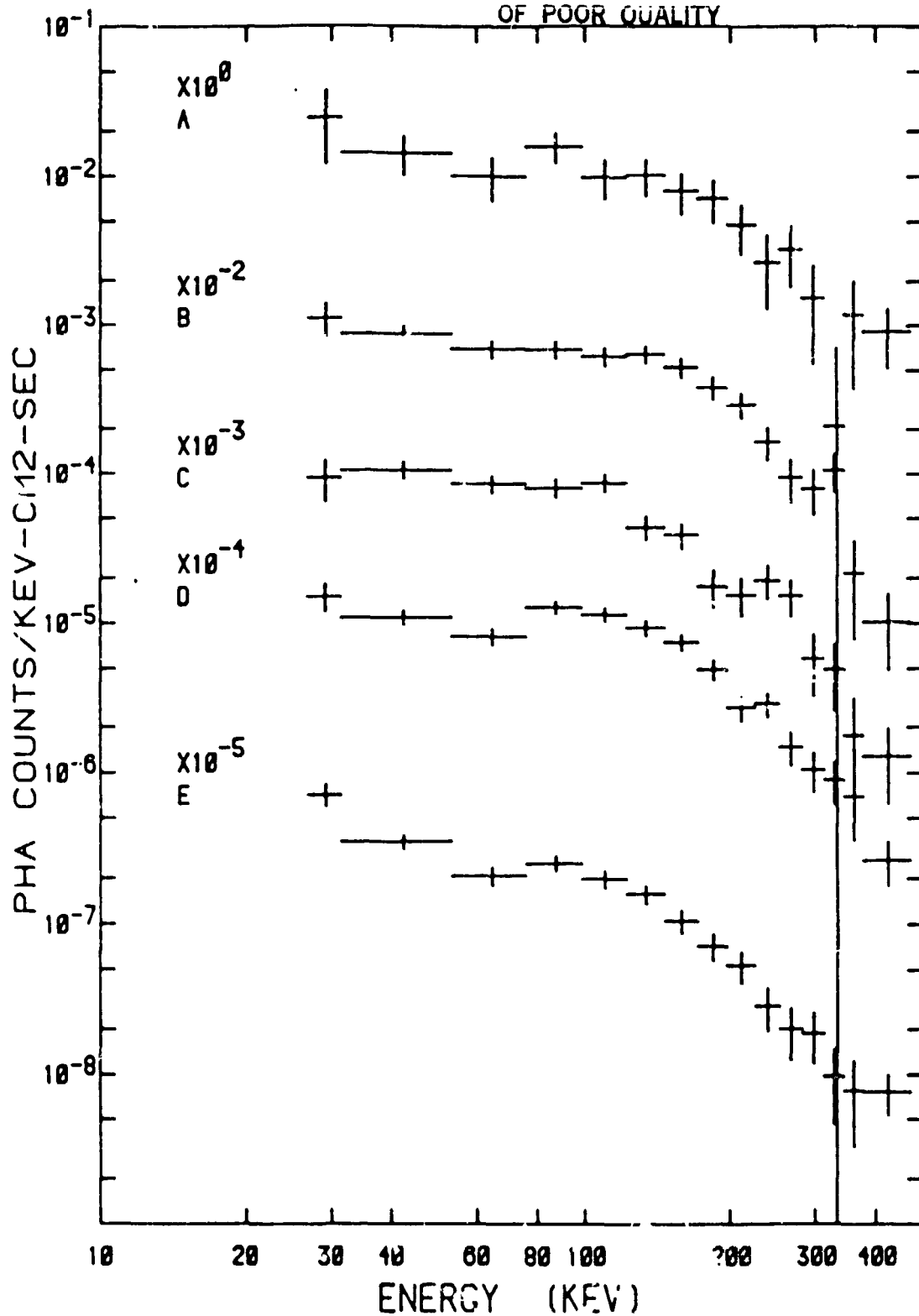


FIG 5.26 PHA spectra for Intervals A, B, C, D, and E of 19 APR 80 event.

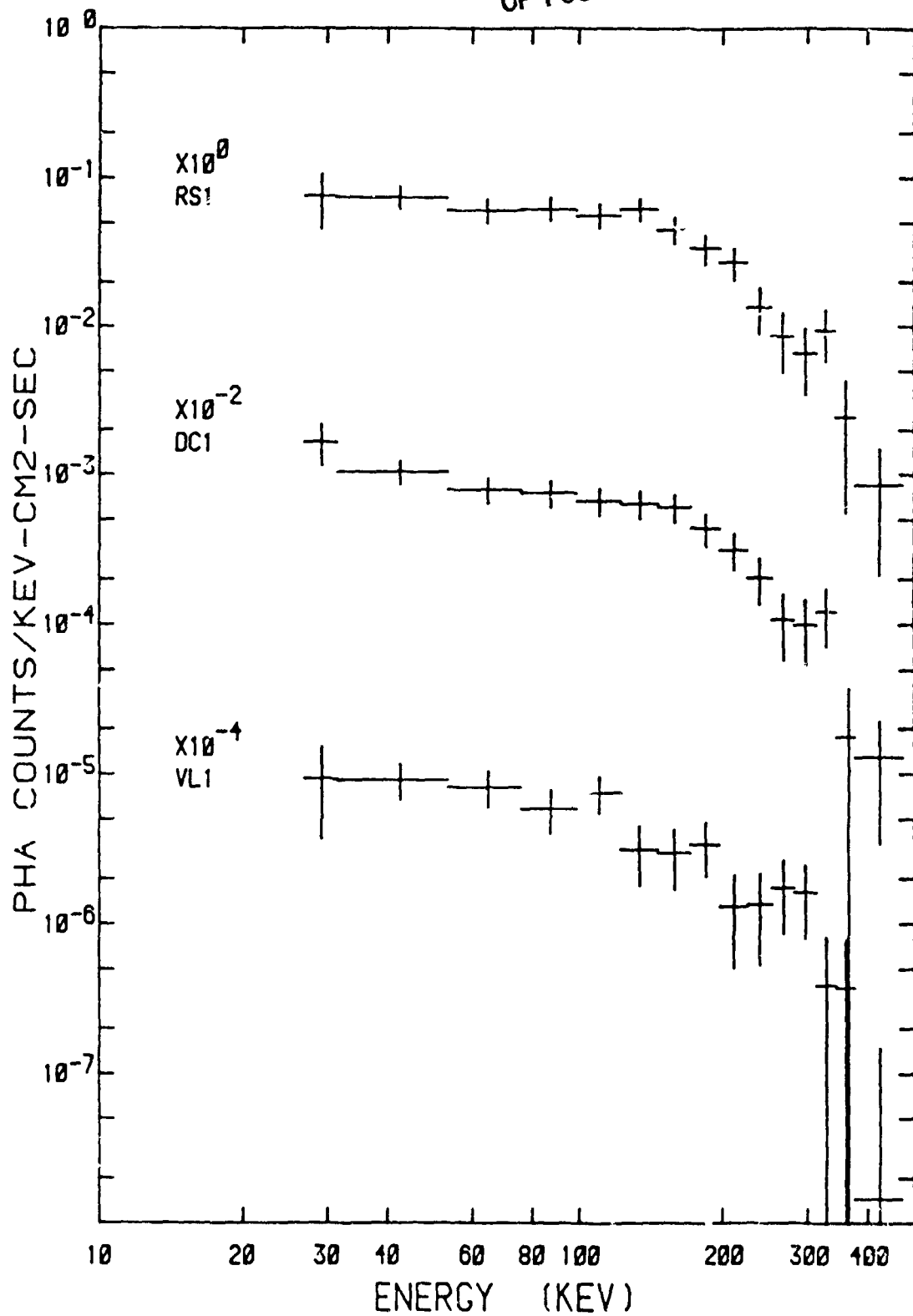


FIG 5.27a PHA spectra for intervals RS1, DC1, and VL1 of 19 APR 80 event.

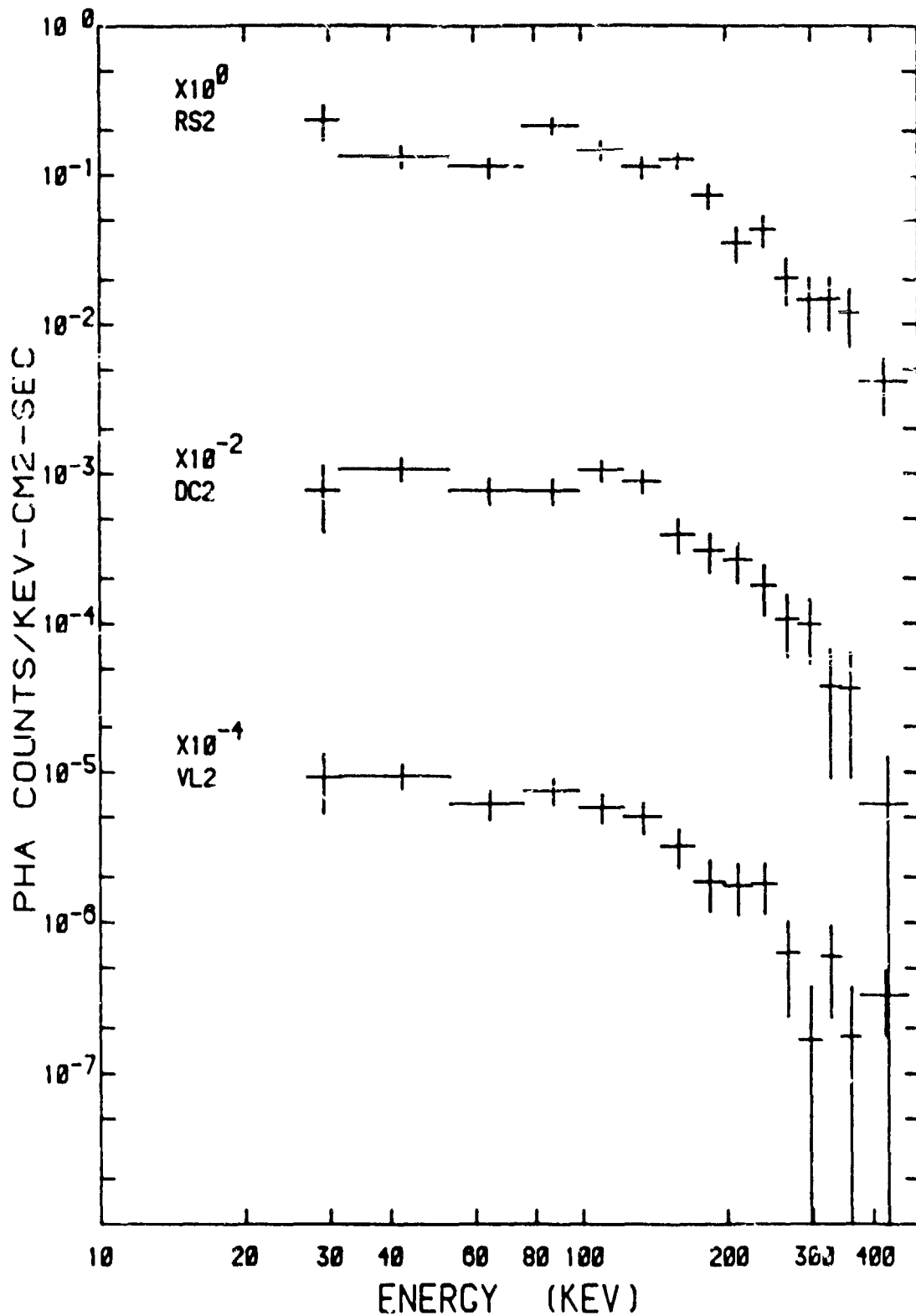


FIG 5.27b PHA spectra for intervals RS2, DC2, and VL2
of 19 APR 80 event.

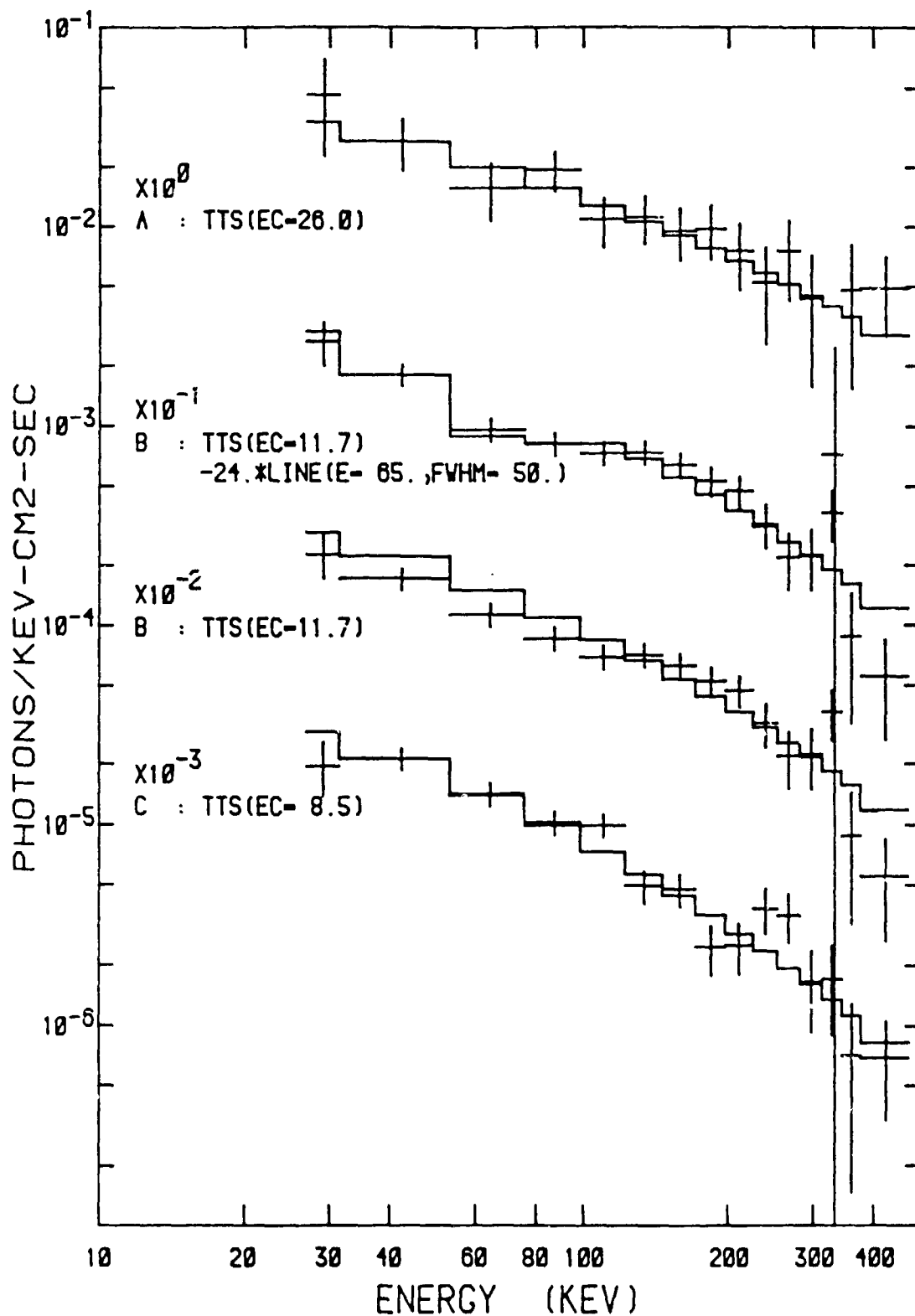


FIG 5.28a TTS fits for Intervals A, B (with line and with extrapolated continuum) and C of 19 APR 80 event.

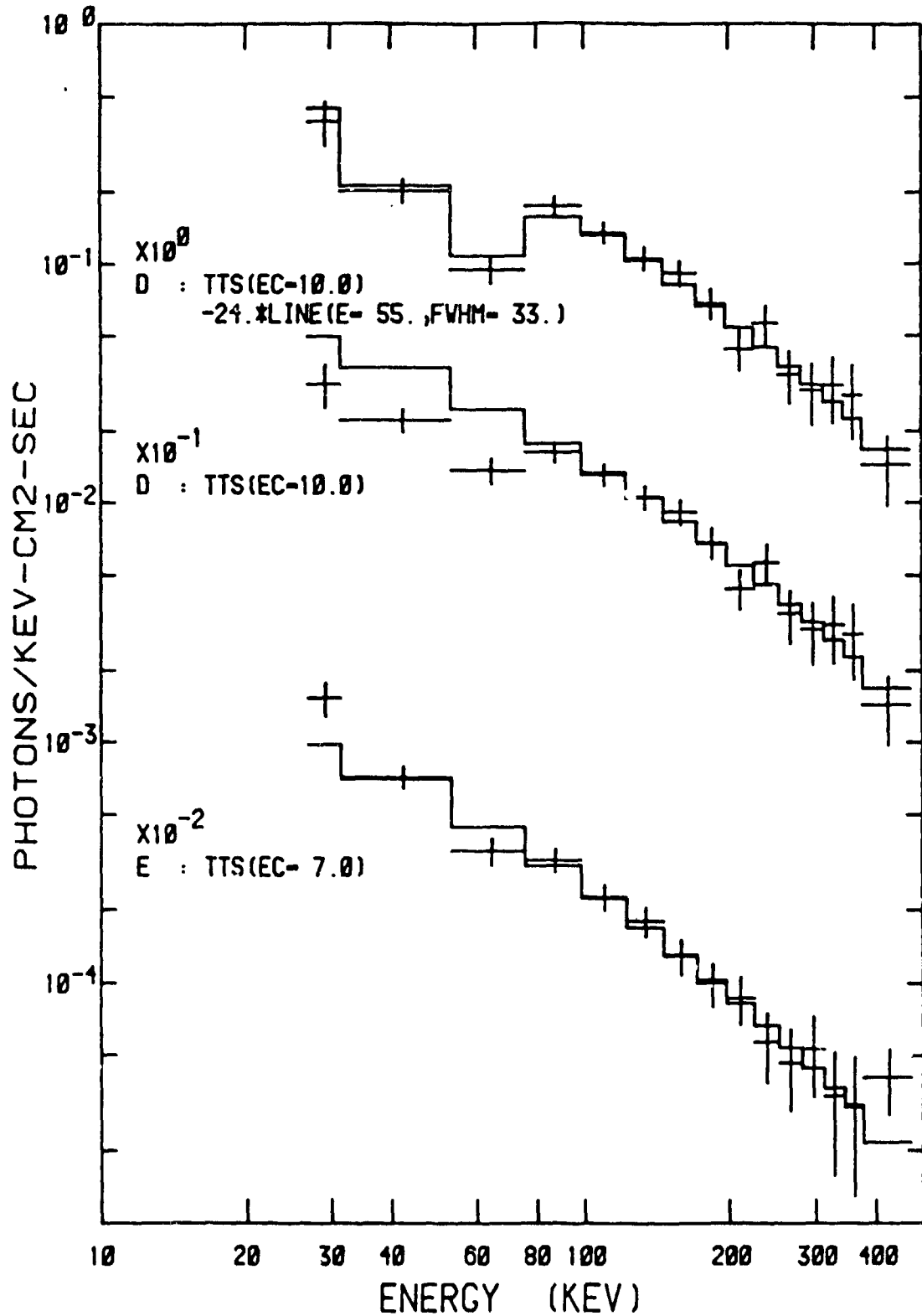


FIG 5.28b TTS fits for Intervals D (with line and with extrapolated continuum) and E of 19 APR 80 event.

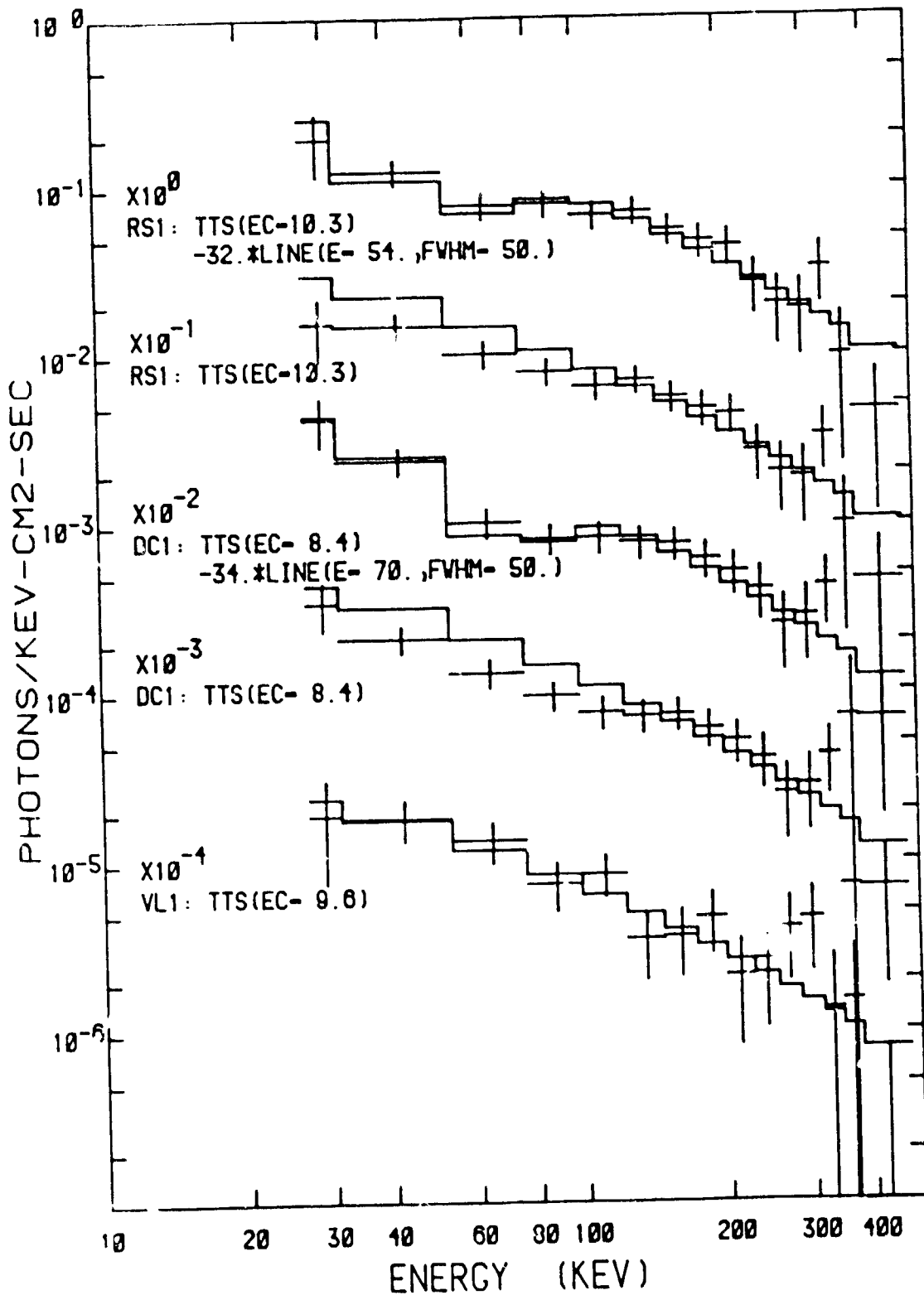


FIG 5.29a TTS fits for intervals RS1, DC1 (with lines and with extrapolated continua) and VL1 for 19 APR 80 event

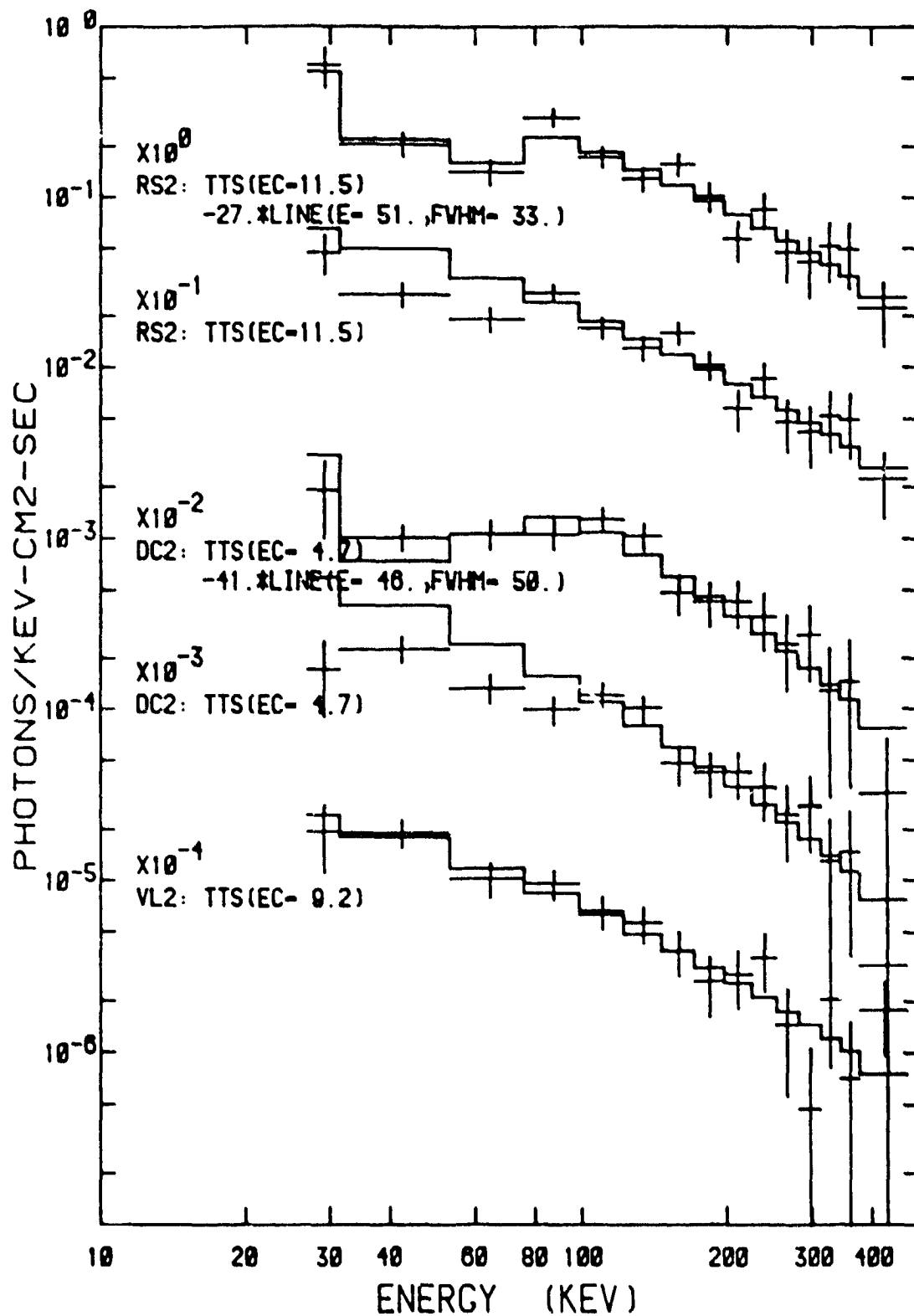


FIG 5.20b TTS file for intervals RS2, DC2 (with lines and with extrapolated continua) and VL2 of 19 APR 80 event.

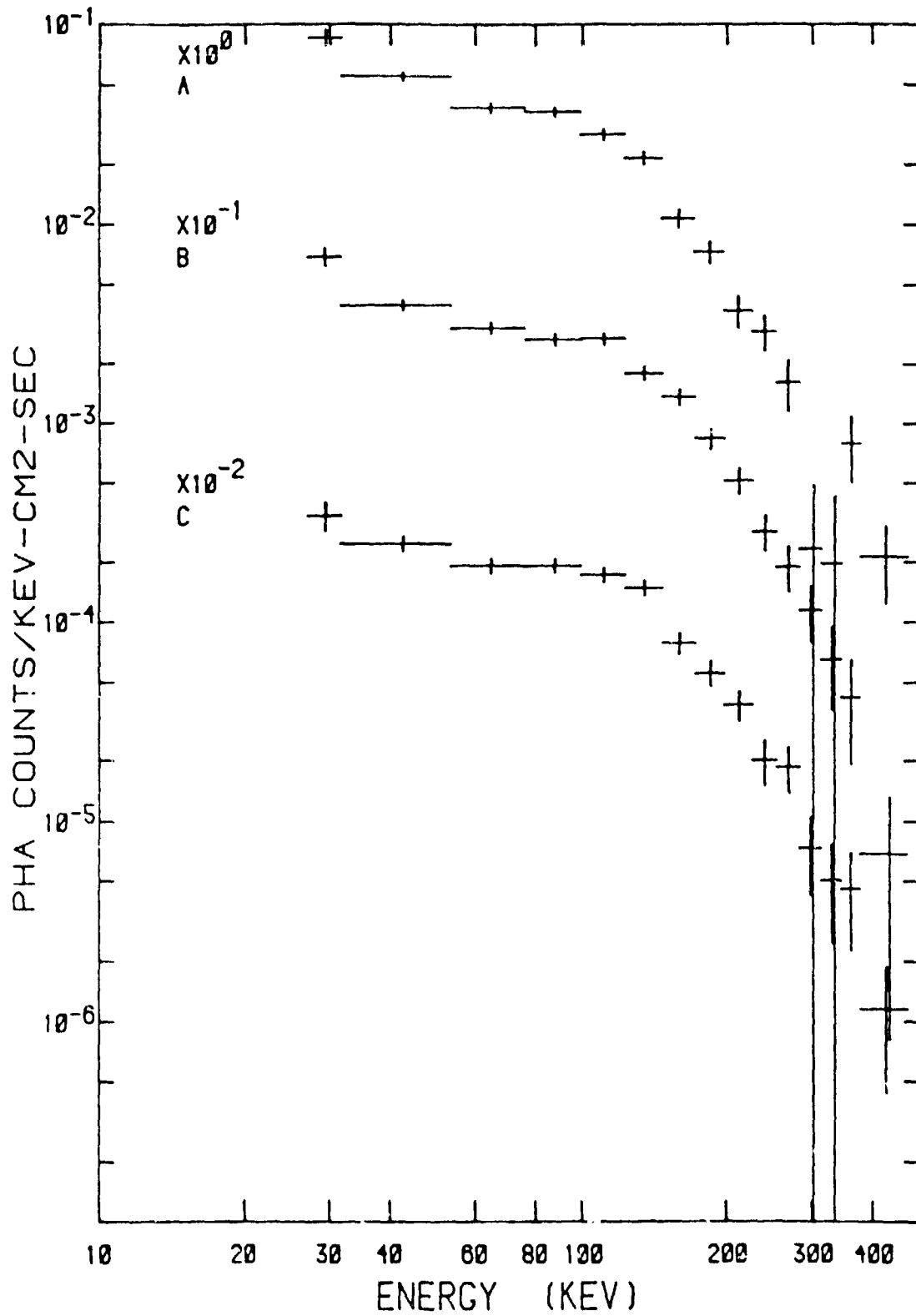


FIG 5.30 PHA spectra for Intervals A, B, and C
of 21 APR 80 event.

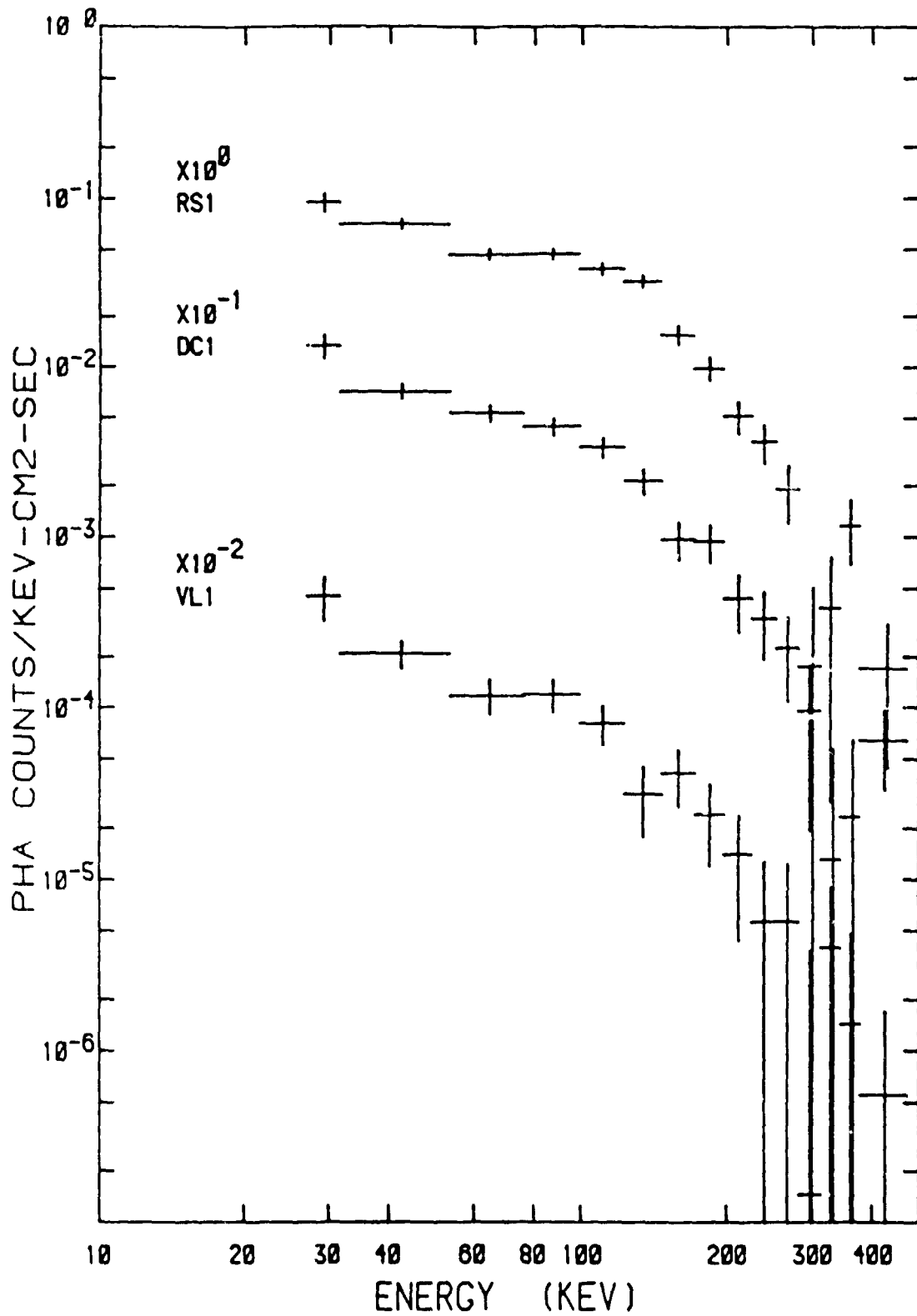


FIG 5.31a PHA spectra for intervals RS1, DC1, and VL1
of 21 APR 80 event.

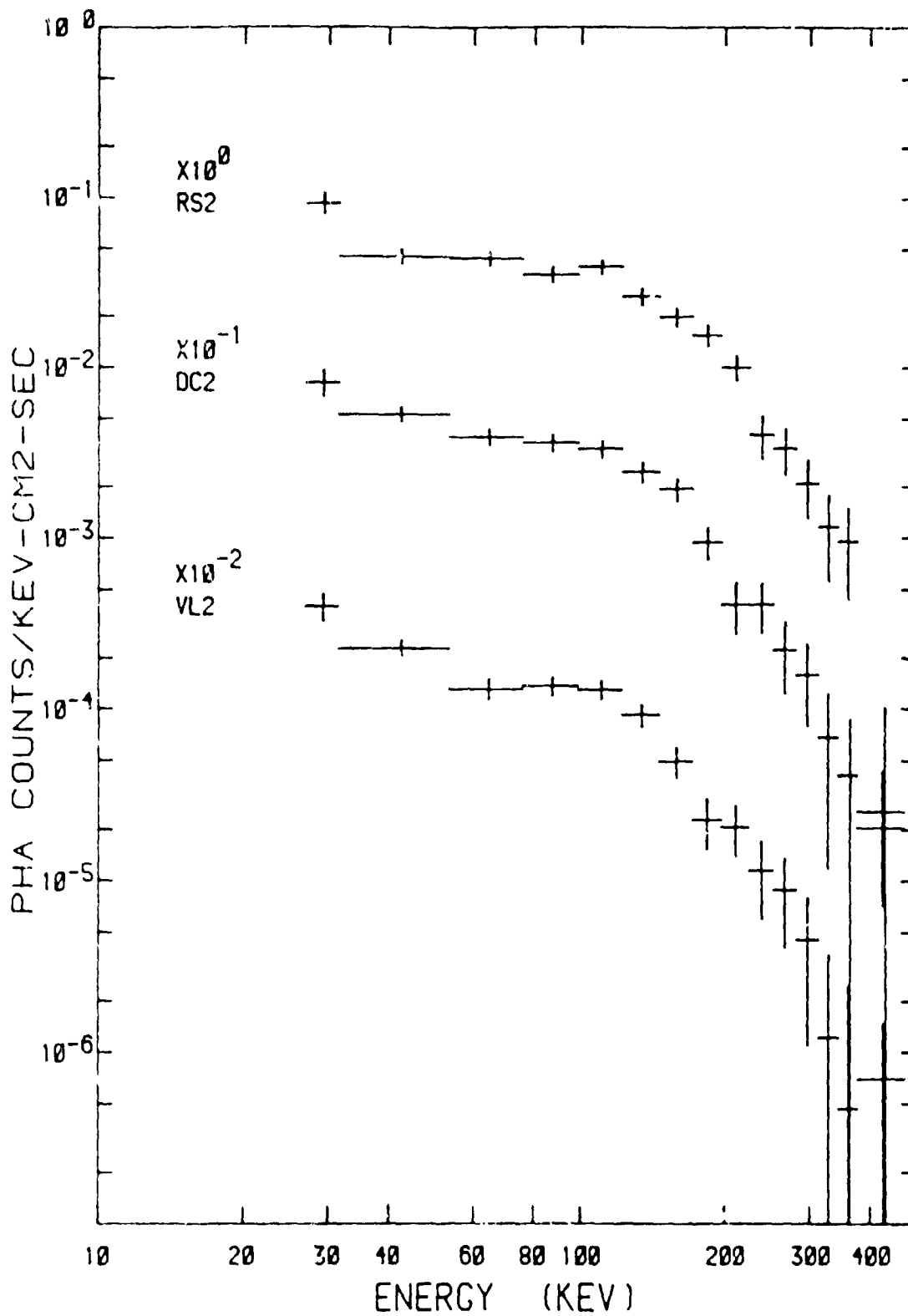


FIG 5 31b PHA spectra for intervals RS2, DC2, and VL2
of 21 APR 80 event

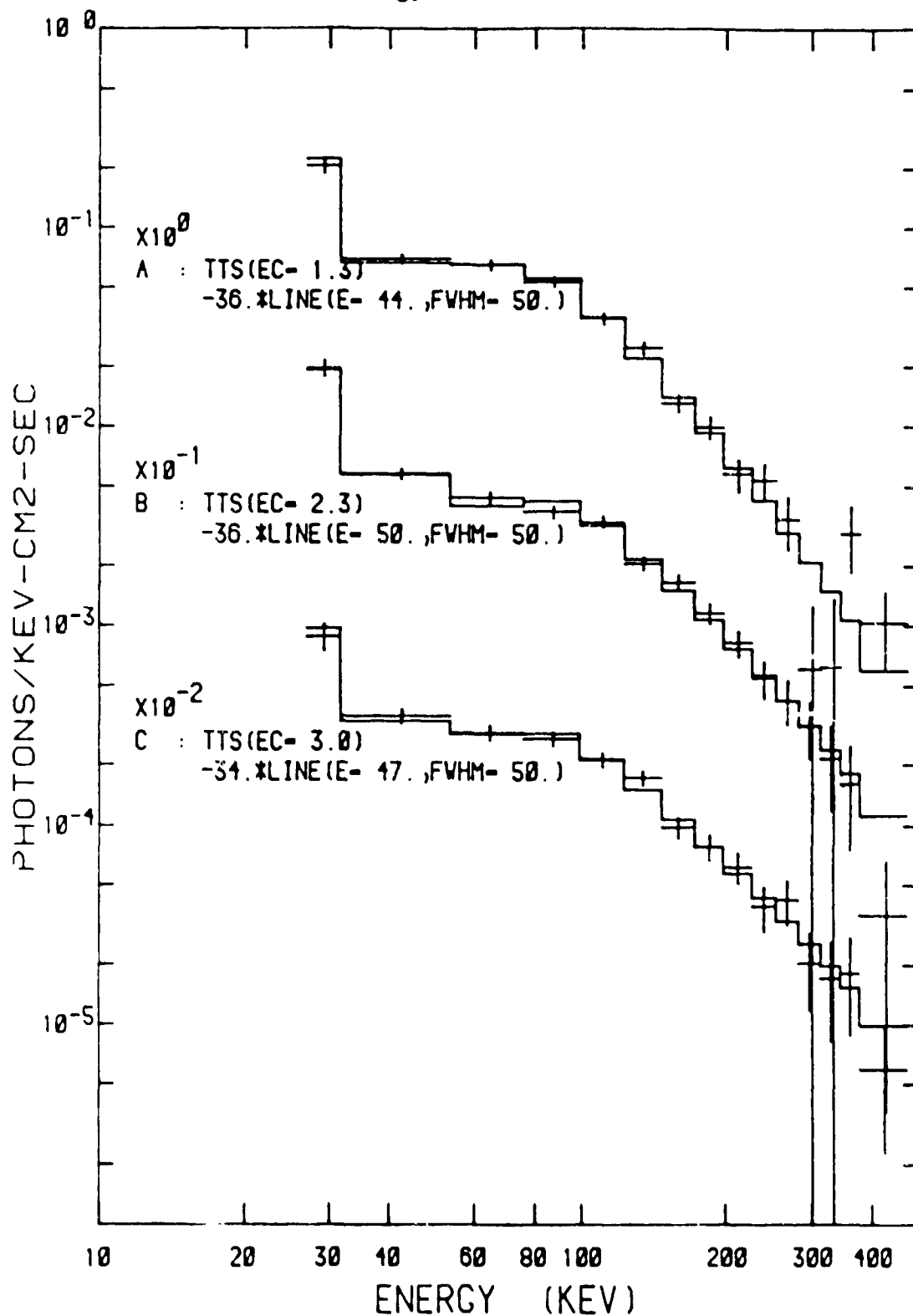


FIG 5 32a TTS fits for intervals A, B, and C (with lines)
of 21 APR 80 event

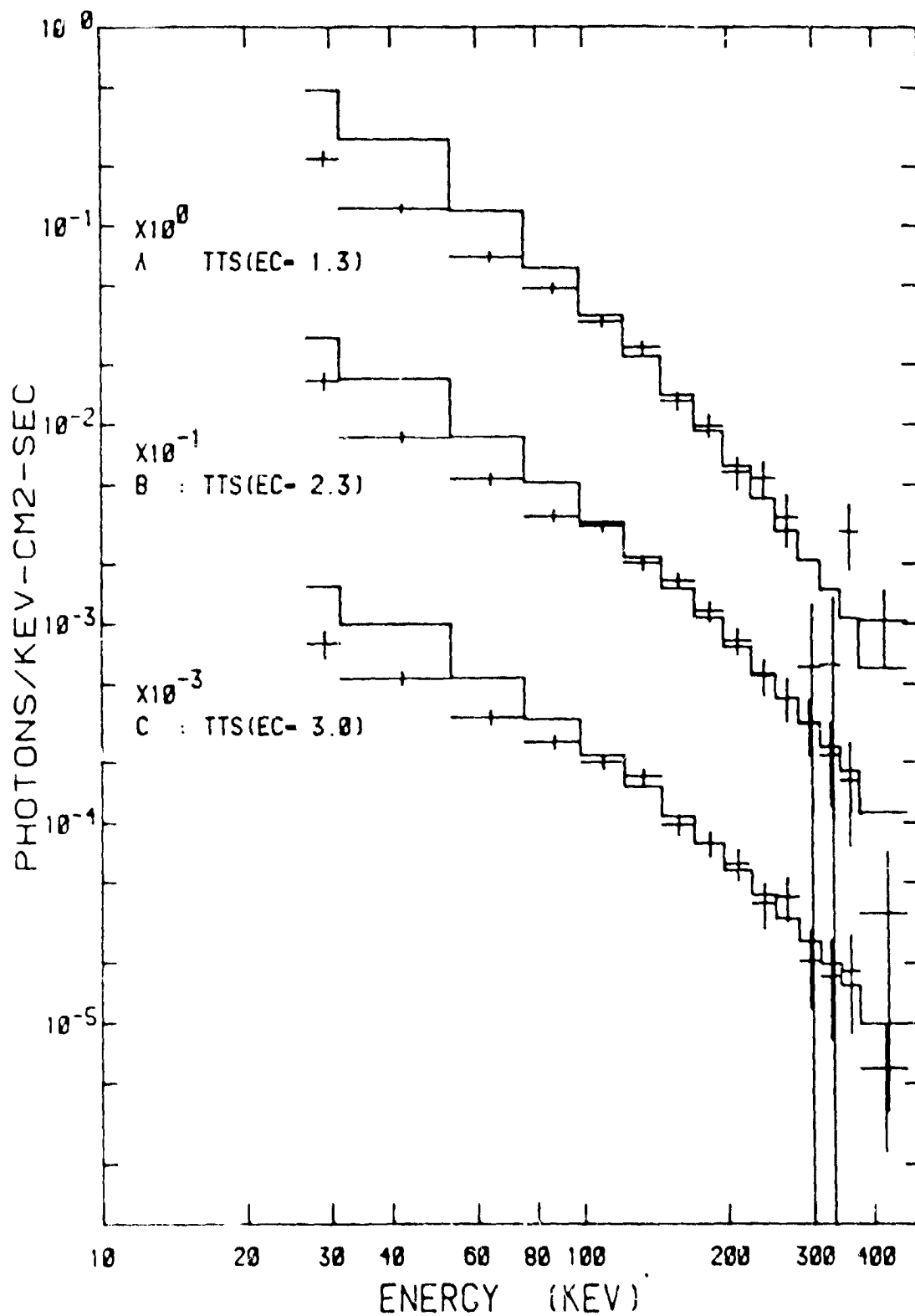


FIG 5 32b TTS fits for Intervals A, B, and C (with
extrapolated continua) of 21 APR 80 event

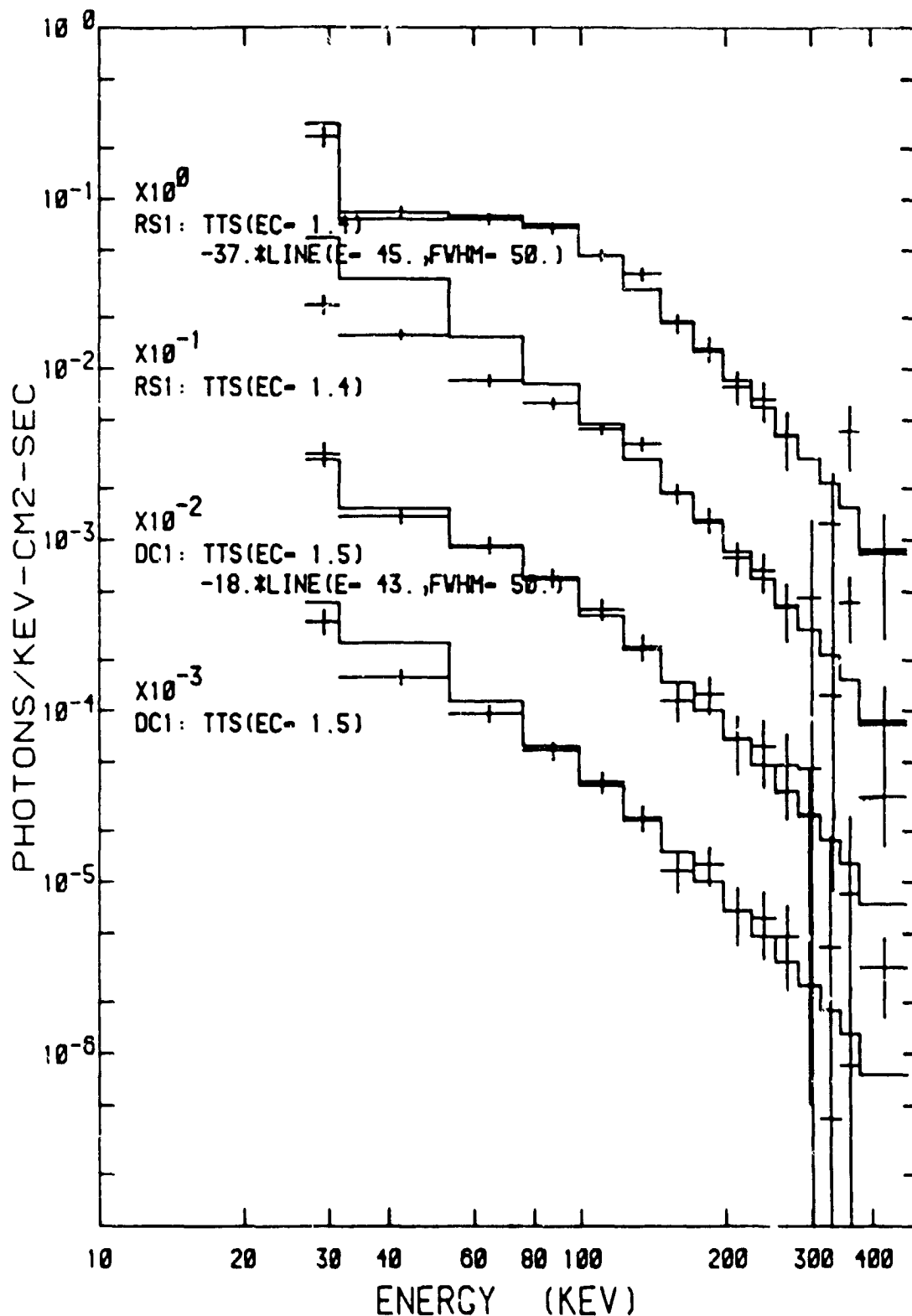


FIG 5.33a TTS fits for intervals RS1 and DC1 (with lines
and with extrapolated continua) of 21 APR 80 event

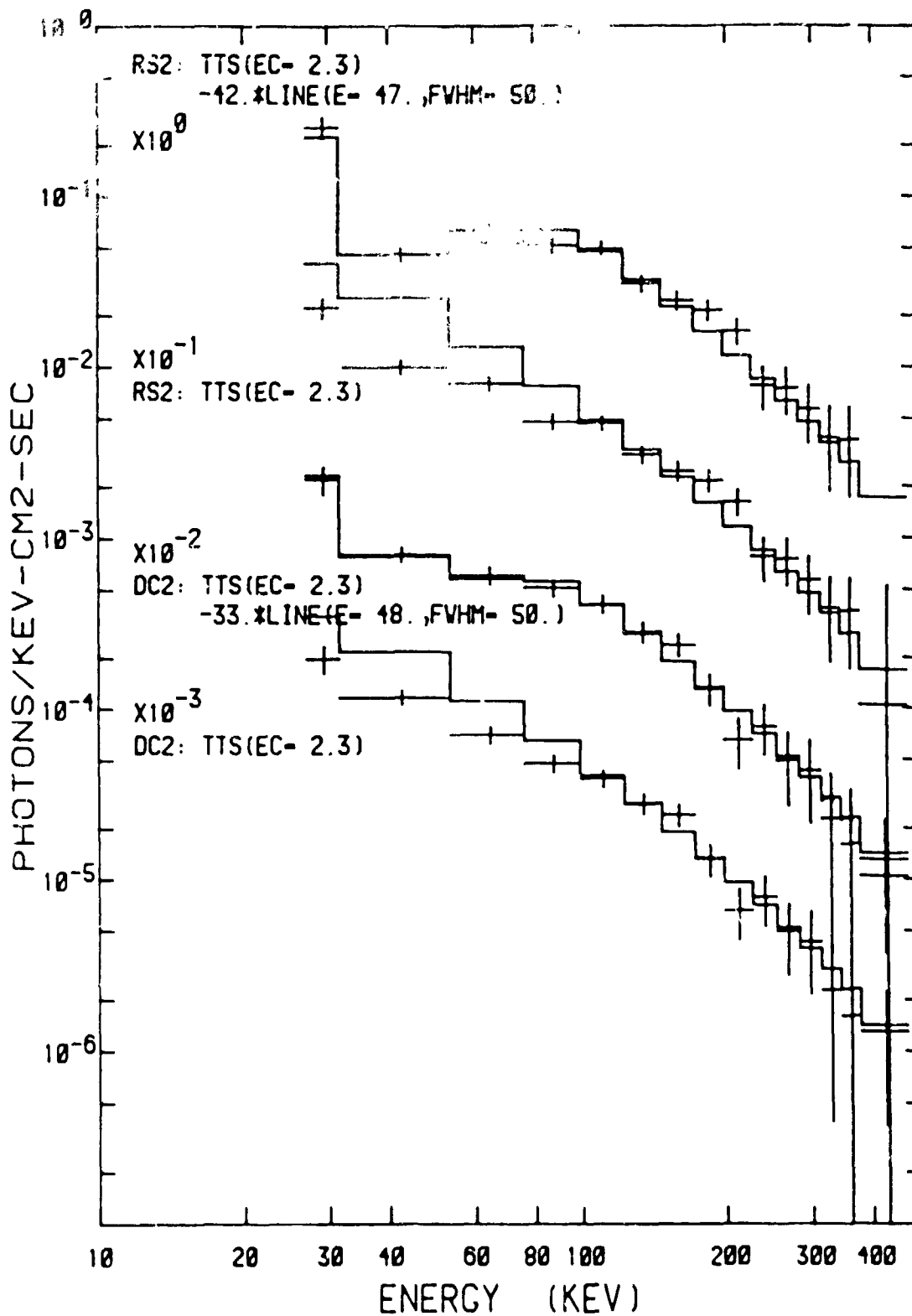


FIG 5.33b TTS fits for intervals RS2 and DC2 (with lines and with extrapolated continua) of 21 APR 80 event

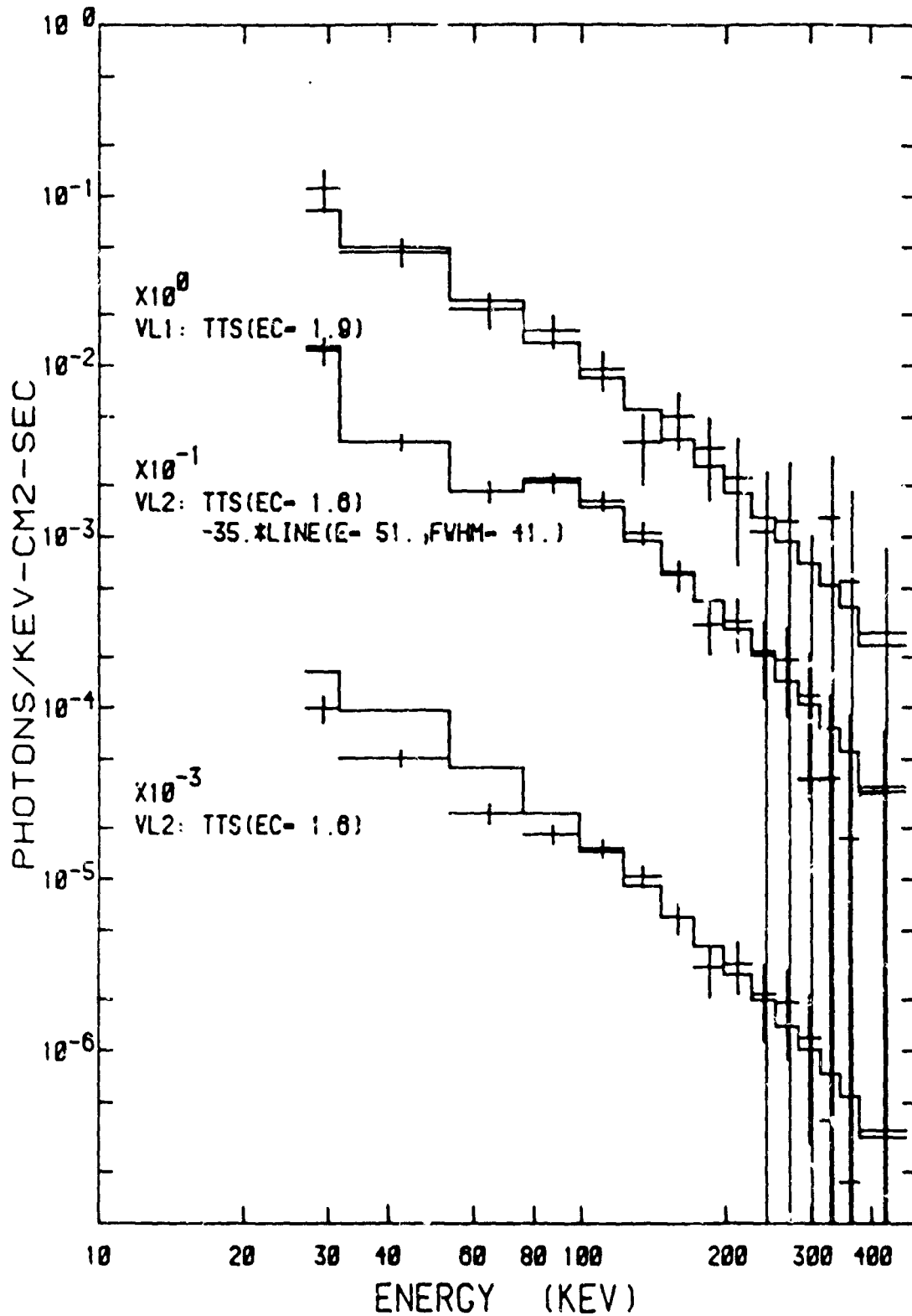


FIG 5 33c TTS fits for intervals VL1 and VL2 (with line and with extrapolated continuum) of 21 APR 30 event.

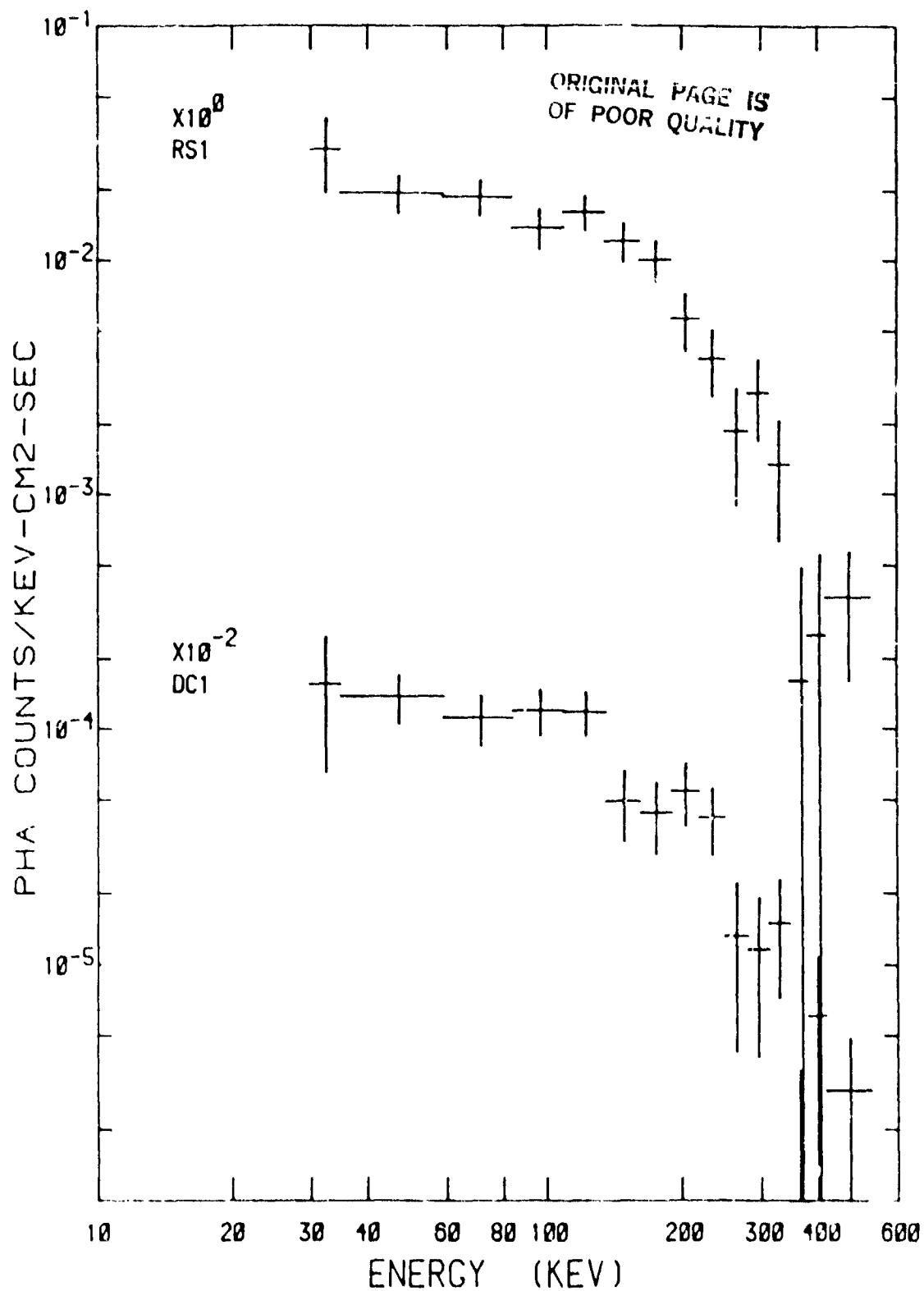


FIG 5 34 PHA spectra for intervals RS1 and DC1
of 01 MAR 81 event

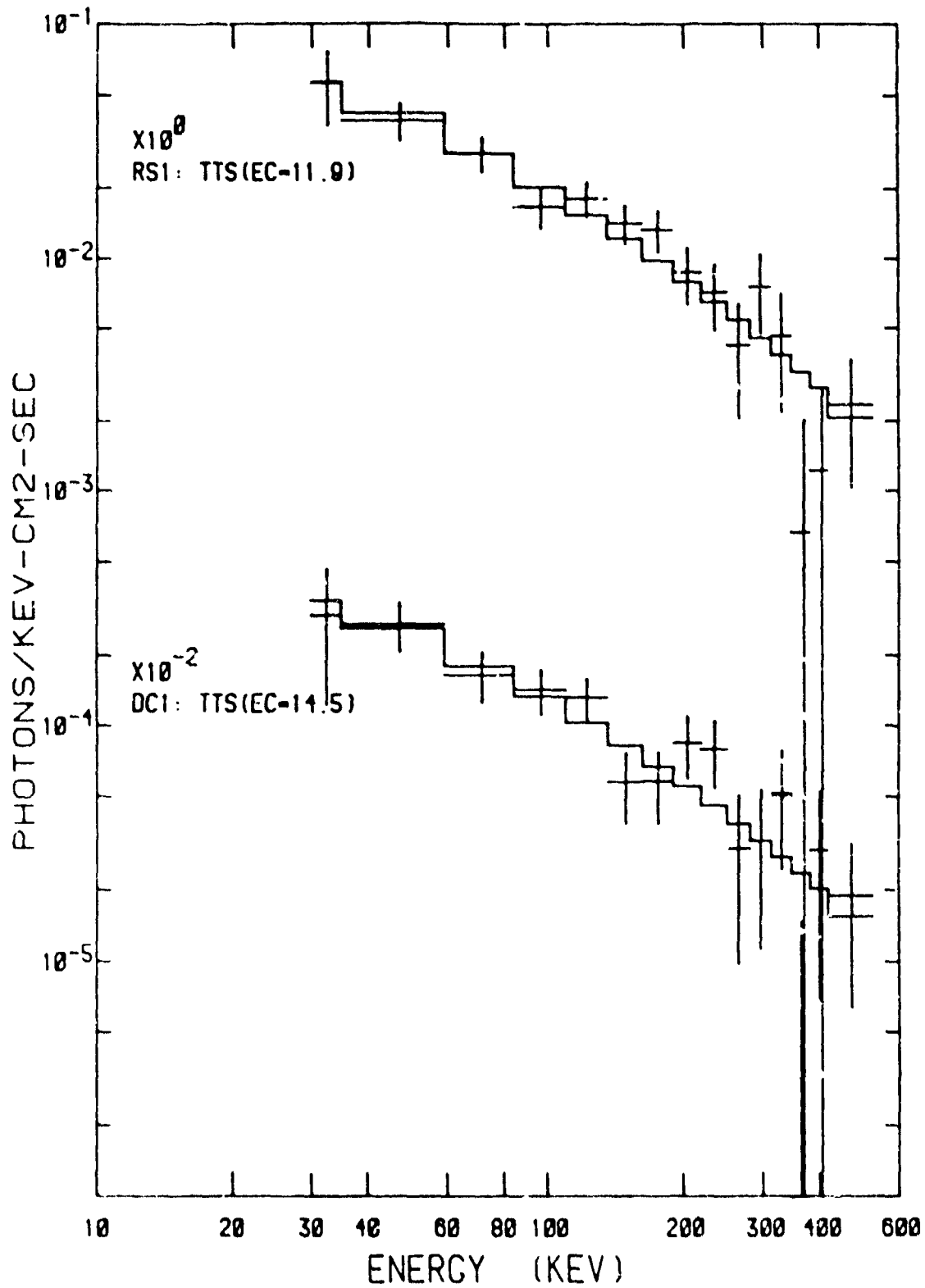


FIG 5.35 TTS fits for intervals RS1 and DC1
of 01 MAR 81 event

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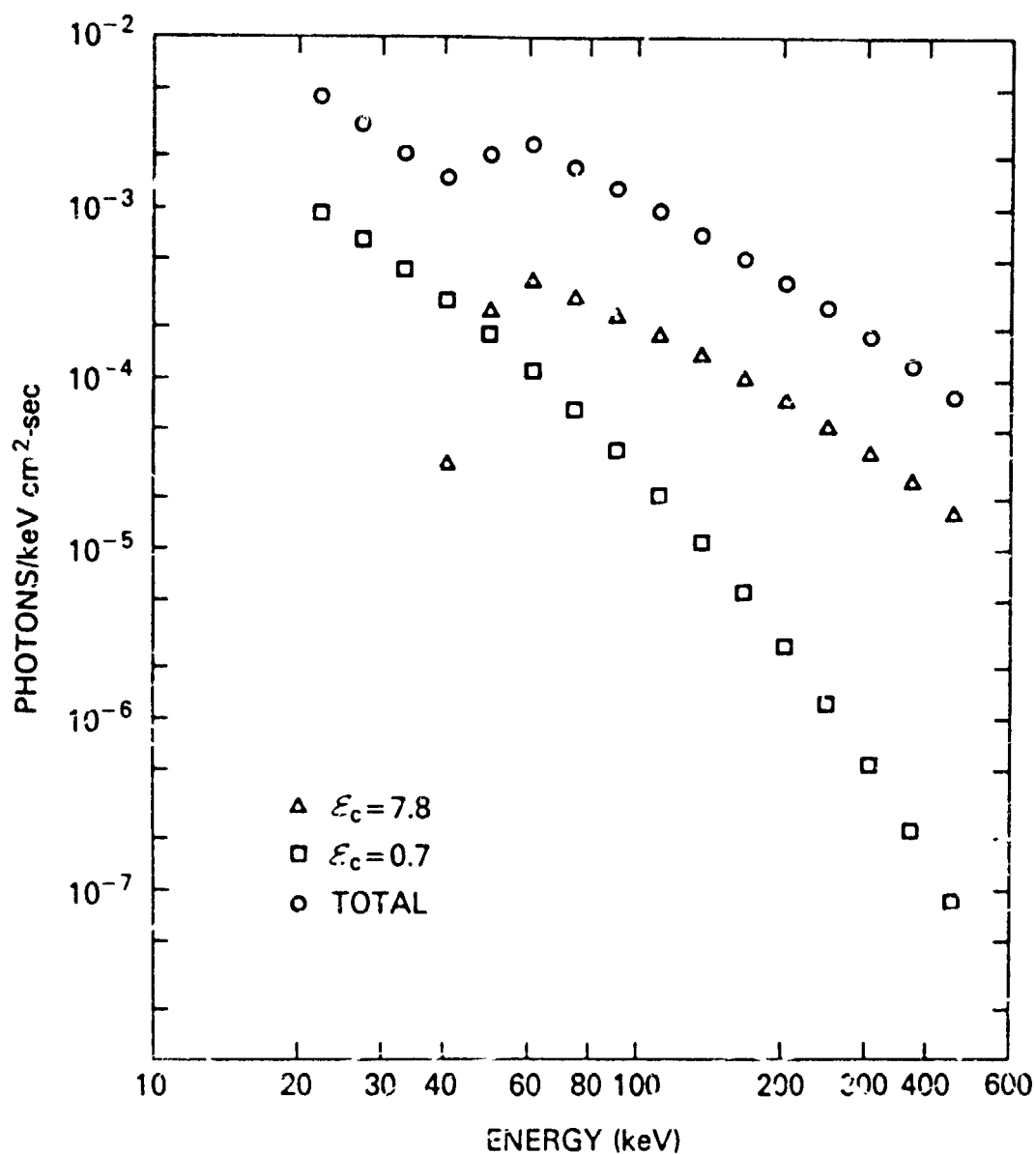


Fig. 5.36. Simulation of a spectral artifact. TTS spectra with magnetic field strengths $B_{12} = 4.4$ and 1.4 (with corresponding synchrotron cutoffs) and temperatures of 200 keV and 100 keV, respectively, and the sum of the two spectra are plotted. The cutoff for the spectrum with $\epsilon_c = 0.7$ is ~ 16 keV, below the lowest channel plotted. The total spectrum is shifted vertically for clarity.

INTERPRETATION OF RESULTS

It is now generally believed that neutron stars are the sources of γ -ray bursts. Several arguments to be presented in this chapter support this conclusion. Recent observations suggest that spike-like bursts and "classical" bursts are generated by different processes. Yet for both classes of bursts the evidence favors a distance of a few hundred parsecs for most sources. The sources are most likely old neutron stars whose rotation periods are longer than the average burst duration. The observed (quasi-) periodicities may be due to source rotation. This would explain why periodic structure is observed in only a small percentage of burst temporal profiles.

Interpretation of the burst spectra as thin thermal synchrotron radiation is consistent with all observed and deduced parameters. Low-energy features observed in some spectra are probably not cyclotron resonance lines. If, indeed, the sources are within a few hundred parsecs, the source is optically thin. Then, the features may be due to spectral averaging of a rapidly time-varying low-energy synchrotron cutoff.

Evidence for the neutron star hypothesis will be presented separately for both classes of bursts. The implications of observable properties of bursts are discussed in the context of current neutron star models.

A. Spike-like Bursts

i. Implications of Temporal Characteristics

a. Rise Time and Duration

The typical temporal structure of spike-like bursts gives important clues to the nature of the burst mechanism. The most remarkable property of the burst temporal profiles is the fast rise time, less than a few $\times 10$ ms. Only upper limits to the rise times have been obtained by the KONUS experiment in most cases (Mazets et al. 1981f). From the ISEE-3 experiment the rise time of the 5 MAR 79 superburst was determined to be < 0.25 ms. This is comparable to the radial oscillatory period of a neutron star (Van Horn 1980) and also comparable to the onset time for the neutron star thermonuclear runaway detonation model (Woosley 1982).

The profiles of spike-like bursts are further characterized by relatively smooth decays of duration $\sim$ a few tenths of a second.

b. Periodicity

The double-peaked eight-second oscillating decay phase of the 5 MAR 79 burst suggests a neutron star with nonaligned magnetic and rotational axes. Neutron stars in X-ray binary systems exhibit periods in the range tens of ms to $\sim 10^3$ s (White 1982) and old extinguished radio pulsars probably continue to slow their rotation past the observed pulsar cutoff of ~ 5 s.

Also, a suggestive 22 ms periodicity is apparent during the initial intense spike of the 5 MAR 79 burst (Barat et al. 1983b). The fundamental torsional (toroidal) oscillation mode of a neutron star is predicted to be ~ 20 ms (Van Horn 1980).

c. Repetition

Thirty-three percent of the bursts in the ISEE-3 sample are spike-like with soft spectra. This is a much larger percentage than detected by previous experiments. However, the KONUS experiment (Veneras 11, 12, 13, and 14) has now detected twelve spike-like bursts whose localization arcs (a few arcminutes wide) all intersect at the famous 5 MAR 79 burst error box (Mazets 1983). The fluences of these follow-up bursts are all down by factors 10^{-2} to 10^{-3} from the 5 MAR fluence. The intervals between bursts from this source, during periods of observation, range from 13 hr to 67 dy. At least one other repeating spike-like burst source with comparable recurrence intervals was detected during the Venera 11 and 12 period, and several other spike-like bursts have been detected whose localizations are forthcoming (Mazets, private comm.). Classical burst sources can be inferred to have repetition times ≥ 1 yr from the KONUS results (Mazets et al. 1981a; b) Hence, whereas spike-like bursts are more prevalent than previous evidence indicated, we can conclude that the repeating spike-like burst sources are sparse compared to classical burst sources.

In Table A.3 the events and intervening intervals for the 5 MAR 79 source are listed. Two similar event sequences are apparent beginning with the 5 MAR 79 event and with the 23a APR 82 event. The intervals between first and second events in the two series are about 14 and 13 hr, respectively, with subsequent intervals longer (18 to 39 dy). The 23a APR 82 sequence exhibits strictly monotonically increasing intervals. A third sequence with monotonically increasing intervals starts with the event on 01 DEC 81. The Venera 13 and 14 spacecraft were launched about November 15, 1981; hence, it is not known if the

series commenced before that time.

The series of KONUS spike-like bursts, 24 MAR, 25 MAR, 27 MAR 79, having localizations consistent with a single source (designated B1900 +14, Mazets et al. 1981f), is another example of increasing burst intervals (10 hr, 32.5 hr). This trend of increasing intervals between bursts is suggestive of a relaxation process.

The short time scale for repetition of the burst process, several hours to tens of days, probably excludes some models specifically proposed to explain spike-like bursts (see section iii).

ii. Intrinsic Luminosity

Since localizations have been determined for only two spike-like burst sources, their source distribution on the celestial sphere is unknown. The possible association of the 5 MAR 79 burst with the supernova remnant N49 in the LMC leads to questions concerning the galactic or extragalactic origin of spike-like bursts in general and their intrinsic luminosity function. Presently, the 5 MAR burst is unique among all spike-like bursts in that the 5 MAR fluence, 4.5×10^{-4} erg cm⁻², was 10^2 to 10^3 times greater than most other spike-like bursts. It is interesting that a spike-like burst with a soft spectrum observed by KONUS, 30 SEP 79, exhibited an intensity one-third that of 5 MAR. Unfortunately, only one detector on Venera 11 observed the event and its direction was not established (Mazets, et al. 1981f). No evidence of an oscillating decay was observed.

Spike-like bursts from other sources deliver fluences comparable to those of the 5 MAR follow-up bursts, $\sim 10^{-7}$ to 5×10^{-6} erg cm⁻². The spectra of most short duration (≤ 0.5 s) bursts are soft, $I(\text{ph cm}^{-2} \text{s}^{-1})$

$\text{keV}^{-1}) = E^{-1} \exp(-E/\sim 30 \text{ keV})$, compared to classical burst spectra (see Table A.1). If one makes the simplest assumption that the burst mechanisms for the 5 MAR source and other spike-like bursts are generically similar, and most are galactic, then either the 5 MAR source produces bursts scaled up by a factor $\sim (55 \text{ kpc}/\lesssim 500 \text{ pc})^2 \gtrsim 10^4$ (by $\sim 10^7$ for events like 5 MAR 79 itself), or the 5 MAR source is not associated with the supernova remnant in the LMC.

Our galaxy and M31 compose more than 90% of the mass of the local group; it is very unlikely that spike-like burst sources are located just in nearby satellite galaxies and not in our own galaxy. However, the spike-like sources could be in nearby clusters of galaxies. The ratio of most spike-like burst fluxes to the 5 MAR flux (in the LMC), $\sim 10^{-2}$ to 10^{-3} , is comparable to the inverse-square attenuation factor $(55 \text{ kpc}/\gtrsim 10^3 \text{ kpc})^2$ if the spike-like sources are at extragalactic distances; hence, the smaller spike-like bursts would be as energetic as 5 MAR itself.

One observation is contrary to this possibility. The other repeating (soft spectra, spike-like) source, B1900 +14 (Mazets et al. 1981f), produced three bursts in two days with fluences $\sim 10^{-2}$ to 10^{-3} that of 5 MAR. If a core phase transition, a rare and possibly singular event in the lifetime of a neutron star, is the mechanism for 5 MAR - like bursts (see section iii.b below), the 5 MAR burst and bursts from B1900 +14 were probably caused by different mechanisms.

It remains to explain the $\sim 10^3$ range in luminosity for the 5 MAR source. It is possible that the flux from spike-like bursts is beamed in a narrow angular pattern. The dynamic range in fluences observed from the 5 MAR source would then be a consequence of the rotating

source. If this is the case, other sources should also be observed to produce large bursts infrequently. Alternatively, the follow-up bursts from the 5 MAR source may be small readjustments of the crust subsequent to a core phase transition.

iii. Models for Spike-like Bursts

a. Improbable Models

Quasi-steady accretion onto a neutron star in a binary system as the energy source for spike-like bursts (and for classical bursts as well) appears to be ruled out for several reasons. Most physically expected variations on accreting neutron stars have been observed, leaving hardly any room for modification of the theme for γ -ray bursts. X-ray binary pulsars with high and low mass companions and with large ranges in orbital periods, eccentricities, and inferred magnetic field strengths have been detected (White 1982). Type I X-ray bursters (Lewin 1982), believed to be powered by thermonuclear hydrogen explosions, manifest observable properties quite different than those of γ -ray bursts (however, see Woosley's thermonuclear model below). X-ray burst rise times, a few tenths of a second, are comparable to the total event durations of spike-like γ -ray bursts. X-ray burst characteristic temperatures are an order of magnitude smaller than those of spike-like γ -ray bursts. Type I and II bursters exhibit persistent X-ray emission due to accreting matter, while the smallest ($\sim$ few arcmin²) γ -ray burst source boxes contain only weak background X-ray sources or none at all (Cline 1981; Hurley 1982).

Three classes of neutron star γ -ray burst models have been proposed which may be capable of producing spike-like bursts: thermonuclear

helium explosions (Woosley 1982), accretion of asteroids (Newman and Cox 1980; Van Buren 1981; Colgate and Petschek 1981), and structural changes in the neutron star - crustquakes or "glitches" (Fabian, Icke, and Pringle 1976; Pacini and Ruderman 1974), and phase transitions (Ramaty et al. 1980).

In Woosley's (1982) γ -ray burst model II (see chapter I, section C.11), detonation of a 1 km radius helium lake (10^{22} gm) on a neutron star magnetic polar cap, produces theoretical bursts with characteristic energies, rise times, and durations comparable to those of the observed spike-like bursts. A strong magnetic field of $\sim \text{few} \times 10^{12}$ G is required to channel the accreting material onto the small polar region where stable hydrogen burning via the CNO-cycle eventually builds to a critical helium mass. Ventura (1982) concluded that the required temperature for the CNO-mediated burning is not achieved when cooling through the body of the neutron star and the effects of magnetic opacity are included in the calculations. However, the deciding factor which appears to exclude this model as the explanation for the observed spike-like bursts is the model's repetition rate, 240 yr. This is clearly too long to explain the bursts which come from the two established repeating sources.

Models invoking neutron star - asteroid collisions (Colgate and Petschek 1981) predict spike-like bursts but with very low repetition rates. Even with an increased cross-section due to magnetic drag, Van Buren (1981) estimates such encounters would occur every $\sim 10^6$ yr per neutron star, still inadequate to account for the repeating spike-like bursts. If the burst distribution is limited to the galactic disk, with a neutron star density of 0.03 pc^{-3} (Lamb, Lamb, and Pines 1973), within

a sphere of radius 400 pc, only about 8 events per year would be generated.

b. Models Involving Neutron-Star Glitches

It is possible that structural changes in neutron stars produce γ -ray bursts. According to pulsar models (Manchester and Taylor 1977), as radiation processes extract rotational energy from the star, the decrease in centrifugal force results in a building up of stress in the solid crust. Periodically, the stress exceeds the strength of the crust, the stellar oblateness decreases, the moment of inertia (I) decreases as the crust suddenly adjusts - a starquake and a "glitch" occur. Since the magnetic field is anchored in the crust, the quake perturbs the magnetosphere near the surface, inducing large electric fields capable of accelerating particles to relativistic energies and producing a γ -ray burst.

Alternatively, the sudden expulsion of plasma from the magnetosphere and contraction of remaining plasma in reaction may torque the neutron star to produce a glitch (Ruderman 1972).

Glitches are inferred from pulsar period discontinuities which have been observed to recur on time scales of a few years in the Crab pulsar ($\delta = \Delta\Omega/\Omega = \Delta I/I \sim 10^{-8}$) and the Vela pulsar ($\delta \sim 10^{-6}$). Smaller glitches with $\delta \sim 10^{-10}$ have been observed in other pulsars (Manchester and Taylor 1974).

For a glitch resulting from crustal adjustment with $\delta \sim 10^{-10}$, Pacini and Ruderman (1974) estimate a lower limit to the total energy released to be $\delta(B_0^2/4\pi)(4\pi/3)r_0^3 > 10^{34}$ ergs, where B_0 is the surface magnetic field and r_0 is the neutron star radius. For a magnetospheric

glitch, the energy release is $\sim \delta M r_0^2 \Omega_{\text{rot}}^2$, where Ω_{rot} is the rotational angular velocity. In the latter case for $\delta \sim 10^{-10}$, $r_0 = 10$ km, $M = 1 M_\odot$, and $P_{\text{rot}} = 6$ s, this available energy is 4×10^{35} ergs. To account for the small spike-like bursts ($\sim 10^{-7}$ erg cm^{-2}), if 1% of this energy is radiated as γ -rays, the required distances of the sources would be ~ 30 pc. With a space density for neutron stars of $\sim 0.03 \text{ pc}^{-3}$ (Lamb et al. 1973), only a small portion of $\sim 10^3$ old neutron stars in the solar neighborhood would be required to generate the observed spike-like bursts. To match the observed burst frequency, most of these are normally quiet. A repetition interval of days to $\sim 1 - 2$ months may conceivably obtain for sources only during particular epochs. The increasing intervals between bursts for these sources may be naturally explained by a relaxation mechanism in which burst intervals are approximately proportional to residual crustal stress.

γ -ray bursts were not observed at the times of major glitches in the Vela and Crab pulsars, although burst sensors were operating at the time of two of these events (Brecher 1982). At the distances of the Crab (2 kpc, $\delta \sim 10^{-8}$) and Vela (0.5 kpc, $\delta \sim 10^{-6}$), the bursts should have been detected if the total glitch energy (see below) were converted into γ -rays and radiated isotropically. However, they need not have been detected if they were beamed or represent $\sim 1\%$ of the total energy.

In the case of the 5 MAR 79 source, if the source is in the LMC, the superburst may have had a more catastrophic origin. Ramaty et al. (1980) suggest an internal phase transition and the resulting release of gravitational energy as the cause of the 5 MAR 79 event. In this model the energy is transported to the surface by vibrations of the neutron star which are damped by quadrupole gravitational radiation (Detweiler

1978) in ~ 0.15 s, in agreement with the duration of the intense spike. The energy source of the oscillating decay phase may be radial vibrations which are damped by the L^- process (Langer and Cameron 1969) on a time scale of ~ 50 s. Since the bulk of the energy was delivered in the spike rather than the decay phase, the nonradial modes are required to be preferentially excited, presumably by an asymmetric event. The smaller (down by factors of 10^{-2} to 10^{-3}) follow-up bursts would be reorderings of the star as the mass distribution seeks equilibrium.

B. Classical Bursts

The collective evidence suggests that the sources of classical γ -ray bursts are also neutron stars. However, the burst durations of several to 10^2 s of seconds, complex temporal profiles, characteristic energies of a few $\times 100$ keV, and repetition on time scales > 1 yr indicate that classical bursts are generated by a mechanism distinct from that which produces spike-like bursts.

1. Implications of Temporal Characteristics

a. Temporal Structure

The fast rise times and widths of substructure in pulses (Table 1.1) imply formation in sources with radius less than a few $\times 10^3$ km. The burst time scales are much shorter than those for most solar flares and the implied burst energies, if observed burst sources are $\sim$ few $\times 100$ pc distant, are $\sim 10^{10}$ larger than solar flare energies (Ruderman 1975).

The high energy densities deduced from such large luminosities and short time scales may require intense gravitational and/or magnetic fields. These considerations point to compact objects as the burst sources.

Burst durations of several seconds and multiple pulses appear to require a process unlike the "one-shot" mechanism operating in spike-like bursts.

b. Periodicity and Burst Source Objects

The case for periodicity in classical burst temporal profiles is not clearly established. Several bursts have been shown to exhibit quasi-periodic, or possibly periodic, structure for the range of periods searched, 0.1 to 4.0 s (Loznikov and Kuznetsov 1983). Many bursts in the KONUS catalog exhibit quasi-periodic structure on a time scale of ~ 5 to 15 s.

True periodic behavior due to a rotating source may be camouflaged by spatial flickerings. Alternatively, quasi-periodicity may reflect characteristic time scales of fundamental processes in bursts. A third possibility is that random distribution of pulses could account for the appearance of periodicity, given the small percentage (1 to 3 %) of bursts displaying convincing or even suggestive periodic structure.

A few classical bursts have been observed in which strictly periodic structure is discernable: 29 OCT 77, 4.2 s period (Wood et al. 1981); 13 JAN 79, 5.5 s period, although not claimed by the authors (Mazets et al. 1981a, see also Figure 1.3); and three ISEE-3 events with suggestive periodic intervals of 9.9 s, 16.7 s, and 18.0 s (chapter IV). Only two to six apparent periods are present in any of these

bursts. The only irrefutable evidence of strictly periodic behavior is for the spike-like burst of 5 MAR 79 (> 22 cycles, 8 s period).

The time scale for the observed quasi-periodic and periodic structure in γ -ray bursts is comparable to the rotation periods (≥ 5 s) of extinct pulsars. That periodic structure is rare in bursts may be accounted for by burst durations and old neutron star rotation periods. The convolution of the burst duration distribution and rotation period distribution yields a small percentage (~ 1 to 3 %) of observable periods, according to Wood et al. (1981). In their analysis, they used the distribution of rotation periods among X-ray binary pulsars; however the distribution (unknown) of old neutron stars probably would give a similar result.

For completeness consider the most likely alternative, namely that very young neutron stars are the burst sources. Recently formed neutron stars may be more "glitch"- or quake- active (Brecher 1982). If this is the case and glitches do produce bursts, young neutron stars would be better burst candidates than old ones. In Brecher's scenario then, the rotational periods are few $\times 10$ ms (e.g., the 22 ms suggestive periodic structure in the initial spike of the 5 MAR 79 event, Barst et al. 1983b), and the free precessional periods are ~ 10 s.

The precessional angular velocity Ω_p is determined by the rotational angular velocity ω_3 , and the principle moments of inertia, I_3 and $I_1 = I_2$,

$$\Omega_p \sim \frac{I_3 - I_1}{I_1} \omega_3 = \frac{15 \omega_3^2}{16\pi G\rho} \omega_3 = \epsilon \omega_3 \quad (6.1)$$

where ϵ is the stellar oblateness (Manchester and Taylor 1977). For a

star with a fast spinning (~ 33 ms), solid core (low mass, $M \sim 0.5 M_0$), ϵ is $\sim 3 \times 10^{-4}$. If solid core neutron stars retain their oblateness at birth, then ϵ is increased by the factor $(\omega_{\text{init}}/\omega_{\text{pres}})^2$, and may be as high as 10^{-3} for the Crab pulsar (Baym and Pines 1971). A precessional period of ~ 110 s or 33 s is expected for the second fastest pulsar (the Crab, $M \sim 0.5 M_0$) if $\epsilon \sim 3 \times 10^{-4}$ or 10^{-3} , respectively. Since the precessional period decreases as ω_3^{-3} , neutron stars with $P_{\text{rot}} \sim 15$ ms would have $P_{\text{prec}} \sim 10$ s, comparable to the observed several-second apparent periodicities in γ -ray bursts. [For a liquid core (high mass $M \gtrsim 1 M_0$) star, ϵ is a factor 10^{-2} to 10^{-3} smaller than for a low mass star (Pines, Shaham, and Ruderman 1972).]

However, several lines of observational evidence are inconsistent with γ -ray bursts from radio pulsars. First, precessional periods in pulsars have been searched for but not found (for example, Groth 1975). The newly discovered 1.6 ms pulsar offers the best promise of detecting a short precessional period (P_{prec} should be ~ 0.01 s); none has been reported yet (Backer et al. 1982). The forces which tend to change the relative alignment of rotational, symmetry, and magnetic axes are not well understood (Goldreich 1970; Manchester and Taylor 1977); perhaps alignment is attained shortly after formation. Second, within the handful of arcmin-sized γ -ray burst error boxes, no pulsars are found. Pulsars have been detected out to several kpc, whereas the nearly isotropic distribution of observed bursts indicates the burst sources are probably located within the galactic disk. Third, $\sim$ few $\times$ 10 ms periodicities have not been reported in bursts except for the 5 MAR 79 burst.

ii. Replenishment of Energy

In section i.a it was mentioned that multiple-pulse profiles in classical bursts imply a "several-shot" mechanism. From the consideration of cooling times and source optical thickness, we obtain an additional indication that quasi-continuous supply of matter or energy is required to power the burst. Cooling time scales of basic energy-loss processes are much shorter than classical burst durations. The cooling time for optically thin bremsstrahlung by non-relativistic electron-ion collisions is

$$t_{br} = \frac{3}{2} \frac{n_e kT}{\Lambda_{br}} = 5 \times 10^{-11} n_{26}^{-1} Z^{-2} T_9^{1/2} \text{ s} \quad (6.2)$$

where Z is atomic number, and Λ_{br} is the bremsstrahlung cooling rate (Allen 1973; for relativistic corrections see eq. 3.5, or Gould 1980). The synchrotron cooling time scale is

$$t_{syn} = \frac{3\pi m_e c}{\sigma_T} B^{-2} = 4 \times 10^{-16} B_{12}^{-2} \text{ s} \quad (6.3)$$

where σ_T is the Thompson cross-section (Trubnikov 1960) and $B_{12} = B/(10^{12} \text{ G})$. Hence, energy or matter must be supplied during the course of the burst unless the source is extremely optically thick (Lamb 1982). This argument is also applicable for spike-like bursts, whose durations are also much greater than the cooling time scales. In section iii.d below it is shown that the sources are optically thin if they are within a few hundred parsecs and if synchrotron radiation from a $\sim 10^{12} \text{ G}$ field is the energy-loss mechanism.

If TTS is to work, the energy must not only be supplied continuously but thermalized. Liang (1982) mentions a possible thermalization process with time scale comparable to or faster than bremsstrahlung (6.2) and synchrotron (6.3) cooling times, the electron gyration period $\tau_{\text{cyc}} \sim 3 \times 10^{-19} B_{12}^{-1}$ s. This process may provide a means of thermalizing the confined plasma for fields $\geq 10^{10}$ G.

iii. Implications of Spectral Characteristics

a. Magnetic Confinement

The high spectral temperatures in γ -ray bursts imply the presence of very strong magnetic fields in the burst source, as can be seen from the following argument. If the temperature of a source exceeds the Eddington temperature,

$$T_{\text{edd}} = \left\{ \frac{4\mu m_H g}{\sigma_T a} \right\}^{1/4} = 1.8\mu^{1/4} \left\{ \frac{M}{M_0} \right\}^{1/4} R_6^{-1/2} \text{ keV} \quad (6.4)$$

where μ is the mean molecular weight, g the stellar surface gravity, and a the radiation constant, then the plasma cannot be contained by the source gravitational field (Colgate and Petschek 1981). For neutron stars $T_{\text{edd}} \sim 2$ keV; the ratio of radiation to gravitational pressure is $(T_{\text{burst}}/T_{\text{edd}})^4 \sim 10^8$. The ensuing explosion absorbs most of the energy, and the expanded photosphere radiates at temperatures much less than those characteristic of γ -ray bursts (Newman and Cox 1980).

A strong magnetic field is the likely agent to confine the hot plasma, preventing the rapid expansion and thereby allowing the possibility of maintaining thermalization of the plasma. The field strength must be such that the magnetic pressure exceeds the higher of

the radiation or gas pressures. For radiation pressure at $T \sim 200$ keV, $B^2/8\pi > aT^4/3$ implies $B > 5 \times 10^{11}$ G. Lamb (1982) argues that the radiation pressure indeed exceeds the particle pressure, that is,

$$\frac{1}{3}aT^4 > n_e kT \rightarrow n_e < 10^{29} \text{ cm}^{-3} \quad (6.5)$$

for $T \sim 200$ keV. Assume the emission volume is a fraction, f , of a neutron star surface times the emission region thickness ($V = (A/f)\ell \sim 10^{19}/f \text{ cm}^3$, for $\ell \sim 10$ km). Then an upper limit to the particle density of $n_e \lesssim 10^{26}/f \text{ cm}^{-3}$ is obtained assuming the total burst energy ($\sim 10^{38}$ ergs, for $d \sim 100$ pc) is transferred to the particles instantaneously (a maximum of 3×10^{44} particles, so that each particle retains at least 200 keV). If matter or energy is supplied throughout the duration of the burst, the particle density can be much lower.

The requirement of $\sim 10^{12}$ G fields strengthens the case for neutron stars as the sources. Since the dipolar field decreases as $(r/r_0)^{-3}$, bursts must be produced close to the neutron star surface.

b. Spectral Evolution

Early measurements of event-integrated spectra were consistent with a single shape: an exponential with characteristic energy 150 keV, and a power-law tail above 400 keV to ~ 2 MeV with photon index ~ -2.5 (Cline and Desai 1975). The results of recent burst experiments have established that spectra vary from event to event and that the spectrum evolves during a given event (Mazets et al. 1981d). Experiments capable of measuring spectra rapidly indicate that at least some bursts evolve on time scales commensurate with the fast temporal variations, a few $\times$

10 ms (the SIGNE experiment - Vedrenne 1981; Barat et al. 1983a; HXRBS - chapter V).

Two aspects of burst spectral evolution give clues to the nature of the burst mechanism. First, the KONUS results (Mazets et al. 1981d), with the relatively coarse spectral integration time of 4 s, reveal the tendency for correlation of hard spectra with intense pulses. Usually, the course of spectral evolution is from hard to soft with the pattern sometimes repeating. This suggests a process involving fluctuating injections of matter or energy, each occurrence initially producing preferentially hard photons. The explanation of this behavior is a fundamental requisite for classical γ -ray burst models (see section iv).

Second, in the SIGNE spectra for at least three events, spectral turnovers at energies 350 to 450 keV (or depressions in the continuum below these energies) are evident in the burst onset (Barat et al. 1983a). The spectra subsequently "unfold" at lower energies, becoming monotonically decreasing within $\lesssim 1$ to 2 s. This phenomenon has been observed in both spike-like and classical bursts. In the 5 MAR 79 burst, the spectral turnover below ~ 350 keV is apparent in the first 25 ms of the initial 150 ms spike, and is not discernable in the spectrum of the remainder of the spike.

One additional result is relevant to this picture of burst spectral turnovers. Ambruster et al. (1983) report the observation of a probable γ -ray burst at low X-ray energies with the LASS experiment on HEAO-1. The event-averaged spectrum is turned over at ~ 2 keV.

Besides cyclotron features, there are two plausible explanations for a wide range in turnovers or apparent depressions and evolution of the same in burst spectra. First, if the energy-loss mechanism is

synchrotron radiation, self-absorption or synchrotron cutoff could account for the spectral evolution. In the former case, the source may be initially optically thick at low energies, and as the emitting region expands, the plasma becomes optically thin and the low-energy spectrum unfolds. Second, electrons do not radiate below the cutoff (gyro) frequency, $eB/(2\pi m_e c) = 11.6 B_{12}$ keV. The expansion of radiating plasma from regions of high magnetic field strength near the neutron star surface (where the plasma may be marginally confined) in the initial stage of the burst to regions of lower field strength removed from the star would produce a synchrotron cutoff evolving towards lower energies with time.

If repetitive injections of matter/energy near the stellar surface occur, as suggested in section b, in subsequent intervals radiation would emerge from regions with a range of field strengths as the plasma expands outward. If the emitting region expands in times less than intervals between injections (~ 1 s), later spectra would not exhibit low-energy depressions. Also the later spectra would reflect a heterogeneous field and would tend to be softer than in the initial stage due to contribution from emission in lower field strength regions. A migration of the plasma through field strengths varying by a factor of ~ 5 would be sufficient to move the synchrotron cutoff from ~ 70 keV to energies below the KONUS or HXRBS energy ranges ($\lesssim 20$ keV). This scenario is consistent with the observation of low-energy turnovers only in the initial burst stage (Mazets et al. 1981e), and with the tendency for the initial stage to exhibit a harder spectrum than subsequent intervals (Mazets et al. 1981d).

c. Spectral Features

1. Absorption Features

About 20% of the KONUS events exhibit spectra in the initial 4 s with significant departures at low energies, < 100 keV, from an exponential shape. These depressions have been interpreted as cyclotron absorption features. The existence of low-energy depressions in some burst spectra is corroborated by the present work (chapter V).

In view of the discussion above concerning fast spectral evolution, the interpretation of the spectral features as "lines" is questionable, especially for the low-energy features. Since the KONUS low-energy depressions, and the ~ 400 keV emission features, are observed only in the initial 4 s integrations and some bursts have been shown to evolve on time scales less than 4 s, it is possible that the low-energy features are the result of temporal averaging of spectra with an evolving low-energy turnover. The addition of two spectra with different turnover energies can produce a spectral artifact which imitates an intrinsic spectral line (see Figure 5.36).

Furthermore, there are theoretical problems with the widths of the low-energy features interpreted as cyclotron absorption lines. If the continuum is thin thermal synchrotron (TTS) from mildly relativistic electrons, the emission from the low harmonics, which would be discernable in discrete peaks at lower temperatures, is doppler-broadened into a smooth continuum for $T \gtrsim 75$ keV (Lamb and Masters 1979). For a representative $\nu_c \sim 5$ keV (Liang, Jernigan, and Rodrigues 1983; Table A.1 and chapter V), and a cyclotron line energy of ~ 50 keV, implying $B_{12} \sim 4$, one obtains from eq. 6.7, $T \sim 150$ keV. Hence, cyclotron lines observed to be a few $\times 10$ keV wide are incompatible with

the plasma temperatures required to produce the synchrotron continuum. At the very least, if the low-energy features are due to cyclotron absorption, the region of line formation must be significantly cooler and overlies the region of continuum formation.

2. Emission Features

Emission features at energies ~ 400 to 450 keV have also been observed in about 7% of the KONUS events and interpreted as the 511-keV annihilation line redshifted by about 20%, a value appropriate for radiation escaping from the surface of a $\sim 1 M_{\odot}$ neutron star.

For two events in which ~ 400 keV emission features were reported by Mazets et al. (1981e), the SIGNE experiment spectra exhibit turnovers at 350 to 450 keV at the burst onset (Barat et al. 1983a); for this reason the annihilation line interpretation is not firmly established.

The ~ 400 keV peaks observed in the initial stages of some SIGNE spectra may indeed be predominantly annihilation radiation. However, the SIGNE channel widths, ≥ 100 keV, are too broad to admit meaningful determination of a spectral line shape. That the emission features are always observed at approximately the same energies strengthens the case for their reality.

d. Energy-loss Mechanisms

Three radiation mechanisms have been proposed to account for the nearly uniformly observed exponential shape of spectra in γ -ray bursts: 1) inverse Comptonization of an X-ray burst by a hot overlying plasma (Fenimore et al. 1982c), 2) thin thermal bremsstrahlung (Mazets et al. 1981d), and 3) thin thermal synchrotron radiation (Liang 1982).

The inverse Compton explanation suffers problems with geometry and confinement. If neutron stars are the source objects, and the electron scattering optical depth $\tau_{es} > 1$ as required to produce the hard γ -ray spectrum, then the magnetic field is constrained to be less than 10^9 G (Fenimore et al. 1982c). Otherwise, the synchrotron emission contribution dominates the inverse Compton spectrum. However, a field strength $\sim 10^{12}$ G is required to restrain the expansion of the 100 to 200 keV Comptonizing plasma (section a). Furthermore, Fenimore et al. do not address the question of how to establish the hot plasma suspended above an X-ray burst.

The requirement of a $\sim 10^{12}$ G field to restrain the radiating plasma against expansion leads one to a comparison of bremsstrahlung and synchrotron emissivities (see Liang 1982). A simple calculation shows that TTS radiation dominates TTB under the probable conditions obtaining in γ -ray bursts, $B \sim 10^{12}$ G, $n_e < 10^{26} \text{ cm}^{-3}$. The specific emissivity for TTS (eq. 3.6) integrated over frequency gives the energy loss per unit volume per steradian,

$$\frac{1}{4\pi} \frac{L_{\text{syn}}}{V} = \frac{120 e^4 B^2 T_*^4 K_2^{-1} (T_*^{-1}) n_e}{81/2 \pi m_e^2 c^3} e^{-x_m} \int_{r=0}^5 \frac{x_m^{(5-r)}}{(5-r)!} \quad (6.6)$$

with $x_m = \left\{ \frac{4.5\nu_{\text{min}}}{\nu_c} \right\}^{1/3}$, K_2 a modified Bessel function, ν_{min} a minimum frequency below which the emission is extinguished (self-absorbed or cutoff), and

$$\nu_c = \frac{eB}{2\pi m_e c} T_*^2 \quad \text{or} \quad \epsilon_c = h\nu_c = 11.6 B_{12} T_*^2 \text{ keV} . \quad (6.7)$$

It was stated in section b above that $h\nu_{\text{min}}$ ranges from ~ 1 to 100 keV

in some bursts. However, after the onset of the bursts with evidence of low-energy turnovers, and for the majority of bursts, the spectra continue smoothly down to the lowest detector channel (Mazets et al. 1981e), and therefore $h\nu_{\min} \lesssim 20$ keV. Regardless, since $x_m = \nu_{\min}^{1/3}$, over the probable energy range of $\nu_{\min}$, the product of the exponential and summation in (6.6) is of order unity. Then (6.6) may be written

$$L_{\text{syn}} \sim 10^{10} n_e V B_{12}^2 T_*^{-4} K_2^{-1} (T_*^{-1}) \text{ erg s}^{-1}. \quad (6.8)$$

The TTB luminosity is given by Gould (1980). The ratio of synchrotron to bremsstrahlung luminosity is

$$\frac{L_{\text{ts}}}{L_{\text{tb}}} = 6 \times 10^{31} n_e^{-1} B_{12}^2 T_*^{3/2} K_2^{-1} (T_*^{-1}). \quad (6.9)$$

Assuming $T \sim 300$ keV, $B_{12} \sim 1$, synchrotron dominates bremsstrahlung for $n_e \lesssim 3 \times 10^{31} \text{ cm}^{-3}$. This condition would clearly be fulfilled even if the burst energy were deposited instantaneously rather than continuously during the burst (cf., section iii.a).

Therefore, in the following discussion thermal synchrotron is assumed to be the energy-loss process. Also, the source objects are assumed to be a subset of old neutron stars which retain magnetic fields $\sim 10^{12}$ G. This argument parallels that of Liang (1982) with the alteration that the source objects are assumed to be within the galactic disk, rather than in the galactic halo. The galactic disk hypothesis is more consistent with the observed, nearly isotropic distribution of bursts and especially the lack of a galactic center/anticenter bias. From the burst luminosities implied by a disk source distribution, it is

shown below that the low-energy turnovers or depressions observed in some bursts are probably not due to self-absorption, a possibility suggested by Liang. Instead, since the sources would be optically thin if located within a few hundred parsecs, the remaining natural and consistent explanation is the low-energy cutoff in the synchrotron spectrum.

The optical depth for synchrotron self-absorption is

$$\tau_{\text{syn}}(\omega) = \alpha_{\omega} l = \frac{\omega_p^2 l}{\omega_g c} \sum_m \Phi_m(\omega) \quad (6.10)$$

where α_{ω} is the absorption coefficient, l is the emission region thickness, ω_p is the electron plasma frequency and $\omega_g = 2\pi\nu_g$, ν_g = electron gyrofrequency. The summation is over the contributions from the m harmonics. The specific emissivity is

$$j_{\omega}(\omega) = \left\{ \frac{\omega_p^2}{\omega_g c} \right\} \left\{ \frac{\omega^2 kT}{8\pi^3 c^2} \right\} \sum_m \Phi_m(\omega) \quad (6.11)$$

for a uniform magnetic field (Bekefi 1966). Combining these two equations yields an expression in terms of the turnover frequency due to self-absorption, ν_{min} , below which the source is optically thick,

$$\tau_{\text{syn}} = \frac{l j_{\omega} 8\pi^3 c^2}{\omega^2 kT} = \frac{2l}{m_{\text{min}}^2 T_{\star}} j_{\nu_{\text{min}}}, \quad (6.12)$$

where again, $T_{\star} = kT_e/m_e c^2$. Upon substituting for the specific emissivity j_{ν} (3.6) and rearranging, one obtains the condition for an optically thin source,

$$n_e \lesssim \frac{3/2 m_e v_{\min} T_* e^{x_m} K_2(T_*^{-1})}{2\pi e^2} \quad (6.13)$$

$$\approx 1.9 \times 10^{19} v_{\min}(\text{keV}) T_* K_2(T_*^{-1}) e^{x_m} \text{ cm}^{-2}.$$

Combining this with the expression for the synchrotron luminosity (6.8) yields the luminosity given an observed self-absorption turnover at $\nu_{\min}$,

$$L_{\text{thin}} \lesssim 2 \times 10^{29} A B_{12} v_{\min}(\text{keV}) T_*^5 \sum_{r=0}^5 \frac{x_m^{(5-r)}}{(5-r)!} \quad (6.14)$$

$$\approx 1.4 \times 10^{37} A(\text{km}^2) v_{\min}(\text{keV}) v_c^2(\text{keV}) T_* e^{x_m} \text{ erg s}^{-1}.$$

We may argue that the source is optically thin if L_{obs} is less than eq. 6.14. The parameter values in this expression will be estimated conservatively to give a low but realistic value for L_{thin} . Assume $A = 1 \text{ km}^2$, an area comparable to the size of a neutron star's magnetic polar cap. Since the depressions are observed only in some bursts in the initial stage (Mazets et al. 1981e), estimate $\nu_{\min}$ to be below the lowest detector channel, $\sim 25 \text{ keV}$ (KONUS, HXRBS). Then for some bursts

$1 \text{ keV} \lesssim \nu_{\min} \lesssim 10 \text{ keV}$ and $1 \lesssim x_m \lesssim 2$. Choosing a representative value for ν_c of $\sim 5 \text{ keV}$ one finds $T_* \sim .66$ for $B_{12} \sim 1$. Using these values, the burst source is optically thin if $L_{\text{obs}} \lesssim 6 \times 10^{38}$ to $10^{40} \text{ erg s}^{-1}$.

Now estimate the observed luminosity liberally, the only assumption being a galactic disk burst population. For a bright burst with average flux $F \sim 3 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$, burst duration $\sim 10 \text{ s}$, the fluence is $\sim 3 \times 10^{-4} \text{ erg cm}^{-2}$, placing it at the upper end of the $\log(N>S) - \log(S)$ curve. For most galactic populations $\rho(N/\text{pc}^3) = \rho_0 \exp[-(z/z_0)^m]$

with $1.2 < m < 1.7$ (Guibert, Lequeux, and Viallefond 1978). For radio pulsars z_0 is 230 pc (Manchester and Taylor 1977) or 380 pc (Gailly Lequeux, and Masnou 1978). For this calculation assume $d \sim 400$ pc. Such a burst would then be at the high end of an intrinsic luminosity distribution. Then

$$L_{\text{obs}} = 4\pi d^2 F \sim 6 \times 10^{38} \text{ erg s}^{-1} < L_{\text{thin}}, \quad (6.15)$$

indicating that the sources are optically thin at ~ 1 keV for galactic disk distances and that the turnovers are not due to self-absorption.

For the observed low-energy depressions at ~ 70 keV to be due to synchrotron self-absorption, some sources would have to be located at distances ≥ 4 kpc (as Liang suggests). This would require old extinguished pulsars with velocity components perpendicular to the galactic plane of 150 km s^{-1} (Manchester and Taylor 1977) to retain $\sim 10^{12}$ G fields for $\geq 2 \times 10^7$ yr, a duration comparable to or greater than the predicted time scale for decay of the crustal field (Flowers and Ruderman 1977). Furthermore, a galactic center/anticenter bias should be observed if most sources were at halo distances.

Assume then, that the burst sources are located within a few hundred pc and $L_{\text{obs}} \leq 1.5 \times 10^{38} \text{ erg s}^{-1}$. From (6.12), using $T_e \sim .66$, $B_{12} \sim 1$, one finds $n_e V \leq 4 \times 10^{28}$. The volume of the emitting region must be some fraction of the neutron star surface times a characteristic depth. For a plausible lower limit on V (upper limit on n_e), assume an area $A \sim 1 \text{ km}^2$ and a depth $l \sim 4 \text{ km}$. This value for l allows for some expansion of the plasma outward through the dipole field to be

consistent with the observed variations in the low-energy turnovers. Then $V \geq 4 \times 10^{15} \text{ cm}^3$, yielding $n_e \leq 10^{13} \text{ cm}^{-3}$.

The optical depths for electron scattering and cyclotron absorption, assuming $l \sim 10 \text{ km}$ and $n_e \sim 10^{13} \text{ cm}^{-3}$ are

$$\tau_{es} \approx n_e \sigma_T l \sim 7 \times 10^{-6} \quad (6.16)$$

$$\tau_{cyc} \approx \frac{\pi}{3} \frac{\omega_p^2 l}{\omega_c} (2T_*)^{1/2} \approx 5 \times 10^{-3} B_{12}^{-1} T_9^{-1/2} n_{e,13} l(\text{km}) \quad (6.17)$$

where $T_9 = T_e/(10^9 \text{ K})$ and $n_{e,13} = n_e/(10^{13} \text{ cm}^{-3})$ (Lamb 1982). For $B_{12} \sim 1$ and $T_* \sim .66$ ($T_9 \sim 4$), τ_{cyc} is $\sim 2 \times 10^{-2}$. Since under the above assumptions, the source will be optically thin, and the synchrotron cooling time (eq. 6.3) is very much shorter than burst durations, energy or matter must be continuously supplied during the burst.

iv. Models for Classical Bursts

Models for classical bursts must differ from spike-like burst models in at least three aspects: 1) event duration $\sim \text{few} \times 10 \text{ s}$, 2) spectral energies $\sim \text{few} \times 100 \text{ keV}$, and 3) recurrence times $\geq 1 \text{ yr}$. Also, it appears that a "several-shot" or extended process is necessary to produce multiple pulses (section i.a) and repeating hard-to-soft spectral evolution (section iii.b) observed in some bursts.

Asteroid accretion scenarios appear to be ruled out for classical bursts on the basis of the insufficient total event rate ($\sim 8 \text{ yr}^{-1}$, section A.iii). Furthermore, the asteroid collision model does not appear capable of producing an extended duration burst.

A variation on the thermonuclear model (Woosley 1982) appears to account for some of the observed properties of classical bursts. In Woosley's Model I, $\sim 10^{20}$ gm of accreting hydrogen, focussed by a $\sim 10^{12}$ G field onto the magnetic polar cap of a neutron star, is steadily converted to helium via the CNO cycle. Upon accumulation of a critical mass, the convective deflagration burning of an uneven distribution of fuel sites might, according to Woosley, reproduce the durations and chaotic temporal structure observed in classical bursts. The model predicts a recurrence rate ~ 0.4 yr, somewhat lower than the (unfirm) lower limit implied by available observations (KONUS catalog). The burst generates $\sim 10^{38}$ ergs in γ -rays, which for a source distance of ≤ 400 pc, delivers a fluence $\geq 10^{-6}$ erg cm^{-2} , in agreement with observed fluences. However, preliminary calculations indicate that the characteristic photon energies produced are an order of magnitude lower than that of classical burst energies. Further, the lack of X-ray detections again presents a difficulty. For Model I, an accretion rate of $4 \times 10^{-13} M_{\odot} \text{ yr}^{-1}$ is required to sustain the temperature at which the CNO-mediated hydrogen burning occurs (see also chapter I concerning viability of this process, or Ventura 1982). For this accretion rate, a steady-state X-ray source should be visible for a source distance < 500 pc (Ventura 1982), but the lack of detections (Helfand et al. 1980; Cline 1981; Hurley 1982) for several burst error boxes requires source distances > 1 kpc. For such distances, the model is at odds with the lack of a galactic center/anticenter bias in the $(l, b)^{\text{II}}$ distribution.

Fleeting episodes of accretion onto neutron stars (Lamb, Lamb, and Pines 1973) may reproduce the observed properties of classical bursts and avoid the problem of a steady-state X-ray source. In this scenario,

the burst is powered by the $\sim 100\%$ conversion of gravitational energy into radiation. A flare from a companion star delivers $\sim 10^{16}$ to 10^{17} gm onto one area of the neutron star. Variations in flare ejection velocity and geometry may account for the range in classical burst durations. No specific predictions concerning spectral energies are made by the authors; however with free-fall energies of ~ 100 Mev per nucleon, the necessary energy is available to produce hard burst spectra. Estimates of the density of neutron stars in binary systems with companions capable of producing such flares would require recurrence intervals ~ 16 yr. Since, the companion is quiescent between flares, no steady-state X-ray source is predicted.

C. Directions for Future Gamma-Ray Burst Investigations

A complete understanding of γ -ray bursts awaits development of much more sophisticated and dedicated observational tools. Satellites with the level of integrated experiments comparable to the SMM are necessary for burst investigations. Efforts in several directions will help to solve the mysteries of γ -ray bursts.

The first priority should be to re-establish an interplanetary network of several burst sensors, such as the one which operated in 1978-79. Detectors with better sensitivity and faster temporal resolution would produce sub-arcmin-sized source localizations. X-ray or optical associations would provide conclusive burst source identifications.

Improved detector systems with wider spectral coverage ($\lesssim 1$ keV to $\gtrsim 50$ MeV), higher sensitivity, faster spectral integration times, and finer energy resolution are required to obtain the necessary quality

spectra in order to study burst processes. The information derived from these experiments should determine the true nature of features observed in some burst spectra. Perhaps additional discoveries such as narrow spectral lines will be made.

Continuous surveillance of the 5 MAR 79 source should be established in the optical, X-ray, and γ -ray energy bands to determine 1) the event size spectrum from this source, 2) the recurrence intervals, and 3) the spectrum over a wide frequency range.

In the very near future, the reduction of KONUS 13 and 14 data should provide an improved picture of the γ -ray burst distribution in galactic latitude and longitude. If a tendency for lower fluence events at low latitudes emerges, the galactic disk hypothesis will be strengthened. With the addition of ~ 100 more events by KONUS 13 and 14, perhaps some truly periodic temporal structure in classical bursts will be seen.

APPENDIX

Gamma-Ray Burst Information Derived from the KONUS Catalog

The KONUS catalog (Mazets et al. 1981a; b; c) contains the largest sample of γ -ray bursts with spectra and temporal profiles of any experiment to date. The KONUS experiment, carried on the Venera 11 and 12 spacecraft, recorded bursts from September 1978 to January 1980. The experiment is described in chapter II.

The peak intensities (cts/ $1/4$ s) and durations of the KONUS bursts were measured directly from temporal profiles.

The KONUS spectra, including error bars, were digitized using a Tektronics 4081 Graphics Tablet. The digitized errors were increased by 5%. This measure was performed since 1) the manual digitization technique may have produced occasional shifts in the apparent values, and 2) the published graphs were sometimes obviously distorted by the reproduction process. An adaptation of the LSPEC spectral fitting program, described in chapter III, was used to fit the digitized spectra. The program was modified to circumvent the detector matrix multiplication since the published spectra were already corrected for the detector response (Mazets, private comm.).

Two spectral models were used to fit the KONUS spectra: 1) the same model employed by Mazets et al. (1981d), $\propto E^{-1} \exp(-E/T)$, representing a thin thermal bremsstrahlung (TTB) model without a gaunt factor, and 2) the thin thermal synchrotron (TTS) model described by eq. 3.6. Fitting deconvolved spectra with a model other than the one used in the actual deconvolution is not a strictly correct procedure. However, the TTS form does approximate that of the TTB, and therefore the detector

responses to the two models are quantitatively similar. In fact, the TTS model almost always provided as good or better a fit to the data as did the TTB model. The TTB temperatures derived by this procedure compared very well with the temperatures published for some KONUS spectra (Mazets et al. 1981d; 1981e).

In Table A.1 spectral fits for the two models (see Figure A.4 for histogram of ϵ_c values), the peak intensities, and durations are assembled. For TTB, the continuum parameter is the temperature, T . For TTS, this parameter is the critical energy, ϵ_c . The chisquared parameter and the number of degrees of freedom are also listed for both model fits. Occasionally, two events occurred on the same day. The first event is subscripted .A1, the second .B1. If more than one 4 s spectrum was published for an event, each spectrum was fit. For the third spectrum of the second event on November 4, 1978, the designation is NV0478.B3. In some spectra there are apparent absorption or emission features, indicated by a # or *, respectively, following the event designation. When lines were included in the models, better fits were obtained for these spectra; the fits with lines are therefore included in the table. The continuum parameters only are listed (for the line energies, etc., see Mazets et al. 1981e).

In Table A.2 the short duration bursts (≤ 1 s) detected by KONUS experiment on Venera 11 and 12 are listed (extracted from Table A.1). The spectra of these bursts are usually much softer than the spectra of classical γ -ray bursts, as can be seen from a comparison of the thermal bremsstrahlung temperatures in Tables A.1 and A.2. Table A.3 lists the events detected by the KONUS experiments on Venera 11 and 12, and Venera 13 and 14 which have localizations consistent with the 5 MAR 79 source

(Mazets, private comm.). The events are arranged in groups to suggest a trend of increasing intervals between events. The Venera 11 and 12 spacecraft ceased recording bursts in January 1980 and the Venera 13 and 14 spacecraft became operational in November 1981.

The directions of sixty bursts were uniquely triangulated by the KONUS experiment. One-position localizations have been determined for a few additional bursts by Strong, Klebesadel, and Olson (1974) and Hurley (private comm.). These 67 unique localizations are plotted in galactic coordinates in Figure A.1. Histograms of the number of positions versus $\sin(b^{II})$ and l^{II} are illustrated in Figures A.2 and A.3, respectively.

Table A.1

Spectral Fits, Peak Intensities, and Durations
For KONUS 11 and 12 Events

Event Spectrum	Therm Brem Temp & Err (keV)		Chi Square /DOF	Therm Sync ϵ_c & Err (keV)		Chi Square /DOF	P.I. (cts/ .25s)	Dur (s)
SP1478.A1	102.	7.	36.2/ 7	2.3	0.2	43.1/ 7	67.	21.0
SP1478.B1 *	179.	11.	22.9/ 7	4.0	0.1	110.1/10	174.	19.0
SP1478.B2	86.	6.	11.2/ 8	1.7	0.2	19.6/ 8	174.	19.0
SP1478.B3	84.	13.	2.2/ 7	1.6	0.3	2.2/ 7	174.	19.0
SP1678.A1	901.	340.	14.0/10	12.3	3.1	10.6/10	49.	9.0
SP1878.A1	118.	21.	6.8/ 7	2.7	0.6	7.4/ 7	204.	29.0
SP1878.A2 *	218.	25.	13.4/10	4.9	0.5	10.6/10	204.	29.0
SP1878.A3 *	126.	28.	2.8/ 8	2.9	0.6	2.7/ 8	204.	29.0
SP2178.A1	432.	1.	12.1/13	8.0	1.0	13.6/13	125.	20.0
SP2278.A1	184.	37.	13.4/ 9	4.2	0.0	12.7/ 9	49.	7.0
SP3078.A1	202.	19.	10.1/12	4.2	0.4	7.7/12	62.	38.0
OC0578.A1	169.	3.	7.2/ 8	3.4	0.6	5.8/ 8	49.	26.0
OC0678.A1	355.	3.	19.8/14	7.6	0.8	11.3/14	52.	41.0
OC0678.B1	183.	14.	20.8/11	4.0	0.3	16.8/11	113.	15.0
OC1178.A1	116.	30.	2.2/ 5	2.6	0.8	2.1/ 5	25.	10.0
OC1278.A1	131.	12.	5.0/ 8	2.8	0.3	4.8/ 8	50.	22.0
OC1278.B1	517.	16.	41.1/ 8	9.8	1.5	36.4/ 8	88.	37.0
OC2278.A1	135.	26.	5.2/ 8	2.9	0.1	4.6/ 8	43.	9.0
OC2378.A1	621.	227.	12.4/12	11.2	2.4	11.7/12	48.	31.0
OC2578.A1	207.	33.	4.1/ 9	4.7	0.3	3.9/ 9	66.	52.0
OC2678.A1	357.	44.	8.0/11	7.7	0.8	9.0/11	65.	18.0
NV0278.A1	107.	16.	10.3/ 9	2.2	0.4	9.4/ 9	88.	18.0
NV0478.A1	104.	15.	5.9/ 7	2.3	0.4	7.0/ 7	63.	12.0
NV0478.B1 *	796.	75.	17.3/11	14.1	1.1	13.3/11	728.	45.0
NV0478.B2 *	604.	22.	17.9/11	10.9	0.4	17.9/11	728.	45.0
NV0478.B3	200.	9.	13.1/12	4.1	0.0	10.1/12	728.	45.0
NV0478.B4	99.	10.	7.1/ 8	1.9	0.3	3.5/ 8	728.	45.0
NV0778.A1	151.	34.	9.5/ 7	3.6	0.9	9.8/ 7	47.	5.0
NV0978.A1	223.	98.	4.9/ 8	5.2	2.7	4.8/ 8	73.	1.3

Table A.1 -- continued

Event	Therm Brem		Chi	Therm Sync		Chi	P.I.	Dur
Spectrum	Temp & Err		Square	ϵ_c & Err		Square	(cts/ .25s)	(s)
	(keV)		/DOF	(keV)		/DOF		
NV1178.A1	80.	30.	12.4/ 5	1.8	0.4	4.6/ 5	49.	6.0
NV1378.A1	369.	102.	21.3/ 8	9.3	0.8	17.8/ 8	40.	26.0
NV1578.A1	1438.	333.	68.4/12	20.7	2.1	26.9/12	169.	10.0
NV1578.B1	53.	5.	10.5/ 7	0.9	0.1	7.4/ 7	23.	9.0
NV1778.A1 #	579.	11.	20.3/ 9	10.0	1.2	13.8/ 9	35.	25.0
NV1978.A1 *	>9000.	---	184.0/11	94.5	0.8	31.3/11	181.	42.0
NV1978.A2	2318.	197.	10.7/14	21.0	2.5	15.8/14	181.	42.0
NV1978.A3	324.	11.	19.3/13	6.4	0.8	17.3/13	181.	42.0
NV1978.A4	80.	15.	2.1/ 7	1.7	0.4	2.3/ 7	181.	42.0
NV2178.A1	217.	18.	18.7/12	4.9	0.4	17.0/12	71.	65.0
NV2178.B1	94.	11.	6.2/ 7	2.0	0.2	6.9/ 7	28.	27.0
NV2378.A1	76.	9.	7.3/ 8	1.6	0.3	9.4/ 8	62.	8.0
NV2478.A1	177.	8.	32.9/11	3.8	0.3	36.1/11	536.	19.0
NV2478.A2	54.	3.	19.6/ 8	0.8	0.1	9.3/ 8	536.	19.0
NV2478.A3	37.	5.	6.2/ 5	0.6	0.1	2.8/ 5	536.	19.0
DC0778.A1	81.	10.	1.6/ 4	1.1	0.2	1.9/ 4	22.	6.0
DC2978.A1	168.	40.	8.1/ 6	4.0	0.8	8.6/ 6	81.	3.6
JA0179.A1	316.	12.	22.4/11	6.5	0.4	19.9/11	116.	57.0
JA0279.A1	111.	7.	17.8/ 7	2.4	0.2	25.9/ 7	145.	5.0
JA0779.A1	26.	3.	15.1/ 4	0.5	0.0	24.9/ 4	390.	0.2
JA1379.A1	124.	4.	73.0/13	2.4	0.1	29.4/13	502.	40.0
JA1679.A1 *	148.	11.	11.9/ 8	3.4	0.1	12.7/ 8	215.	37.0
JA1979.A1	138.	9.	26.1/11	2.9	0.2	20.4/11	136.	39.0
JA3179.A1	115.	15.	6.2/ 6	2.6	0.4	8.0/ 6	57.	18.0
FB0879.A1	131.	17.	8.6/ 7	3.0	0.5	11.1/ 7	31.	12.0
FB1379.A1	234.	44.	7.4/ 9	5.0	0.9	7.7/ 9	45.	9.0
FB1479.A1	140.	17.	19.2/ 9	3.3	0.5	19.8/ 9	66.	8.0
FB1579.A1	259.	26.	11.8/13	5.4	0.5	12.1/13	35.	65.0
FB2479.A1	170.	55.	2.6/ 9	3.9	1.3	2.7/ 9	23.	9.0
MR0579.A1 *	44.	1.	59.1/11	0.6	0.0	149.3/11	50000.	65.0
MR0579.A2	37.	0.	47.3/ 7	0.4	0.0	262.0/ 7	50000.	65.0
MR0679.A1	36.	1.	36.7/ 4	0.5	0.0	76.0/ 4	405.	1.6

Table A.1 -- continued

Event	Therm Brem		Chi	Therm Sync		Chi	P.I.	Dur
Spectrum	Temp & Err		Square	ϵ_c & Err		Square	(cts/ .25s)	(s)
	(keV)		/DOF	(keV)		/DOF		
MR0779.A1 #	512.	25.	16.5/11	10.4	0.4	7.2/11	189.	50.0
MR1379.A1	331.	30.	22.4/12	7.1	0.6	18.1/12	215.	41.0
MR1379.A2	62.	9.	14.5/ 4	1.0	0.1	12.4/ 4	215.	41.0
MR1479.A1	110.	24.	12.4/ 6	2.4	0.6	12.4/ 6	34.	37.0
MR2379.A1 #	395.	35.	5.9/ 7	12.4	1.1	6.1/ 7	53.	55.0
MR2479.A1	33.	4.	2.0/ 4	0.4	0.1	1.6/ 4	902.	0.1
MR2579.A1	33.	3.	3.1/ 5	0.4	0.1	4.8/ 5	1088.	0.2
MR2579.B1 #	363.	40.	7.4/ 8	8.6	1.0	9.8/ 8	184.	32.0
MR2579.B2	116.	7.	13.8/ 8	2.2	0.2	29.3/ 8	184.	32.0
MR2779.A1	30.	9.	0.5/ 3	0.5	0.2	1.0/ 3	518.	0.3
MR2779.B1	434.	156.	13.6/ 8	9.0	2.3	12.0/ 8	33.	13.0
MR2979.A1 #	452.	74.	58.4/11	8.7	1.1	65.8/11	93.	49.0
MR2979.A2	6.	1.	4.8/ 3	0.1	0.0	22.0/ 3	93.	49.0
MR3179.A1	324.	28.	15.3/13	7.0	0.6	10.9/13	116.	12.0
AP0279.A1	105.	18.	8.0/ 8	2.0	0.4	5.7/ 8	45.	17.0
AP0279.B1 #	2185.	376.	30.7/10	37.0	7.9	22.8/10	57.	42.0
AP0279.B2	1457.	173.	18.3/10	17.1	3.5	13.6/10	57.	42.0
AP0479.A1	30.	5.	3.8/ 3	0.4	0.1	3.3/ 3	192.	0.2
AP0679.A1 *	3623.	213.	11.9/11	42.5	1.6	10.6/11	154.	0.3
AP1279.B1 #	291.	11.	13.8/ 6	8.0	0.1	13.7/ 6	49.	32.0
AP1579.A1	79.	11.	17.4/ 5	1.7	0.3	21.8/ 5	52.	4.0
AP1879.A1 *	1052.	238.	14.2/10	20.5	2.7	7.4/10	146.	15.0
AP1979.A1	294.	14.	40.4/1	5.9	0.2	31.7/14	184.	65.0
AP2479.A1	68.	33.	2.7/ 5	1.5	0.6	3.1/ 5	33.	11.0
AP2479.B1	31.	7.	2.4/ 3	0.6	0.2	3.1/ 3	6.	0.3
AP3079.A1	219.	49.	3.6/ 6	5.3	1.1	3.7/ 6	73.	16.0
MY0279.A1	150.	7.	15.1/14	3.1	0.2	11.9/14	157.	15.0
MY0479.A1	213.	35.	5.5/ 9	4.8	0.1	4.9/ 9	57.	9.0
MY1479.A1	301.	78.	9.8/ 8	6.4	1.5	10.5/ 8	92.	15.0
MY1979.A1	257.	8.	5.8/ 6	5.9	1.5	5.2/ 6	23.	14.0
MY2479.A1 #	233.	10.	20.6/ 9	5.0	0.4	23.1/ 9	41.	33.0
MY2679.A1 @	232.	44.	6.8/ 7	4.9	0.8	6.2/ 7	48.	41.0

Table A.1 — continued

Event	Therm Brem		Chi	Therm Sync		Chi	P.I.	Dur
Spectrum	Temp & Err		Square	ϵ_c & Err		Square	(cts/ .25s)	(s)
	(keV)		/DOF	(keV)		/DOF		
MY2979.A1 #	119.	3.	3.0/ 5	2.2	0.9	2.7/ 5	26.	37.0
JU0479.A1	100.	8.	21.0/ 8	2.1	0.1	28.5/ 8	93.	33.0
JU0479.A2	35.	3.	2.5/ 4	0.5	0.1	5.1/ 4	93.	33.0
JU0579.A1	160.	24.	1.8/ 8	3.5	0.6	2.0/ 8	67.	8.0
JU1079.A1 #	142.	7.	12.2/ 6	3.5	0.0	14.0/ 6	66.	36.0
JU1279.A1 #	166.	46.	3.0/ 5	3.5	1.3	3.4/ 5	38.	4.0
JU1379.A1	87.	44.	3.7/ 4	2.1	1.3	4.1/ 4	530.	2.0
JU2279.A1 #	608.	54.	15.9/10	10.8	0.6	14.4/10	114.	65.0
JU2879.A1	592.	279.	4.4/10	10.6	1.6	4.1/10	23.	40.0
JL0579.A1	84.	14.	10.0/ 6	1.8	0.4	12.7/ 6	42.	7.0
JL0579.A2	37.	15.	7.5/ 2	0.6	0.2	7.5/ 2	42.	7.0
JL0979.A1	43.	14.	1.4/ 4	0.8	0.4	1.6/ 4	171.	0.1
JL1279.A1	83.	16.	6.0/ 6	1.7	0.4	6.5/ 6	48.	40.0
JL2079.A1	221.	35.	6.5/ 8	5.2	0.4	6.5/ 8	60.	7.0
JL2879.A1	108.	30.	12.6/ 6	2.5	0.9	13.3/ 6	52.	1.6
JL3179.A1	452.	30.	25.0/13	9.4	0.3	18.2/13	62.	48.0
AU1079.A1	34.	5.	7.2/ 3	0.5	0.1	9.3/ 3	30.	1.0
AU1879.A1	45.	21.	1.3/ 4	0.8	0.5	1.2/ 4	24.	4.0
AU2679.A1	247.	36.	31.1/ 8	6.0	0.7	28.4/ 8	81.	23.0
AU2679.A2	58.	6.	1.2/ 5	1.1	0.0	3.0/ 5	81.	23.0
AU2979.A1	131.	18.	9.9/ 9	2.9	0.1	8.6/ 9	32.	10.0
SP1079.A1	181.	36.	8.0/ 7	4.3	0.4	8.2/ 7	43.	13.0
SP1379.A1	89.	17.	15.8/ 6	1.9	0.5	16.3/ 6	55.	22.0
SP2479.A1	127.	38.	5.0/ 6	2.9	1.1	5.1/ 6	46.	18.0
SP2579.A1	72.	9.	38.1/ 7	1.3	0.2	29.4/ 7	87.	38.0
SP3079.A1	10.	0.	5.7/ 3	0.2	0.0	68.5/ 3	2750.	0.3
OC0379.A1	175.	24.	4.6/ 9	3.8	0.5	3.4/ 9	42.	21.0
OC0679.A1	125.	14.	5.3/ 9	2.7	0.3	6.0/ 9	43.	25.0
OC0779.A1	194.	34.	17.1/10	4.6	0.8	17.3/10	28.	15.0
OC1479.A1	704.	15.	16.5/11	13.1	1.7	8.6/11	65.	25.0
OC1479.A2	174.	10.	8.1/ 8	3.9	0.6	7.9/ 8	65.	25.0
OC1479.A3	83.	16.	7.5/ 5	1.6	0.4	7.0/ 5	65.	25.0

Table A.1 -- continued

Event	Therm Brem		Chi	Therm Sync		Chi	P.I.	Dur
Spectrum	Temp & Err		Square	ϵ_c & Err		Square	(cts/ .25s)	(s)
	(keV)		/DOF	(keV)		/DOF		
OC1679.A1	76.	22.	2.3/ 4	1.6	0.2	2.4/ 4	21.	9.0
OC2379.A1	73.	15.	5.5/ 7	1.3	0.4	3.5/ 7	38.	8.0
OC3079.A1	129.	17.	2.5/ 8	2.8	0.4	2.6/ 8	23.	28.0
OC3079.B1	133.	24.	5.4/ 7	3.0	0.6	6.5/ 7	43.	12.0
OC3179.A1 #	202.	36.	3.1/ 5	4.6	1.1	4.0/ 5	33.	4.0
NV0179.A1	522	32.	12.5/13	10.3	0.5	16.0/13	93.	53.0
NV0579.A1	122.	16.	8.5/ 7	2.5	0.4	9.7/ 7	49.	6.0
NV0579.B1	145.	8.	9.8/12	3.1	0.2	16.4/12	335.	2.6
NV0979.A1 #	131.	2.	8.3/ 6	2.6	0.0	9.1/ 6	93.	4.0
NV0979.A2	84.	15.	3.2/ 4	1.8	0.6	3.2/ 4	93.	4.0
NV1179.A1	962.	57.	79.6/12	17.8	2.5	47.8/12	60.	14.0
NV1179.A2	98.	19.	10.9/ 6	2.2	0.6	12.3/ 6	60.	14.0
NV1379.A1	199.	21.	9.0/10	4.5	0.5	9.7/10	78.	39.0
DC1579.A1	258.	48.	27.7/ 8	6.6	1.1	24.3/ 8	40.	26.0
DC2779.A1 #	329.	17.	11.7/11	7.0	0.5	13.6/11	305.	25.0
DC2979.A1	92.	13.	20.3/ 6	1.8	0.3	18.4/ 6	40.	17.0
DC3079.A1	170.	9.	24.3/11	3.8	0.2	26.0/11	66.	65.0
JA0580.A1	192.	9.	21.0/13	4.0	0.2	11.4/13	146.	38.0
JA1280.A1	150.	33.	6.1/ 7	3.6	0.9	6.5/ 7	29.	20.0
JA1680.A1	130.	28.	2.3/ 6	3.0	0.8	2.6/ 6	117.	65.0
JA2680.A1	101.	34.	6.7/ 5	2.4	1.0	6.7/ 5	26.	27.0
JA2780.A1	70.	9.	6.4/ 5	1.4	0.2	9.5/ 5	76.	45.0
JA2780.B1	52.	4.	13.1/ 6	0.9	0.1	26.3/ 6	60.	65.0

* Indicates apparent emission feature at energies 350 keV to 450 keV

Indicates apparent absorption feature at energies 30 keV to 70 keV

@ Indicates apparent emission feature at energy 45 keV.

Table A.2

KONUS 11 and 12 Short Duration Events

<u>Date</u> <u>Dy/Mon/Yr</u>	<u>FWHM</u> <u>(ms)</u>	<u>FWZA</u> <u>(ms)</u>	<u>kT</u> <u>(keV)</u>	<u>Venera</u> <u>Spacecraft</u>
03/JAN/79	16	16	---	V11
07/JAN/79	200	200	26	V11
05/MAR/79	120	300	46	V11 V12
06/MAR/79	700	1500	36	V11 V12
24/MAR/79	60	100	33	V11 V12
25/MAR/79	110	200	33	V11 V12
27/MAR/79	16	300	30	V11 V12
04/APR/79	170	200	30	V11 V12
06/APR/79	160	250	3600	V11 V12
24/APR/79	170	300	31	V11 V12
13/JUN/79	50	2000	87*	V11
09/JUL/79	32	100	43	V11
30/SEP/79	32	300	10	V11

* kT = 660 (SIGNE experiment, Barat et al. 1983b)

Table A.3

Bursts from the 5 March 79 Source

<u>Date</u> <u>Dy/Mon/Yr</u>	<u>Time</u> <u>U.T.C.</u>	<u>Interval</u> <u>(days)</u>	<u>Duration</u> <u>(s)</u>	<u>kT</u> <u>(keV)</u>	<u>Venera</u> <u>Spacecraft</u>
05/MAR/79	15:51:39	0.6	0.25	35	V11 V12
06/MAR/79	06:17:25		1.5	31	V11 V12
04/APR/79	00:43:31		0.2	30	V11 V12
24/APR/79	18:27:18	20	0.2	30	V11 V12
01/DEC/81	09:18:02	32	3.5	30	V13 V14
02/JAN/82	17:11:11		1.5	26	V13 V14
15/FEB/82	10:36:31		0.1	40	V13 V14
23/APR/82	03:43:17	0.5	0.1	36	V13 V14
23/APR/82	16:29:21		0.15	45	V13 V14
10/MAY/82	13:27:56		0.1	—	V13 V14
30/MAY/82	12:46:14	20	0.1	35	V13 V14
08/JUL/82	10:18:19	39	0.1	30	V13 V14

The information in this table from Venera 13 and 14 was provided prior to publication, courtesy of E. P. Mazets.

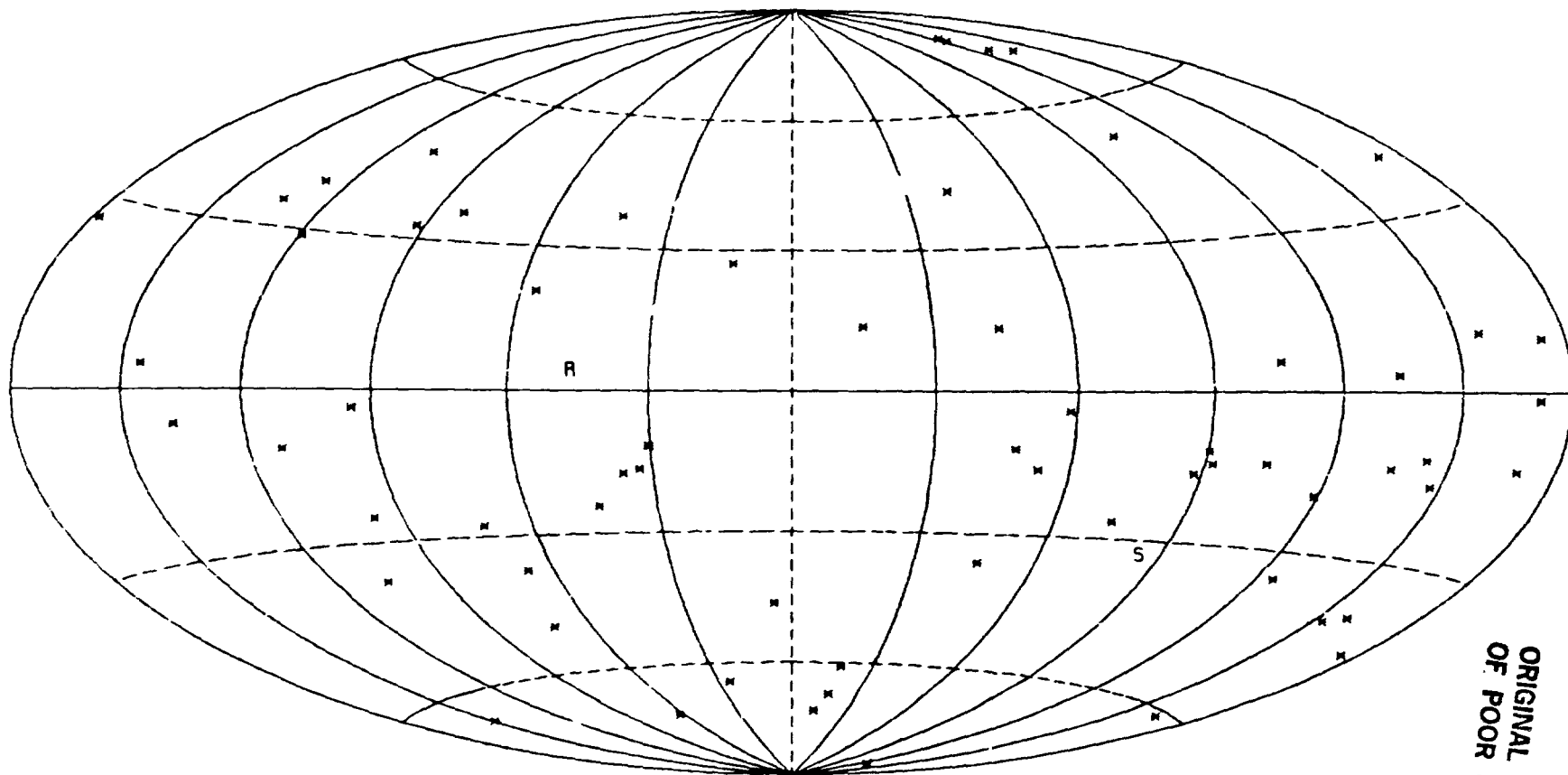


Fig. A.1. Plot of number of gamma-ray bursts (with unique localizations) versus galactic longitude. No excess is apparent in the direction of the galactic center region.

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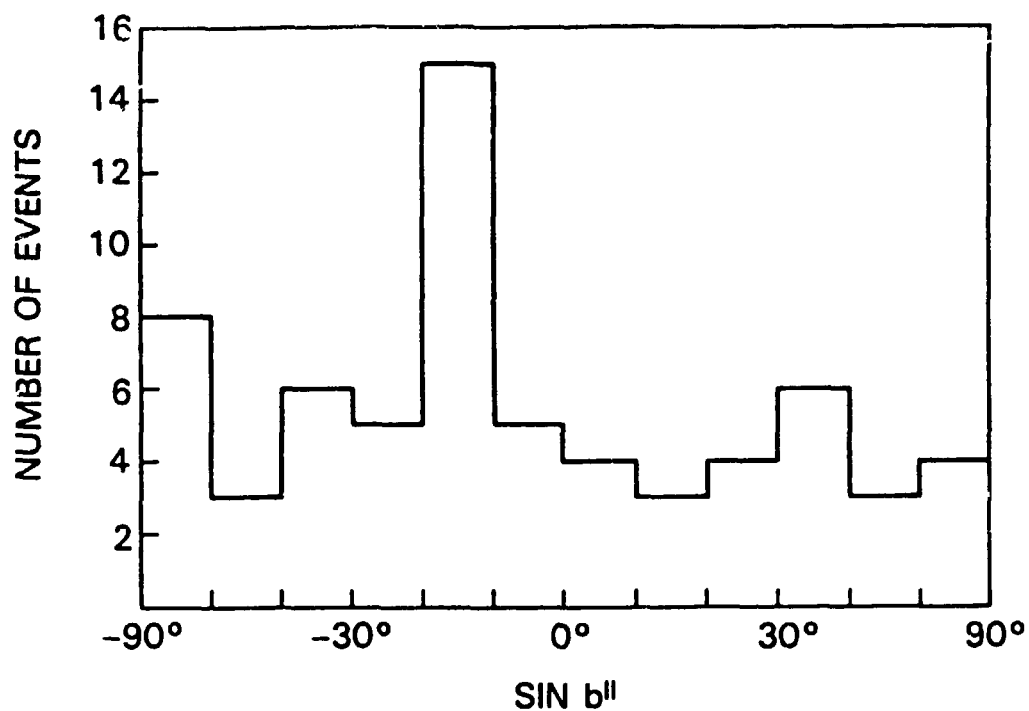


Fig. A.2. Plot of number of gamma-ray bursts (with unique localizations) versus galactic latitude. No concentration towards $b^{\text{II}} = 0^\circ$ is apparent, however, an excess appears near $b^{\text{II}} = -15^\circ$. The excess may be due to the statistics of small numbers or to a possible anisotropic response of the KONUS detector systems (Laros et al. 1982).

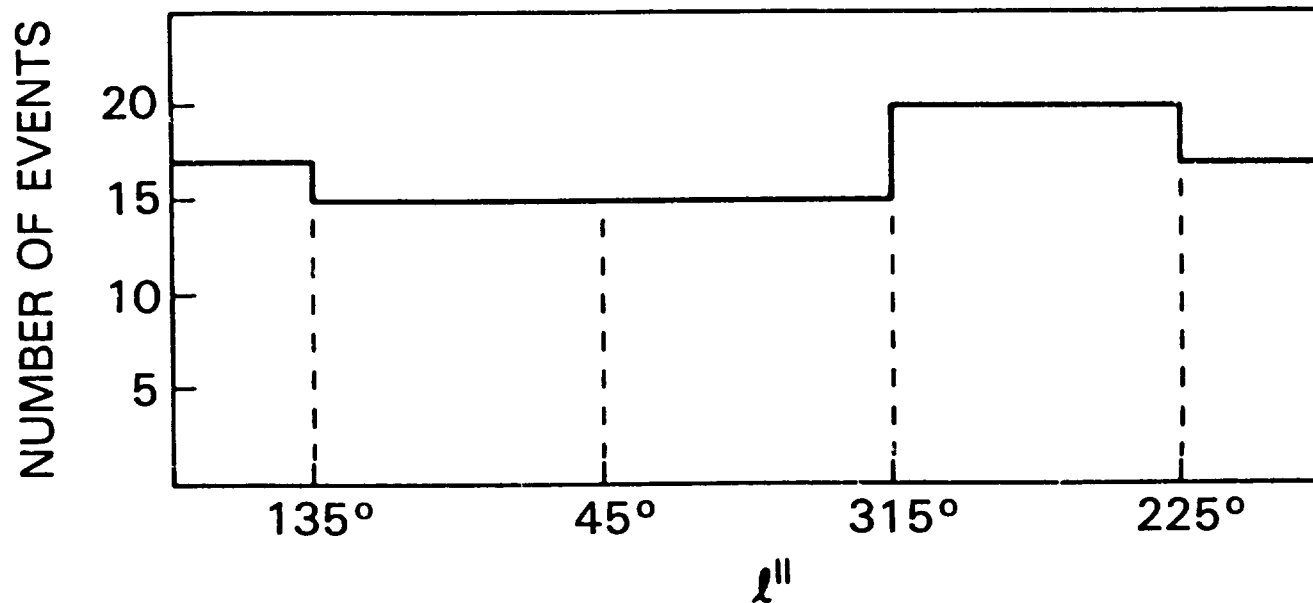


Fig. A.3. Plot of number of gamma-ray bursts (with unique localizations) versus galactic longitude. No excess is apparent in the direction of the galactic center region.

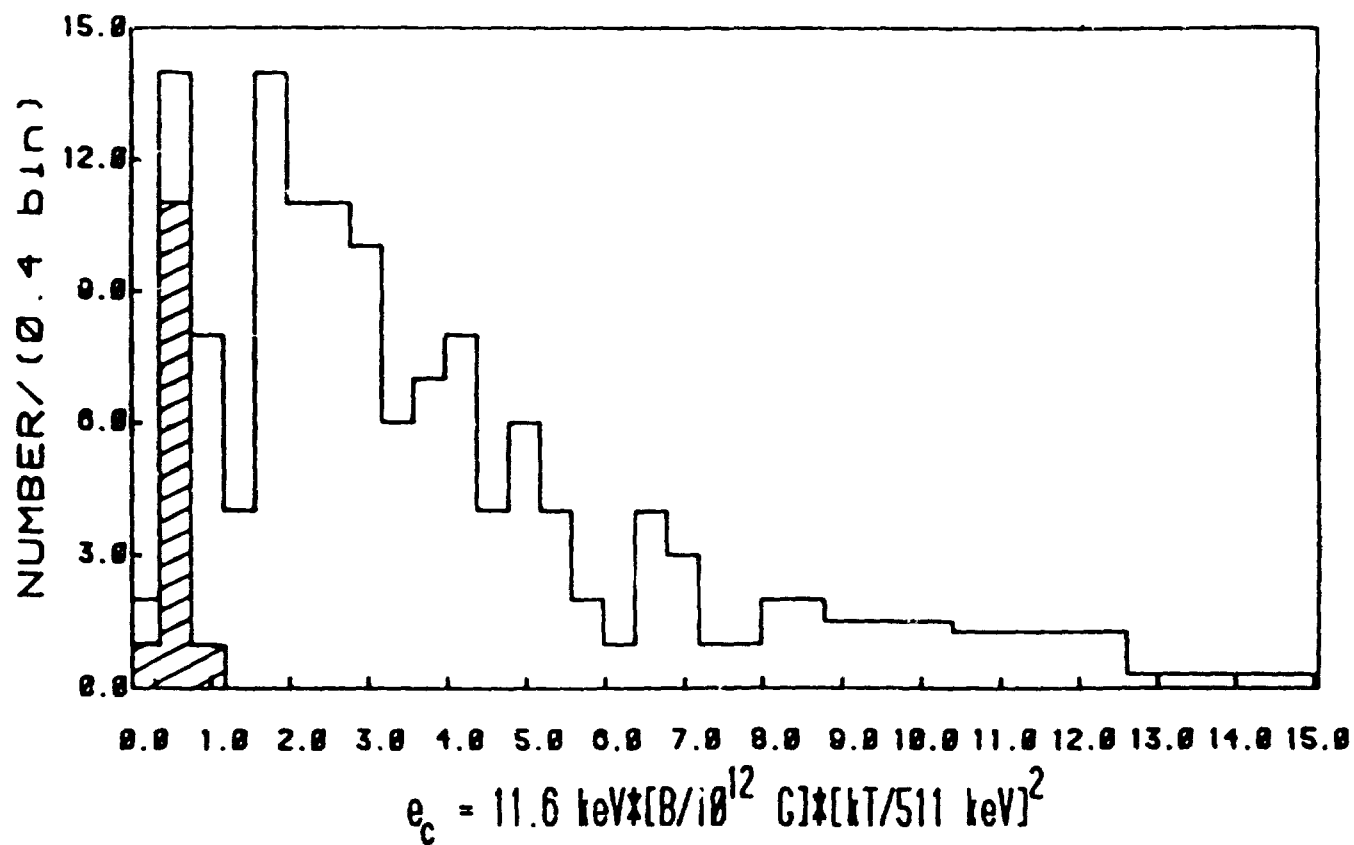


Fig. A.4. Thermal synchrotron fits for spectra from Venera 11 and 12 KONUS experiments (listed in Table A.1). Multiple spectra for a given event are included. The peak at $e_c \sim 0.6$ is almost entirely due to spike-like events (hatched area) and the spectra of later stages of "classical" gamma-ray bursts. The two repeating spike-like burst sources account for seven of the spectra.

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