INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6” x 9” black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
RICE UNIVERSITY

Analysis and Interpretation of Gamma-Ray Burst Continuum Spectral Evolution with BATSE Data

by

Anthony W. Crider

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

APPROVED, THESIS COMMITTEE:

Dr. E. P. Liang, Chairman
Professor of Space Physics & Astronomy

Dr. F. C. Michel
Professor of Space Physics & Astronomy

Dr. J. W. Freeman
Professor of Space Physics & Astronomy

Dr. D. D. Cox
Professor of Statistics

Houston, Texas
April, 1999
Abstract

Analysis and Interpretation of Gamma-Ray Burst Continuum Spectral Evolution with BATSE Data

by

Anthony W. Crider

Once a day, a flash of gamma-rays erupts somewhere in space and is detected by an international fleet of satellites. Since their first detection over a quarter century ago, these gamma-ray bursts have puzzled researchers who could not determine their distance, emission mechanism, or progenitor. Much of this confusion arose as theorists attempted to create a single model to explain what we now believe are at least two, and probably more, populations of gamma-ray transients. Within the past two years, thanks largely to the Dutch-Italian satellite BeppoSAX, astronomers discovered that bursts have multiwavelength fading afterglows. This helped them determine that most gamma-ray bursts are from distant galaxies. However, it did not answer the questions regarding the emission mechanism or the progenitor.

We place constraints on the emission mechanism by closely examining the spectral evolution of gamma-ray bursts observed by the American instrument BATSE. From a sample of 41 distinct pulses in 26 bright gamma-ray bursts, we have determined that the pulses appear to be radiatively cooling. We also studied the evolving spectral shape in 79 bursts. In particular, we found that both the range and evolution of
the spectral index below the spectral break conflict with the predictions of a popular synchrotron shock model. They instead suggest inverse Comptonization in a hybrid thermal plus nonthermal plasma as the emission mechanism.

With our Monte Carlo codes, we have begun the generation of a library of inverse Compton spectra. Using them, we have made preliminary fits to two bursts with prompt multiwavelength data. The characteristic "terrace-shaped" Compton spectrum is evident in both using BATSE data alone. This shape appears to be confirmed for the January 1, 1997 burst using BeppoSAX X-ray data and for the January 23, 1999 burst using using optical data from the ground-based robotic telescope, ROTSE. Both bursts appear to be enshrouded in a material with a high initial Thomson scattering depth $\tau_T \gtrsim 20$. Fitting with a larger, more organized library of Monte Carlo simulations will be required before precise limits can be placed on physical parameters such as the energies, masses, and densities of bursters.
Acknowledgments

I would like to begin by thanking my thesis advisor, Edison Liang, who has been a guiding figure in this research. When I first approached Edison about affiliating with him, he recommended that I study (1) black hole accretion disks, (2) soft gamma repeaters, or (3) gamma-ray bursts. While his order of preference was 1-2-3, mine was 3-2-1. I am thankful that he allowed me to follow my own interests.

I would also like to thank Ed Fenimore, who has given me invaluable career advice as long as I've known him and has always been the model scientist. Incidentally, Ed was the speaker at the first gamma-ray burst lecture I attended. Although I slept through that talk, the notes he handed out eventually led me to writing this thesis.

I must, of course, acknowledge my many collaborators in this endeavor. The team here at Rice, including Markus Böttcher, Masaaki Kusunose, Ian Smith, and Dechun Lin, were primarily responsible for the development and execution of the Monte Carlo codes used in this thesis. My University of Alabama at Huntsville and University of California at San Diego collaborators instructed me in the analysis of BATSE spectra and the statistics used in evaluating it. In particular, I greatly appreciated David Band and Michael Briggs for their valuable input into our papers and Rob Preece whose spectral catalog made this work possible. I also would like to thank my GSRP sponsor at Marshall Space Flight Center, Jerry Fishman, who gave me what few other collaborators could...funding.

I feel it is appropriate to mention the extremely useful abstract service offered by NASA’s Astrophysics Data System (http://adsabs.harvard.edu/) and the pre-print
server (http://xxx.lanl.gov/) at Los Alamos National Laboratory. I do not want to imagine trying to do science without them.

In the past four years, I have had several useful discussions which influenced my research. For the valuable input they provided, I would like to thank Chuck Dermer, Reggie Dufour, John Freeman, Robert Haymes, Andrew Lemanski, and Andrew Urquhart.

Although being in graduate school has kept me geographically distant from my family, they have remained close at heart. I would like to thank them for their loving support and encouragement.

My graduate school experience would not have been complete if if weren’t for my “SPAC family”. They are the reason I came to Rice and the reason I stayed...until I left. The heads of this household are without a doubt Maria and Umbe. Vayan con Dios. Then there are my first-year officemates (Christopher, Matt, and Parviz), second-year lunch dates (Tim and Cindy), and fifth-year “caffeinates” (Katherine, Andrea, and, again, Parviz). They laughed at all my jokes even when they weren’t funny, which is surely the truest measure of a friend.

Finally, there is my loving and Talented wife, Dana Hurley Crider. While the people above have all played a role in my graduate career, she has played all of the roles: mentor, consultant, family, and friend. There is no way I can appropriately thank her in words.
Contents

Abstract ii
Acknowledgments iv
Preface viii

1 History of Gamma-Ray Burst Studies 1

1.1 The Early Years (1969-1990) ............................................ 1
  1.1.1 General Properties of Gamma-Ray Bursts .................. 2
  1.1.2 The March 5th Event ............................................ 5
  1.1.3 Observations of Cyclotron Lines? ............................ 11
  1.1.4 The First Paradigm ............................................ 13

1.2 The Reign of BATSE (1991-1996) .................................... 15
  1.2.1 Isotropy and Inhomogeneity .................................. 15
  1.2.2 The Great Debate ............................................ 16

1.3 The Afterglow Era (1997-present) .................................. 18
  1.3.1 BeppoSAX X-ray Counterparts and Afterglow ............ 18
  1.3.2 Optical Afterglows ........................................... 20
  1.3.3 Radio and Millimeter Afterglows ......................... 22
  1.3.4 Detection of Iron Lines? .................................... 24
  1.3.5 The Current Paradigm ....................................... 27

2 Spectral Evolution of Gamma-Ray Bursts 30

2.1 Previous GRB Continuum Studies .................................. 31
  2.1.1 Description of Gamma-Ray Spectral Analysis ............ 31
  2.1.2 Earlier Attempts at Fitting GRB Spectra .................. 34
  2.1.3 Relation between Energy and Pulse Duration ........... 39

2.2 The Evolution of $E_{pk}$ as a Function of Fluence ........... 40
  2.2.1 Confirmation of $E_{pk}$-Fluence Relation ................. 42
  2.2.2 Distribution of $\Phi_0$ .................................... 52
  2.2.3 Invariance of $\Phi_0$ within Gamma-Ray Bursts .......... 53
  2.2.4 Hardness Evolution of Co-added Bursts .................. 56
2.3 The Spectral Slope Below $E_{pk}$ ................................................. 57
  2.3.1 Evolution of $\alpha$ ......................................................... 58
  2.3.2 Steepness of $\alpha$ at the Beginning of Gamma-Ray Bursts .... 64

3 Evaluating GRB Models with Time-Resolved Spectra 68
  3.1 Confronting the Synchrotron Blastwave Model ......................... 68
    3.1.1 Testing for Photoelectric Absorption ............................... 69
    3.1.2 Testing for Synchrotron Self-Absorption .......................... 71
  3.2 Saturated Inverse Comptonization ......................................... 74
    3.2.1 Monte Carlo Simulation of Inverse Comptonization ............... 77
    3.2.2 Comparison with BeppoSAX Time-Resolved Spectra ................. 79
    3.2.3 Comparison with ROTSE Time-Resolved Observations .............. 79

4 Summary and Final Remarks .................................................... 86
  4.1 Applying the Spectral Evolution Results ................................ 87
  4.2 Caveats .............................................................................. 88
  4.3 Future Projects ................................................................. 90
    4.3.1 Construction of a Library of Inverse Compton Spectra ........... 91
    4.3.2 Development of a Semi-Empirical Compton Function ............... 92
    4.3.3 Deconvolution of GRB Data with a Time-Dependent Spectral
         Function ........................................................................ 94
    4.3.4 Identification of Extragalactic SGR Outbursts ................... 94

Bibliography .............................................................................. 95
Preface

As with nearly all Ph.D. theses, the title of this one would not be readily deciphered by those whose do not have their own works with equally cryptic titles cited within. Thus I feel it warranted to explain the title in words that should most anyone comprehend.

“Gamma-Ray” - Ultraviolet light, the kind that presumably causes skin cancer, is just beyond perception by the human eye. An ultraviolet photon, or “light particle”, has a little more energy than a violet photon. Even more energetic are X rays, which pass straight through human skin, yet are blocked by human bone. Beyond X rays are gamma rays, which are energetic enough to pass through both skin and bone.

“Burst” - The universe is a very dynamic place. All of the time, collisions and explosions occur that release a tremendous amount of energy. While scientists think they understand what causes most of the bursts of light we see in the sky, such as supernova, there is still no explanation for bursts of gamma rays seen approximately once a day at random spots on the sky.

“BATSE” - The Burst and Transient Source Experiment, more commonly referred to as BATSE and pronounced bat/ˈsē is actually a set of eight instruments on board the Compton Gamma-Ray Observatory satellite. BATSE sees gamma rays and records their energy and direction. It is used primarily for studying gamma-ray bursts.

“Spectral Evolution” - Light is composed of many colors. We can also imagine that light is composed of photons with different energies. When we break light up, as is done with a prism, we see how many photons are blue, how many are green,
how many are red, and so on. With BATSE, we try to measure the energy of each gamma-ray photon. A spectrum is simply a plot which shows how many photons we find at each energy. If the color of an object changes as time passes, then the spectrum is also changing or evolving.

“Continuum” - A regular old light bulb glows white; its light is composed of many other colors. In contrast, a laser can emit a single color. Some processes in nature are like light bulbs, radiating photons with a continuum of energies, while others are more like lasers, producing photons with only a few different energies. In this thesis, I study the continuum spectra of gamma-ray bursts and how it changes with time.

“Analysis” and “Interpretation” - Many Ph. D. theses include one of these words in its title. I use both. In Chapter 2, I analyzed gamma-ray burst data, which involves writing a lot of computer code and running other people’s computer codes. In Chapter 3, I interpreted my results by showing how the other people’s models do not match what I found but my advisor’s model does.

“Data” - Lieutenant Commander Data of the U.S.S. Enterprise is my favorite character in Star Trek. Thus, I had to mention him in the title.
Chapter 1

History of Gamma-Ray Burst Studies

Approximately once a day, a bright flash of gamma-rays erupts at seemingly random positions on the sky. The flash can last anywhere from a thousandth of a second to nearly an hour. While these “gamma-ray bursts”, or GRB, have been detectable by satellites since the late 1960’s, their origin remains an enigma. Early on, scientists hypothesized that the bursts were from neutron stars within the disk of our very own Milky Way galaxy. For almost 20 years, scientists gathered data which supported this notion. The picture abruptly changed in 1991 when an American experiment, BATSE, with unprecedented sensitivity showed that the bursters must be much further away. Just how far remained a mystery for another seven years until the launch of another pioneering satellite, BeppoSAX. With its ability to quickly and accurately determine the directions of bursts, this Dutch-Italian satellite led astronomers to discover the fading “afterglows” of bursts which would finally prove that they originate near the edge of the Universe.

1.1 The Early Years (1969-1990)

Upon signing of the Limited Nuclear Test Ban Treaty, which prohibited tests of nuclear weapons in space, the United States launched a series of satellites to monitor any treaty violations. These satellites, named Vela, were equipped with X-ray, gamma-ray, and neutron detectors optimized for recording the signatures of a nuclear blast (Bonnell & Klebesadel 1996). Time differences in the onset, as measured by
the widely separated satellites, could be used to gauge the direction of the event. Transient gamma-ray sources were recorded, but from their direction it was clear that they were not from the Earth, Sun (whose flares do in fact emit gamma rays) or Moon (another possible nuclear test site), but were cosmic in origin (Klebesadel, Strong & Olsen 1973). In the years that followed, a large international effort was made to observe and explain these "gamma-ray bursts". Sadly, invalid assumptions made in the data analysis led to misleading conclusions which eventually spawned a well-developed, yet incorrect paradigm.

1.1.1 General Properties of Gamma-Ray Bursts

The time histories of gamma-ray bursts are quite varied. Some bursts are composed of one or a few single, clear pulses. Others are quite chaotic, consisting of several overlapping pulses. Examples of these GRB profiles are plotted in Figure 1.1. To the casual observer, the peaks in bursts sometimes appear to be periodic. In reality, there are very few cases where a significant periodicity is evident (Schaefer & Desai 1988).

The intense gamma-ray emission can persist for milliseconds, days, and anywhere in between. It is difficult in practice to specify the true onset and end of gamma-ray bursts owing to the finite sensitivity of any detector. Therefore, the duration of a burst is commonly reported as $T_{90}$, the interval of burst emission excluding the first and last 5% of the counts observed above background. The distribution of duration values was first suggested to be bimodal with Vela data (Cline & Desai 1974), a fact later confirmed by other instruments (Norris, Cline, Desai & Teegarden 1984, Mazets 1985, Klebesadel 1992, Kouveliotou et al. 1993). As we will discuss in Section 1.1.2,
these two populations also have different spectra. A more recent analysis has also
found evidence for a small third distribution between the two previous ones (Horváth
1998). In Figure 1.2, we plot the $T_{90}$ distribution seen in 1234 bursts from the 4B
BATSE catalog (Meegan et al. 1998), approximately 50% more bursts than were
used in Horváth (1998). (We describe the BATSE instrument in Section 2.1.1.) The
bimodal, and to a lesser extent the trimodal, nature is very clear. Fitting this data
with two log-normal distributions results in a $\chi^2(\nu = 24) = 41.3$. When we added
a third log-normal distribution the $\chi^2$ improves to 18.4. The probability that this
improvement would occur by chance is $4 \times 10^{-5}$. Alternate choices of bin size can
affect this probability, but only by about an order of magnitude.

Bright GRB are observed by BATSE to have a typical peak flux (50-300 keV) of 10
to 100 photons s$^{-1}$ cm$^{-2}$ and a fluence (50-300 keV) of $10^{-6}$ to $10^{-5}$ erg cm$^{-2}$. The
brightness distribution can be used to make statements about the burster popula-
tion. If bursters are standard candles, having the same intrinsic luminosity $L$, then in
Euclidean space as one increases the sampling volume $\frac{4}{3}\pi r^3$, the peak flux of the fur-
thest bursts drops as $L/(4\pi r^2)$. Thus, the number of bursts $N$ with a peak flux greater
than $P$ is proportional to $P^{-3/2}$. Cosmological effects degrade this proportionality at
high redshifts. Evolution of the burster population, either in density or brightness,
can also alter this relation. In Figure 1.3, we show the peak flux distributions of four
burster populations: long/hard, short/hard, short/soft, and long/soft. A summary of
our definitions for these populations appears in Table 1.1. While the long/soft and,
to a lesser extent, the short populations are consistent with the $-\frac{3}{2}$ power law, this is
clearly not the case for the long/hard bursts. With a single population of bursts and
no evolution, one would instead expect soft bursts (which would be more redshifted,
Figure 1.1  The 64-ms BATSE count rate versus time (in seconds) for 8 representative BATSE gamma-ray bursts. Both smooth and chaotic time histories are observed.
and thus further from the observer) to appear less Euclidean than hard bursts. Thus, these observations require multiple populations or strong luminosity evolution if all bursts are cosmological (Tavani 1998).

1.1.2 The March 5th Event

A critical setback in the understanding of gamma-ray bursts came from a very peculiar burst in 1979 commonly known by the date it occurred, "March 5th". This was the
Figure 1.3 The peak flux distribution for 175 short ($T_{90} < 2$ sec) bursts and 381 long ($T_{90} > 5$ sec) bursts from the BATSE 4B catalog. Refer to Table 1.1 for definitions of “hard” and “soft”. While long/soft bursts and short bursts appear to follow a Euclidean $-\frac{3}{2}$ power law, this is not true for long/hard bursts, suggesting either multiple populations or strong evolution in cosmological sources.

brightest gamma-ray transient seen until then, with the intense initial spike having a flux of $\sim 1.5 \times 10^{-3}$ ergs cm$^{-1}$ s$^{-1}$ (Fenimore, Klebesadel & Laros 1996). The large number of well-separated instruments which saw this event (Helios B, ISEE-3, PVO, Vela 5a, Vela 5b, Vela 6a, Venera 11, Venera 12, and Prognoz 7), coupled with the well-defined submillisecond risetime of the initial pulse, meant that it could be localized to a $1' \times 2'$ error box. Inside this region was the supernova remnant, N49, which is in the Large Magellanic Cloud (Evans et al. 1980). Perhaps the most intriguing aspect of
the March 5th event was a fading tail with a clear 8-second periodicity which followed the initial spike (Cline et al. 1980; Mazets & Golenetskii 1981, see Figure 1.4).

![Graph showing time history of March 5th event as seen by Venera 12](image)

**Figure 1.4** Time history of March 5th event as seen by Venera 12. The 8 second pulse/interpulse periodicity is very clear. Adapted from Mazets & Golenetskii 1981.

Much weaker sporadic eruptions were seen from this source in the days and years that followed (Golenetskii, Ilyinskii & Mazets 1984). The high-intensity, the periodicity in the tail, and the reported soft spectra seemed to distinguish this event from other gamma-ray bursts. For many years, researchers waffled over whether this event

<table>
<thead>
<tr>
<th></th>
<th>Short</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{90} &lt; 2 ) s</td>
<td>( T_{90} &gt; 5 ) s</td>
<td></td>
</tr>
<tr>
<td>Hard</td>
<td>( HR_{32} &gt; 8 )</td>
<td>( HR_{32} &gt; 4 )</td>
</tr>
<tr>
<td>Soft</td>
<td>( HR_{32} &lt; 4 )</td>
<td>( HR_{32} &lt; 2 )</td>
</tr>
</tbody>
</table>

**Table 1.1** Definitions of “hard” and “soft” for “short” and “long” bursts used in Figure 1.3. Values for \( T_{90} \) and the channel 3 to channel 2 hardness ratio \( HR_{32} \) are taken from the BATSE 4B Catalog (Meegan et al. 1998).
was an extreme example of "classical" gamma-ray burst or the prototype for some other class of objects. Eventually, three other "soft gamma repeaters" (SGR) were discovered, being identified by their soft gamma-ray spectra, their relatively weak repetitious outbursting, and in some cases their association with supernova remnants (see Table 1.2). Searching the persistent X-ray flux in the direction of SGR1806-20 during a "bunching" of its gamma-ray outbursts also revealed a significant 7.47 s periodicity (Kouveliotou et al. 1998), suggestive of the "March 5th" 8 s periodicity. Finally in August 1998, SGR1900+14 had a very intense series of outbursts, with a peak flux $P_{128 \text{ ms}}(25 - 300 \text{ keV}) = 1.1 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Hurley, Kouveliotou, Mazets & Cline 1998). The intense emission was followed by a gamma-ray tail with a 5.15 s periodicity (Hurley, Kouveliotou & Murakami 1998, Cline, Mazets & Golenetskii 1998). This finally demonstrated that the March 5th event was not unique.

These observations have been used as evidence to confirm the "magnetar" model for SGR. As a neutron star forms, if it is spinning fast enough, the convection within it will be capable of producing a very large ($10^{14-16}$ G) magnetic field. (Thomson & Duncan 1995, Thomson & Duncan 1996). The large magnetic field $B$ will in turn

<table>
<thead>
<tr>
<th>Name</th>
<th>SNR</th>
<th>Periodicity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR0525-66</td>
<td>N49</td>
<td>8</td>
<td>March 5th</td>
</tr>
<tr>
<td>SGR1900+14</td>
<td>-</td>
<td>5.15 ± 0.02</td>
<td>March 5th-like $\gamma$-ray profile</td>
</tr>
<tr>
<td>SGR1806-20</td>
<td>G10.0-0.3</td>
<td>7.47655</td>
<td>ringing in quiescent X-rays</td>
</tr>
<tr>
<td>SGR1815-13*</td>
<td>-</td>
<td>-</td>
<td>discovered June 29, 1997</td>
</tr>
<tr>
<td>SGR1627-41</td>
<td>G337.0-0.1</td>
<td>-</td>
<td>discovered June 15, 1998</td>
</tr>
</tbody>
</table>

**Table 1.2** Known soft gamma repeaters, their associated supernova remnants (SNR), and periodicities observed either in their gamma-ray outbursts or quiescent X-rays. *Contrary to its name, SGR1815-13 has not yet been confirmed as a soft gamma repeater, but is merely a candidate SGR.
radiate away the rotational energy following the dipole formula

\[
\frac{dE}{dt} = I \frac{d\Omega}{dt} = -\frac{B^2 R^8 \Omega^4 \sin^2 \theta}{6c^3}
\] (1.1)

where \(\Omega\) is the rotation frequency, \(R\) is the radius of the neutron star and \(\theta\) is the angle between the rotation and magnetic axes (Shapiro & Teukolsky 1983). Cracking on the metallic solid surface of magnetars would allegedly be responsible for SGR and March-5th like outbursts. The measurement of \(\frac{d\Omega}{dt}\) in the quiescent X-rays of SGR1806-20 suggested a \(2 \times 10^{14}\) G surface magnetic field, strongly supporting this theory as the mechanism behind SGR (Kouveliotou et al. 1998).

While the fading tail of March 5th and the recurrent weaker outbursts of SGR0526-22 had a relatively soft spectra, the spectrum of the March 5th initial spike was very much like that of classical GRB (Fenimore, Klebesadel & Laros 1996), suggesting that some GRB may actually be distant SGR. Indeed, if the March 5th event had occurred in a nearby galaxy, it would likely be mistaken for a "short/hard" GRB (see Figure 1.5). Given the intensity and distance (LMC distance = 55 kpc), we would expect March 5th-like events in other galaxies to have a peak flux \(F[\text{ph cm}^{-2} \text{s}^{-1}] = 15 \text{D}[\text{Mpc}]^{-2}\). The trigger efficiency of BATSE at a 256 ms timescale allows us to detect short bursts with a peak flux as low as \(~0.5\ \text{ph cm}^{-2} \text{s}^{-1}\) (in’ t Zand & Fenimore 1996). Thus, BATSE has likely triggered on March 5th-like events out as far as 5.5 Mpc.

Crider and Fenimore (1996) attempted to find March 5th-like events in the Pioneer Venus Orbiter (PVO) Gamma Burst Detector data. Using a simple model fit to March 5th’s tail, they generated synthetic bursts to determine if the periodicity would be detectable with PVO. A description of this model appears in Table 1.3. Scaling this
Figure 1.5  Hardness ratio versus T90 for the 4B catalog (Kouveliotou et al. 1996). Two distinct populations of gamma-ray bursters are evident, one with relatively long and soft bursts and one with shorter and harder bursts. Also plotted are the estimated hardness ratios and durations for the initial spikes of March 5th (based on PVO data; Fenimore, Klebesadel & Laros 1996) and SGR1900+14 (based on BATSE data; Hurley et al. 1999). This figure suggests that a March 5th-like event occurred in a nearby galaxy, it would be mistaken for a classical “short/hard” gamma-ray burst.
profile to 24 single-pulse PVO bursts revealed that none were bright enough for a March 5th-like tail to be visible. This has yet to be determined for the BATSE data.

1.1.3 Observations of Cyclotron Lines?

Eight years after the discovery of gamma-ray bursts, two Russian satellites (Venera 11 and 12) were reported to have seen absorption lines in 20 out of the ~ 150 bursts they had detected (Mazets et al. 1981). Most of the lines occurred in the 30-70 keV regime. Two subsequent missions, HEAO-1 (Heuter 1987) and Ginga (Murakami et al. 1988), also saw similar lines in this energy range. The lines were interpreted as cyclotron absorption in a $B = 10^{12}$ G magnetic field. Such fields exist on the surfaces of neutron stars, which at the time were already considered prime candidates for GRB production. Observations by the Ginga satellite of two lines ($19.7 \pm 0.7$ and $38.0 \pm 1.6$ keV) in GRB880205 and their subsequent interpretation as cyclotron harmonics supported this argument immensely (Fenimore et al. 1988). Given a column density of $\sim 3.6 \times 10^{22}$ electrons cm$^{-2}$ and a magnetic field of $\sim 1.7 \times 10^{12}$ G, only the first and second harmonics of the cyclotron frequency would be optically thick, explaining the absence of other lines in the spectra. These assumptions required a severe optical depth ($\tau = 98.5$) for the first harmonic, inconsistent with the relatively narrow observed equivalent width (see Figure 1.6). It was presumed that photons from re-emitted from higher levels partially “filled in” the first harmonic.

Researchers hoped that the BATSE Spectroscopy Detectors (SD) would unveil a large sample of bursts with cyclotron absorption features. However, none of BATSE’s instruments found significant evidence for lines (Palmer et al. 1994, Band et al. 1996). Simulations showed that the BATSE SD would likely detect lines in events such as
Figure 1.6 Unfolded photon spectra of GRB990205 assuming a continuum of three connected power-laws and (A) no lines, (B) two Gaussian lines, (C) cyclotron absorption lines dominated by Doppler broadening, (D) one absorption line with an emission core, and (E) H- and He-like iron absorption. Taken from Fenimore et al. 1988.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>$135.8 \pm 0.3$ counts sec$^{-1}$</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$118.5 \pm 2.0$ counts sec$^{-1}$</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>$49.5 \pm 2.5$ sec</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$70.8 \pm 3.2$ counts sec$^{-1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>$7.97 \pm 0.03$ sec</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$1.83 \pm 0.09$ rad</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>$41.3 \pm 4.8$ sec</td>
</tr>
</tbody>
</table>

Table 1.3 Fitting the function $A_0 + A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} \sin\left(\frac{2\pi t}{T} + \phi\right)$ to 512 seconds of PVO real time data (100-2000 keV) for the tail of the March 5th burst resulted in the following parameters. The effective area of the detector was 22 cm$^2$. Taken from Crider & Fenimore (1996).

GRB880205 (probability $\sim 1$) and, to a lesser extent, GRB870303 (probability $\sim \frac{1}{8}$; Band et al. 1995). The apparent discrepancy between the two instruments’ results has stirred concern in the community that either the Ginga lines were spurious or that BATSE is actually incapable of detecting lines. Still, with less than 100 BATSE bursts bright enough for a line detection to be possible, there is currently no inconsistency in the Ginga and BATSE results (Band et al. 1994). The exhaustive search for lines in 16,000 spectra from 117 BATSE bursts recently uncovered 12 significant ($Q = 5 \times 10^{-5}$ to $1 \times 10^{-7}$) spectral “features” (Briggs et al. 1998). These have not yet been conclusively identified as “lines”, however.

1.1.4 The First Paradigm

Prior to the launch of BATSE in 1991, the combined sample of bursts seen from several less sensitive instruments appeared to be isotropic in our sky, coming from no preferential direction (Hurley 1992b). At the time, this suggested that these bursts originated at one of four distance scales:
**Very Near** - Bursts from the Oort Cloud, a sphere of comets surrounding our solar system, could explain the observed isotropy, although at the time there were no known objects at this distance capable of producing intense gamma-ray emission.

**Near** - If bursters were within the disk of our Galaxy and were sufficiently weak, then they would seem to be isotropic when observed with the relatively insensitive pre-BATSE gamma-ray telescopes.

**Far** - A population of neutron stars in the "extended halo" of our Galaxy would also be consistent with some degree of isotropy. However, the closest bursts would have to be at least several kiloparsecs away given the Earth’s offset of ~ 8.5 kpc from the Galactic center and the typical burster would have to be ~ 100 kpc away. When this was first proposed, there were no known progenitors at this distance.

**Very Far** - Bursters in other galaxies could easily explain the observed isotropy. However, the estimated energy required to produce the observed intensities (\( \gtrsim 10^{51} \) ergs in gamma rays alone) was "unpalatable" (Michel 1991)

The most popular belief in 1990 was that bursts originated from nearby magnetized neutron stars within the disk of our Galaxy (see Ho, Epstein & Fenimore 1992 for several examples). This framework seemed logical for several reasons. The March 5th event had convincingly shown that magnetic neutron stars were capable of producing intense gamma-ray outbursts. The many reports of cyclotron lines also meshed well with this model. It was assumed that the limited sensitivity of the pre-BATSE instruments kept them from seeing beyond the disk (see Figure 1.7). Thus,
the early observations of isotropy and homogeneity in burst positions were presumed to be dominated by selection effects. From the dearth of faint bursts seen by its balloon-borne prototype (Meegan et al. 1984), astronomers predicted that BATSE would see more faint bursts in the plane of the Galaxy and fewer towards the poles (see Hurley 1992a for a counter-example).


The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO) radically changed our view of gamma-ray bursts. Its observations of isotropy and inhomogeneity in bursts discredited the Galactic disk model and challenged theorists to develop a new burster paradigm.

1.2.1 Isotropy and Inhomogeneity

The anisotropy scientists expected to see with BATSE never emerged. Instead, BATSE found that bursts were both isotropic and inhomogeneous (Meegan et al. 1992). If bursts were within the Galactic disk as was expected, they should appear either isotropic and homogeneous (if BATSE is only sampling within the disk) or nonisotropic and inhomogeneous (if BATSE sees beyond the disk). An illustration of these two scenarios appears in Figure 1.7. Thus, the Galactic disk population of "near" bursters was incorrect. It was also quickly determined that a "very near" Oort cloud population was too anisotropic (Maoz 1993) and sparse (Clarke, Blaes & Tremaine 1994) to produce BATSE gamma-ray bursts. The remaining two populations, the "far" extended Galactic halo and the "very far" cosmological sources, were the subject of great debate for several years.
Figure 1.7 Cartoon of two possible BATSE sampling depths for sources within the Galactic disk. If gamma-ray bursts were in the Galactic disk and were faint enough so that BATSE could not sample beyond the disk (left grey circle), bursts would appear isotropic and homogeneous. If BATSE could sample beyond the Galactic disk (right grey circle), more bursts would be seen in the Galactic plane then toward the Galactic poles and there would be relatively fewer faint bursts. In reality, BATSE bursts are isotropic and inhomogeneous, ruling out models in which bursters are Galactic.

1.2.2 The Great Debate

In the spirit of the historic 1920 Curtis-Shapley debate regarding the scale of the universe, the supporters of the extended halo and cosmological scenarios met at Smithsonian’s Museum of Natural History in April 1995. Don Q. Lamb of the University of Chicago defended the hypothesis that gamma-ray bursters were part of an extended halo (about 100 kiloparsecs away or one sixth the distance to the Andromeda galaxy) surrounding our Galaxy (Lamb 1995). The extended halo should not be confused with the Galaxy’s halo, which is a relatively well understood region. This extended halo model was controversial in that no population of sources has been directly observed at this distance scale. Lamb argued that high-velocity neutron stars seen emerging from supernova remnants should escape the Galaxy to form an extended halo population (Bulik & Lamb 1995). Given the strong evidence
that neutron stars are capable of producing bursts of gamma-rays (i.e. March 5th and the other SGR), it was logical to credit classical gamma-ray bursts to neutron stars. However, an extended halo burster population would be inconsistent with the homogeneity seen in very bright bursts detected by Pioneer Venus Orbiter and the isotropy seen by BATSE unless one assumed ad hoc “delayed turn-on” or beaming aligned with the neutron star recoil velocity (Li, Duncan & Thompson 1994). In addition, the methodology for determining neutron star proper velocities was still in development (Lyne & Lorimer 1994); the existence of an extended halo neutron star population was tentative.

The second, more popular, scenario, defended by Bohdan Paczyński of Princeton University, involved a population of bursters at cosmological distances (Paczyński 1995). Paczyński argued that all known astronomical populations observed to be isotropic and inhomogeneous were cosmological in origin. Thus, by Occam’s razor, so too were gamma-ray bursts. Bursts originating so far away imply an energy release of approximately $\Omega \times 10^{51}$ ergs, where $\Omega$ is the emission cone ($\Omega = 4\pi$ for isotropic emission). This is approximately the binding energy of a neutron star (NS) and many modelers assumed a NS-NS collision as the energy source. Obviously, less energy would be required in the event of beaming ($\Omega < 4\pi$). However, there is currently little evidence for beaming in bursts (Rhoades 1997, Grindlay 1998; see Kulkarni 1999 for a counterexample). Paczyński dismissed critics of the “astronomical” energy requirements countering that astronomers should be comfortable with such numbers.
1.3 The Afterglow Era (1997-present)

The Italian satellite BeppoSAX, launched in 1996, made it possible to determine the direction of some bursts to within 50 arcseconds in a matter of hours (see Piro et al. 1997 and Frontera et al. 1998 and references therein). It does so by looking for bursts in the X-ray band (1.5 - 26 keV) with two wide-field cameras, each covering an effective $20^\circ \times 20^\circ$ field of view. While this instrument can only detect a few bursts per year, the radius of the $3\sigma$ error region for each burst is only 3 arcminutes, 200 times less than the systematic error in bright BATSE bursts (Graziani & Lamb 1996). Figure 1.8 demonstrates the difference in precision of the two instruments. By pointing the narrow-field instruments aboard SAX toward a burst about 8 hours later, scientists discovered a slowly fading X-tail afterglow, which further pinpointed the event to within 50 arcseconds. Astronomers then searched these prompt, accurate confidence regions with ground-based telescopes and found optical and radio counterparts to the afterglow, ushering in a new era of GRB studies.

1.3.1 BeppoSAX X-ray Counterparts and Afterglow

Using its Narrow Field Instruments, BeppoSAX has found that most of the gamma-ray bursts seen with the Wide Field Camera are followed by a X-ray afterglow. The afterglow flux typically fades slowly ($F \propto t^{-1-\epsilon}$) where $\epsilon$ is typically between 0.1 to 0.35. In Table 1.4, we list bursts which have been well-localized using either the BeppoSAX Wide Field Camera or the Rossi X-ray Timing Explorer’s All Sky Monitor. In some cases, the Interplanetary Network allows improvement of the location.
Figure 1.8 Angular radius of the smallest BATSE error region ($r_{1\sigma, \text{sys}} = 3.7^\circ$) and the average angular diameter of the Moon as seen from Earth ($d \approx 0.518^\circ$). Also shown in the enlarged box are the angular radii of the typical BeppoSAX Wide Field Camera ($r_{3\sigma} \approx 3^\prime$) and Narrow Field Instruments ($r_{90\%} = 50^\prime$) GRB location errors, as well as the Hubble Space Telescope WFPC2 field-of-view (150$''$ × 150$''$).
<table>
<thead>
<tr>
<th>Burst</th>
<th>R.A.</th>
<th>Dec.</th>
<th>Error</th>
<th>Instrument</th>
<th>IPN</th>
<th>XA</th>
<th>OT</th>
<th>RA</th>
<th>IAUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>960720</td>
<td>17h 30' 37&quot; 49' 5.8</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>n</td>
<td>n</td>
<td>6467, 6569</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>970111</td>
<td>15h 28' 15&quot; 19' 36.3</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>6533, 6569</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970228</td>
<td>5h 1' 57&quot; 11' 46.4</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6572</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970402</td>
<td>14h 50' 16&quot; 69' 19.9</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>n</td>
<td>6610</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>970508</td>
<td>6h 53' 28&quot; 70' 17.4</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6649, 6654</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970616</td>
<td>1h 18' 57&quot; -5' 28.0</td>
<td>40' x 2'</td>
<td>XTE/Uly</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>6683, 6687</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970815</td>
<td>16h 8' 43&quot; 81' 30.6</td>
<td>6' x 3'</td>
<td>XTE/ASM</td>
<td>y</td>
<td>n</td>
<td>6718</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>970828</td>
<td>18h 8' 29&quot; 59' 18.0</td>
<td>2.5' x 1'</td>
<td>XTE/ASM</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>6726, 6728</td>
<td></td>
<td></td>
</tr>
<tr>
<td>971024</td>
<td>18h 24' 51&quot; 49' 28.9</td>
<td>9.0' x 1'</td>
<td>XTE/ASM</td>
<td>y</td>
<td>n</td>
<td>priv. comm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>971214</td>
<td>11h 56' 30&quot; 65' 12.0</td>
<td>4'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6787, 6789</td>
<td></td>
<td></td>
</tr>
<tr>
<td>971227</td>
<td>12h 57&quot; 35&quot; 59' 15.4</td>
<td>8'</td>
<td>SAX/WFC</td>
<td>y?</td>
<td>?</td>
<td>6796</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>980109</td>
<td>0h 25' 56&quot;-63' 1.4</td>
<td>10'</td>
<td>SAX/WFC</td>
<td>n</td>
<td>n</td>
<td>6805</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>980326</td>
<td>8h 36' 26&quot;-18' 53.0</td>
<td>8'</td>
<td>SAX/WFC</td>
<td>y?</td>
<td>?</td>
<td>6851</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>980329</td>
<td>7h 2' 41&quot; 38' 50.7</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6853</td>
<td></td>
<td></td>
</tr>
<tr>
<td>980425</td>
<td>19h 34' 54&quot;-52' 49.9</td>
<td>8'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>SN?</td>
<td>y</td>
<td>6884</td>
<td></td>
<td></td>
</tr>
<tr>
<td>980515</td>
<td>21h 18' 4&quot; 67' 14.9</td>
<td>5'</td>
<td>SAX/WFC</td>
<td>?</td>
<td>?</td>
<td>6909</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>980519</td>
<td>23h 22' 14&quot; 77' 15.3</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6910</td>
<td></td>
<td></td>
</tr>
<tr>
<td>980613</td>
<td>10h 17' 46&quot; 71' 29.9</td>
<td>4'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>6938</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>980703</td>
<td>23h 59' 7&quot; 8' 35.6</td>
<td>4'</td>
<td>XTE/ASM</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>6966</td>
<td></td>
<td></td>
</tr>
<tr>
<td>981220</td>
<td>3h 42' 34&quot; 17' 9.0</td>
<td>2' x 4.5'</td>
<td>ASM/Uly</td>
<td>y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>981226</td>
<td>23h 29' 40&quot;-23' 55.0</td>
<td>6'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>?</td>
<td>7074</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>990123</td>
<td>15h 25' 29&quot; 44' 45.0</td>
<td>2'</td>
<td>SAX/WFC</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>7095</td>
<td></td>
<td></td>
</tr>
<tr>
<td>990217</td>
<td>3h 2' 52&quot;-53' 6.0</td>
<td>3'</td>
<td>SAX/WFC</td>
<td>n</td>
<td>n</td>
<td>7110</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.4 Gamma-ray bursts with multiwavelength counterparts. Adapted from the WWW pages of Jochen Greiner. The columns indicate the burst name, its location, the observing instruments, whether or not it was seen by the Interplanetary Network (IPN) the existence of an X-ray afterglow (XA), optical transient (OT), and radio afterglow (RA), the discovery IAU Circular number (IAUC). Refer to http://www.aip.de:8080/~jcg/egrbgen.html for a more up-to-date version of this table.

1.3.2 Optical Afterglows

The rapid, precise BeppoSAX error boxes opened the door to ground-based searches for optical transients. The third burst seen by BeppoSAX, GRB970228, was observed 20.8 hours after the burst to have an optical magnitude \( V = 21.3 \) (van Paradijs et al. 1997). Further measurements showed that the optical afterglow was fading at the roughly same rate as the X-ray afterglow. Images from Hubble revealed that
the burst was on the fringe of a "fuzzy" region. Immediately, the supporters of the cosmological paradigm touted this as the host galaxy of the burster. However, spectra from Keck II found no evidence for emission or absorption lines to support this in either the transient or the nebulous "fuzz" (see Figure 1.9).

Figure 1.9  Gamma-ray burst candidate host galaxies observed by the STIS instrument on the Hubble Space Telescope. The optical counterparts of both GRB970228 and GRB990123 are clearly offset from the centers of their candidate host galaxies. The dwarf host galaxy of GRB970508 is not visible in this image due to the magnitude of the optical transient.
The cosmological camp would find vindication in the next BeppoSAX burst, GRB970508. Its optical counterpart had a measurable redshift and finally settled the long-standing question regarding the distance to these objects. Emission (one [O II] line) and absorption (five Fe II lines, four Mg II lines, one Mg I line) features confined it to a redshift of $0.835 \leq z \leq 2.3$ (Metzger et al. 1997). This minimum distance of 4 gigaparsecs (assuming $H_0 = 65 \text{ km s}^{-1} \text{ megaparsec}^{-1}$) and the observed gamma-ray flux imply that at least $7 \times 10^{51} \text{ ergs}$ was released in gamma rays, assuming isotropic emission. As the transient faded, a coincident dwarf galaxy emerged; its presence had already been inferred from the [O II] emission line.

Subsequent observations have measured redshifts to more bursts, some as high as $z=3.42$. These appear in Table 1.5. It is important to note that only GRB970508 and GRB990123 showed evidence for redshifted lines \textit{in the optical transient}. The rest of the values are determined from lines in the coincident galaxies. Given the current poor understanding about the density of these distant, faint galaxies, it may be unwise to assume that these bursters are associated with the galaxies.

1.3.3 Radio and Millimeter Afterglows

Observations of radio afterglows GRB provide even more information about the nature of the emitter. The first gamma-ray burst with a radio counterpart, GRB970508, exhibited a rapidly changing $300 - 1300 \mu\text{Jy}$ flux at 8.46 GHz. After three weeks, the variations damped to a range of 400 to 800 $\mu\text{Jy}$ (Frail et al. 1997). The fluctuations were interpreted as interstellar scattering from an inhomogeneous medium of free electrons (Goodman 1997). Refractive scintillation occurs as the GRB flux passes through a turbulent interstellar medium and is independent of wavelength. Diffractive
<table>
<thead>
<tr>
<th>Burst</th>
<th>Redshift</th>
<th>Emission Lines</th>
<th>Absorption Lines</th>
<th>Source</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>970508</td>
<td>0.835</td>
<td></td>
<td>5 Fe II</td>
<td>OT</td>
<td>Metzger et al. 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[O II]</td>
<td>4 Mg II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Ne III]</td>
<td>Mg I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>971214</td>
<td>3.42</td>
<td>Lα</td>
<td>CG</td>
<td></td>
<td>Bloom et al. 1998</td>
</tr>
<tr>
<td>980703</td>
<td>0.966</td>
<td>[O II]</td>
<td>5 Fe II</td>
<td>CG</td>
<td>Djorgovski et al. 1999b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[O III]</td>
<td>2 Mg II</td>
<td></td>
<td>Djorgovski et al. 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hδ</td>
<td>Mg I</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hγ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hβ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>990123</td>
<td>1.600</td>
<td></td>
<td>5 Fe II</td>
<td>OT</td>
<td>Kelson et al. 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 Mg II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mg I</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si II</td>
<td></td>
<td>Hjorth et al. 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C IV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Al II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 Zn II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fe II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Al III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.286</td>
<td>[O II]</td>
<td></td>
<td>5 Fe II</td>
<td>CG</td>
<td>Djorgovski et al. 1999a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 Mg II</td>
<td></td>
<td>Hjorth et al. 1999</td>
</tr>
<tr>
<td>0.210</td>
<td>[O II]</td>
<td></td>
<td>Ca H &amp; K</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ca K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.5 Bursts with reported redshifts. Lines are seen in either the optical transient (OT) or coincident galaxy (CG).
scintillation results from the interference of photons which traveled different paths en route to the observer and can vary by the magnitude of the average flux. Using "standard assumptions" for the interstellar scattering, the candidate GRB counterpart should have an angular size less than 3 microarcseconds (Frail et al. 1997). Assuming $H_0 = 60 \text{ km s}^{-1} \text{Mpc}^{-1}$ and a distance of $10^{28} \text{ cm}$ (from $z=0.835$), the linear source size would be less than $10^{17} \text{ cm}$, about a tenth of a lightyear. Other candidate radio counterparts have since been observed to have similar dampenings of their fluctuations (Taylor et al. 1998).

The multiwavelength (X-ray, optical, and radio) afterglow spectrum of GRB970508 12.1 days after the burst is consistent with the synchrotron spectrum (Galama et al. 1998) which is well-described by four power-laws (Sari, Piran & Narayan 1998). It should be noted that the radio counterpart may not be related to the gamma-ray burst at all. The mean flux level at 4.86 GHz and 8.46 GHz was roughly constant for the duration of the observations. Only the 1.43 GHz signal shows significant variation, with an increase in flux occurring about two months after the burst. The source is presumed to be related to the GRB only after elimination of most conventional extragalactic radio sources (Taylor, Frail, Beasely, & Kulkarni 1997). Still, the abundance of radio transients at this level is poorly understood, a fact evident by the many false identifications of radio counterparts to previous GRB (Frail, private communication).

1.3.4 Detection of Iron Lines?

While observations of most afterglows have been consistent with a simple power-law decay $F \propto t^{-(1+c)}$, one notable exception is GRB970508. Approximately one day after
Figure 1.10 The time-varying flux of the radio source associated with GRB970508. Measurements taken with the VLA (filled circles) were centered at 8.46 GHz and measurements using the VLBA (open squares) at 8.41 GHz flux are in agreement during simultaneous measurements. The early variability in the flux is attributed to interstellar scattering whose effect is diminished once the radio source grows to an angular size of 3 microarcseconds. Adapted from Frail et al. (1997) and Taylor, Frail, Beasley, & Kulkarni (1997)

this gamma-ray burst triggered, its X-ray flux (2-10 keV) began to increase. During the observations made just prior to the swelling X-ray flux, the BeppoSAX team found evidence for an emission line (Piro et al. 1999). The position of this line (3.4 ± 0.3 keV) is consistent with Fe Kα emission at the redshift (z=0.835) of the host galaxy (Bloom, Djorgovski, Kulkarni & Frail 1998, Metzger et al. 1997). Figure 1.11 shows
the decay of the X-ray afterglow. Also plotted are the spectra both before and after the onset of the late-time X-ray outburst.

![Graph showing the X-ray afterglow time history of GRB970508 and the spectra immediately before and after the late surge in X-ray. Figures adapted from Piro et al. (1998) and Piro et al. (1999). BeppoSAX WFC (stars) and LECS/MECS (squares) observations of the X-ray prompt emission and afterglow. Dashed line represents an extrapolation from the decay observed immediately after the burst with the BeppoSAX WFC (Piro et al. 1998).]

**Figure 1.11** The X-ray (2-10 keV) afterglow time history of GRB970508 and the spectra immediately before and after the late surge in X-ray. Figures adapted from Piro et al. (1998) and Piro et al. (1999). BeppoSAX WFC (stars) and LECS/MECS (squares) observations of the X-ray prompt emission and afterglow. Dashed line represents an extrapolation from the decay observed immediately after the burst with the BeppoSAX WFC (Piro et al. 1998).

Curiously, this line disappeared just as the flux began to rise. This is suggestive of anisotropic circumburst material (e.g. a torus) which is ionized by the approaching photons shortly before being struck by the relativistic blastwave (Böttcher 1999).
Based on the required density ($\sim 10^9$ cm$^{-3}$) to produce the observed line, Piro et al. (1999) rule out normal ISM and stellar winds and conclude that the line-emitting material must have been pre-ejected from the burster. However, the relatively weak confidence in this line (F-test giving only 97% confidence in the line, 99.3% confidence if the line is known to be redshifted Fe K$_\alpha$; Piro et al. 1999) and the fact that only two afterglows have shown a hint of such a line (ASCA has reported a $5.04^{+0.23}_{-0.33}$ line in GRB970828 suggesting $z=0.33$; Yoshida 1998) makes conclusions drawn from this feature as questionable as those based on the cyclotron lines from a decade ago.

1.3.5 The Current Paradigm

If $\sim 10^{51}$ ergs of gamma rays were released into the small region dictated by the observed millisecond variability in some bursts, pair production would inevitably occur. The optical depth due to pair production in this region would be

$$\tau_{\gamma\gamma} = \frac{f_\gamma E_{\gamma}}{R^2 m_e c^2} \approx 10^{19} \frac{f_\gamma E_{51}}{R^2_7}$$  \hspace{1cm} (1.2)

where $f_\gamma$ is the fraction of photons with $h\nu > 2m_ec^2$, $E_{51}$ is the initial energy release in units of $10^{51}$ ergs, and $R_7$ is the radius in which the energy is injected in units of $10^7$ cm (Piran 1994). If $f_\gamma$ were non-negligible, the plasma would become optically thick, preventing observers from seeing the original radiation released by the burster. Observations of gamma-ray bursts by the EGRET instrument (20 MeV to 30 GeV) aboard CGRO, however, are consistent with all bursts having a high-energy component above $2m_ec^2$. To avoid this apparent contradiction, one must assume that the sources of CRB have a bulk relativistic motion (Baring & Harding 1996) or that the gamma rays are narrowly beamed.
In an early proposed scenario (Goodman 1986), a relativistically expanding fireball begins radiating once it is large and cool enough to be optically thin. Unfortunately, the quasi-thermal spectrum predicted for a pure radiation fireball does not match observed spectra. To overcome this, some theorists assume the fireball is contaminated with baryonic matter. The kinetic energy of the “polluting” baryons could then be released some distance from the original explosion via synchrotron shocks (Mészáros & Rees 1993). External shocks would arise when the blast wave interacts with surrounding material such as the interstellar medium or nearby starfields. However, as we will describe in Section 3.1, there are many geometric limitations on external shock models which prevent them from being able to reproduce the observed bursts of gamma-rays.

External shocks can explain the X-ray, optical, and radio afterglows of GRBs. The fading multiwavelength tails of GRB970228 and GRB970508, two of the bursts well-localized by BeppoSAX, are consistent with the external shock model, assuming that GRB970228 is surrounded by a uniform medium and GRB970508 is surrounded by a medium with a density dropping off as $r^{-2}$ (Vietri 1997).

Given the success of the blastwave model in explaining the GRB afterglow but its failure to match the observed prompt emission, theorists invoked “internal shocks”. Internal shocks are presumed to appear within the fireball as a fast shell overtakes a slower shell. While the colliding shells in internal shocks would be relativistic, the shock interface does not need to be relativistic, since the shells may have comparable bulk Lorentz factors. Internal shocks are currently not known to suffer from timing or geometric constraints as external shocks do. In fact, the internal shock model should
be able to explain nearly any gamma-ray burst time profile, since they largely reflect the emission of an arbitrary central engine (Kobayashi, Piran & Sari 1997).

A reverse shock into expanding fireball is also anticipated and should have a lower temperature. With a total energy comparable to the forward external shock, this reverse shock was predicted to produce a prompt optical transient completely separate from the prompt gamma rays (Sari & Piran 1999b). While a prompt optical transient was discovered shortly after this prediction was made (Akerlof et al. 1999), it is more likely associated with the prompt gamma-ray emission as we will discuss in Section 3.2.3.
Chapter 2

Spectral Evolution of Gamma-Ray Bursts

Like so many other aspects of gamma-ray bursts, the continuum spectra has been a source of puzzlement to researchers. The earliest works assumed that optically-thin thermal bremsstrahlung was the underlying continuum. Since the choice of function used in processing GRB spectra affects the determined incident flux, incorrect assumptions about the shape of the continuum led to erroneous line identifications. When it was realized that many physical models were consistent with the spectra, scientists shifted to using unbiased empirical functions to deconvolve the data.

It was shown very early on that GRB spectra vary with time. In general, studies of GRB spectral evolution focused on the color or "hardness" of bursts which was found to follow either a "hard-to-soft" trend (Norris et al. 1986), decreasing monotonically while the flux rises and falls, or to "track" the flux during GRB pulses (Golenetskii et al. 1983, Kargatis et al. 1994). Unfortunately, these early conclusions about the evolution were highly dependent on the choice of binning. Due to the limited sensitivity, one could analyze either high-resolution flux profiles calculated from large energy bins or high-resolution spectra from large time bins. Quantitative descriptions of the hardness evolution eluded the community until BATSE provided bursts with both moderately good time and spectral resolution. Since then, it has been found that the duration of GRB pulses is directly related to the energy band they are observed in; a pulse appears to last longer at longer wavelengths. It has also been reported that the hardness of GRB pulses decays as if the burst is radiatively cooling and that
the rate of decay does not change from pulse to pulse within a burst, suggesting a single plasma is responsible for all the pulses within a burst. We rigorously test this conclusion and find it that it is only partially true. While GRB pulses act as if they are radiatively cooling, the apparent invariance of the decay rate is unsubstantiated. We also examine the time-resolved spectral shape of BATSE bursts, particularly the slope below the spectral break. Many GRB models make predictions about the value of this slope, as we will discuss in Chapter 4. By finding the maximum value of this slope, we can place severe restrictions on a number of models. The evolution of this parameter also gives us hints about the physics behind the prompt gamma-ray emission.

2.1 Previous GRB Continuum Studies

2.1.1 Description of Gamma-Ray Spectral Analysis

Before beginning analysis of GRB spectra, it is important to have at least a rudimentary understanding of our gamma-ray telescope. The BATSE Large Area Detectors follow the classic design of the early balloon-borne gamma-ray telescopes. A circular slab (diameter = 20 in, thickness = 0.5 in) of sodium iodide crystal laced with thallium, NaI(Tl), is the principal component. The large radius-to-thickness ratio of the crystal scintillator gives the telescope a cosine angular response function. The BATSE Spectroscopy Detectors (SD) are smaller (diameter = 5 in, thickness = 3 in), designed with a higher spectral resolution to search for lines similar to those seen by Ginga (see Section 1.1.3). A schematic of one out of the eight BATSE modules on CGRO appears in Figure 2.1.
Figure 2.1 Schematic of one Burst and Transient Source Experiment detector module. There are eight such modules on the Compton Gamma-Ray Observatory. Both the Large Area Detector and the smaller Spectroscopy Detector are visible.

While the LAD and SD are different in size and purpose, the physics of both detectors is the same. Gamma rays can interact with the NaI(Tl) slab via three processes: the photoelectric effect, the Compton effect, and pair production (see Figure 2.2). In the photoelectric effect, a gamma-ray photon with energy $E_{\gamma}$ frees an electron with energy $E_e = E_{\gamma} - E_b$, where $E_b$ is the binding energy. Through the
Compton effect, a photon scatters off of an electron and imparts on it

$$\Delta E_e = E_\gamma (1 - [1 + \frac{E_\gamma}{m_e c^2 (1 - \cos \theta)}]^{-1})$$

Pair production occurs in the Coulomb field of the nucleus only if $E_\gamma > 2m_e c^2$. Through these three mechanisms, some fraction of the incident gamma-ray photon energy is absorbed through excitation of the NaI valence electrons. As these de-excite, they emit $\sim 8$ eV UV photons which in turn excite the ground state Tl electrons. Optical photons emerge as the Tl electrons return to the ground state. A photomultiplier tube behind the NaI(Tl) slab detects this optical emission and from the pulse height infers the energy lost by the incident gamma-ray photon as it passed through or was absorbed by the crystal. This information is digitized and transmitted to the ground station for further processing. Of course, the means by which this is accomplished is more complicated. For a more complete description of scintillator physics and construction, refer to Rodnyi (1997).

Since only the energy lost by the gamma-ray photon is measured, the count spectra observed does not directly correspond to the incident photon spectra. In addition, gamma rays scattered off the Earth’s atmosphere and back to the telescope must also be corrected for. Thus, observations of any astronomical gamma-ray source are altered by a “detector response matrix” (DRM). To determine the incident flux, one must assume some parametric spectral function, computationally convolve it with the DRM, and compare the simulated to the observed count spectra using a statistic such as $\chi^2$. By searching the parameter space of the spectral function, one can minimize $\chi^2$ and thus fit the spectral function to the data. If one assumes a poor model, the fit and its subsequent interpretation may be misleading. Many spectral functions may be equally consistent with the data, as well, further complicating the interpretation.
Figure 2.2  Linear absorption coefficient $\mu \equiv n_e \sigma_e / Z$ for NaI(Tl) as a function of the incident gamma-ray energy for (1) photoelectric effect, (2) Compton effect, and (3) pair production. (Adapted from Rodnyi 1997)

2.1.2  Earlier Attempts at Fitting GRB Spectra

Very early studies of GRB spectra commonly assumed an optically-thin thermal bremsstrahlung (OTTB) continuum (Rybicki & Lightman 1979). Bremsstrahlung radiation is produced when a charge is accelerated in a Coulomb field of another charge. The emission from an isothermal plasma is

$$\frac{dW}{d\omega \ dV \ dt} = \frac{16\pi e^6}{3\sqrt{3}c^3 m_e^2v}n_e n_i Z^2 g_{ff}(v, \omega)$$  (2.2)
where $g_{\text{ff}}$ is the Gaunt factor, typically of order unity. If the plasma has a Maxwellian velocity distribution, we find (in erg s$^{-1}$ cm$^{-3}$ Hz$^{-1}$)

$$\frac{dW}{d\omega \, dV \, dt} = 6.8 \times 10^{-38} n_e n_i Z^2 T^{-1/2} e^{-h\nu/kT} g_{\text{ff}}$$  \hspace{1cm} (2.3)$$

where $g_{\text{ff}}$ is the averaged Gaunt factor, also of order unity. Refer to Section 5.2 of Rybicki & Lightman (1979) and references therein for more precise values of the Gaunt factor and the average Gaunt factor. Casting Equation 2.3 in the more conventional photon spectra form used in gamma-ray astronomy, we have

$$\frac{dN}{dE} = A \left( \frac{E}{100 \ \text{keV}} \right)^{-1} \exp\left( -\frac{E}{kT} \right)$$  \hspace{1cm} (2.4)$$

where $E$ is the photon energy, $kT$ is the temperature of the plasma, and $A$ is the amplitude of the photon spectra (in units photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$). This was widely used (with $g_{\text{ff}} = 1$) by the Leningrad group responsible for the KONUS GRB instruments aboard Venera 11 and 12. Any deviations from this shape were interpreted by them as broad absorption (30-70 keV) or emission (400-460 keV) lines (Mazets et al. 1981). Dividing GRB781119 into 5 second intervals revealed that both line features appeared strong early in the burst and diminished as the burst progressed (see Figure 2.3). In Chapter 4, we will show evidence for a similar morphological behavior in BATSE bursts which we interpret instead as evidence for saturated Comptonization.

In the early 1980's, motivated by the relative inefficiency of thermal bremsstrahlung as a radiative process, researchers turned to thermal synchrotron (Liang, Jernigan & Rodrigues 1983) or inverse Comptonization (Fenimore et al. 1982) for their spectral fits. Synchrotron radiation is produced as a charged particle is accelerated around a magnetic field line at a frequency $\omega_B = qB/(\gamma mc)$. The spectrum of a single electron
at a pitch angle $\theta$ with respect to the magnetic field $B$ is

$$P(\omega) = \frac{\sqrt{3} q^3 B \sin \theta}{2\pi \gamma} \frac{F(x)}{mc^2}$$

(2.5)

where

$$F(x) \equiv x \int_x^\infty K_{\frac{3}{2}}(x') dx'$$

(2.6)

$x \equiv \omega/\omega_c$ and

$$\omega_c \equiv \frac{3\gamma^2 qB \sin \theta}{2mc}$$

(2.7)
(Rybicki & Lightman 1979). The emissivity of thermal synchrotron, produced by a relativistic Maxwellian distribution of electrons, is given by (in ergs cm\(^{-3}\) Hz\(^{-1}\) s\(^{-1}\))

\[ j_\nu(\theta) = \frac{\pi e^2}{3c\sqrt{2}} n_e \nu K_2^{-1}(1/T) \exp\left[-\left(\frac{9\nu}{2\nu_c} \sin \theta\right)^{1/3}\right] \]  

(2.8)

where \(n_e\) is the electron density, \(\theta\) is the angle between the line-of-sight and the magnetic field, and \(K_2\) is a modified Bessel function. (Liang, Jernigan & Rodrigues 1983). Again, casting this in the more conventional photon spectra form, we find the spectral shape

\[ \frac{dN}{dE} = A \exp\left[-\left(\frac{9\nu}{2\nu_c} \sin \theta\right)^{1/3}\right] \]  

(2.9)

which was found to be roughly consistent with the 150 bursts in the Russian KONUS catalog (Liang, Jernigan & Rodrigues 1983). Low-energy spectral bins which fell below this shape were assumed to be suffering synchrotron self-absorption. In retrospect, these arguments are fairly weak, given that the thermal synchrotron shape was fit manually (also known as "\(\chi^2\)-by-eye") to spectra already deconvolved with optically-thin thermal bremsstrahlung.

Inverse Comptonization, where photons gain energy by scattering off of a hot plasma (assumed to be thermal), also showed much promise as a means of producing the gamma-ray continuum. The spectral shape is characterized by a Wien hump near the average energy of the leptons below which exists a low energy power-law \((dN/dE \propto E^{-\delta})\). Fitting this spectrum improperly with a thermal bremsstrahlung continuum would result in spurious broad emission (Fenimore et al. 1982) and absorption lines, as is evident in Figure 2.4. As this model was being proposed, the Solar Max Mission made the first detections of very hard (up to 10 MeV) power-law emission (Share et al. 1982). This was inconsistent with the exponential cutoff ex-
pected with saturated Comptonization in a thermal plasma and no further attempts to fit GRB with saturated Comptonization spectra were made until this work.

![Graph showing energy versus log photon flux](image)

**Figure 2.4** Optically-thin thermal bremsstrahlung (OTTB; long-dashed lines) and saturated Comptonization (solid lines) models fit to three spectra from GRB781104. The short dashed curves represent the input X-ray blackbody photon spectra. Deviations from the OTTB continuum had previously been interpreted as broad annihilation and cyclotron absorption lines. Here, saturated Comptonization by a thermal plasma naturally reproduces the observed continuum without the need for lines.

Another factor which may have stymied this early attempt at fitting saturated Comptonization was a somewhat misleading figure in Liang, Jernigan, & Rodrigues (1983). The authors used "χ²-by-eye" fits to demonstrate that thermal bremsstrahlung, thermal synchrotron, and inverse Comptonization spectra could all be fit to the same
GRB spectra. The failure to deconvolve the spectra using the models being compared, or even to evaluate quantitative $\chi^2$ values, coupled with the irregular use of a linear-log spectra, made this conclusion unsubstantiated. Nonetheless, several review articles cited this figure and studies involving the deconvolution of gamma-ray burst spectra using physical functions were abandoned for almost 15 years.

Currently, the standard function used in deconvolving GRB spectra is that of Band et al. (1993), namely

$$N \propto \left( \frac{E}{E_0} \right)^\alpha \exp \left( -\frac{E}{E_0} \right), \quad (\alpha - \beta)E_0 \geq E,$$

$$= A \left[ \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( \beta - \alpha \right) \left( \frac{E}{100 \text{ keV}} \right)^\beta \right], \quad (\alpha - \beta)E_0 \leq E,$$

where $A$ is the amplitude (in photon s$^{-1}$ cm$^{-2}$ kev$^{-1}$) and $E_0 = E_{pk}/(2 + \alpha)$. Thus $\alpha$ is the slope of the asymptotic slope of the $F_\nu/\nu$ photon spectra below the peak, $\beta$ is the $F_\nu/\nu$ slope above the peak, and the maximum of the $\nu F_\nu$ energy spectrum will occur at $E_{pk}$. While the Band GRB function is empirical, it can represent some physical functions, for instance optically-thin thermal bremsstrahlung ($\alpha = -1, \beta = -\infty, E_{pk} = kT$). In Figure 2.5, we illustrate the Band GRB function shape for typical parameters.

2.1.3 Relation between Energy and Pulse Duration

Pulses within bursts generally appear narrower in BATSE's high energy bands and broader in the low energy bands (Fishman et al. 1992). To quantify this intrinsic dependance of pulse width on the energy window, Fenimore et al. (1995) calculated the averaged autocorrelation function of 45 bright BATSE bursts using four energy channels (25-57 keV, 57-115 keV, 115-320 keV, 320-1000 keV). The autocorrelation function provides a measure of the pulse time scale and and in this case is roughly
Figure 2.5  Examples of the Band et al. (1993) GRB function plotted both as photon (or $F_\nu/\nu$) spectra and $\nu F_\nu$ spectra. In both plots, $E_{pk} = 100$ keV (dotted line), $\beta = -3$, and $\alpha = -1, 0, +1, +2$.

exponential with a halfwidth $\propto E^{-0.4}$. A similar result can also be found using the average duration of pulses (Norris et al. 1995). Clearly this represents a softening of the GRB spectra with time. A full interpretation of this relation, however, has not yet been advanced.

2.2  The Evolution of $E_{pk}$ as a Function of Fluence

Studies of gamma-ray burst (GRB) spectral evolution have uncovered many trends which may be used to test possible emission mechanisms. In general, studies of GRB spectral evolution have focused on the "hardness" of bursts, measured either by the ratio between two detector channels or with more physical variables such as the spectral break or peak power energy $E_{pk}$ (Ford et al. 1995) which is the maximum of $\nu F_\nu$, where $\nu$ is photon energy and $F_\nu$ is the specific energy flux. Such hardness
parameters were found to either follow a "hard-to-soft" trend (Norris et al. 1986),
decreasing monotonically while the flux rises and falls, or to "track" the flux during
GRB pulses (Golenetskii et al. 1983, Kargatis et al. 1994).

The discovery that $E_{\text{pk}}$ often decays exponentially in bright, long, smooth BATSE
GRB pulses as a function of photon fluence $\Phi (= \int_{t'=-\infty}^{t'} F_N(t')dt')$ (Liang & Kargatis
1996, hereafter LK96) provided a new constraint for emission models (Liang, Smith,
Kusunose & Crider 1997, Liang 1997, Daigne & Mochkovitch 1998). In their analysis,
LK96 fit the function

$$E_{\text{pk}}(t) = E_{\text{pk}(0)}e^{-\Phi(t)/\Phi_0^{L^K}}$$  \hspace{1cm} (2.11)

to 37 GRB pulses in 34 bursts. To interpret this empirical trend, they differentiated
Eq. 2.11 to find

$$-dE_{\text{pk}}/dt = E_{\text{pk}} F_N/\Phi_0^{L^K} \approx F_E/\Phi_0^{L^K}$$  \hspace{1cm} (2.12)

where $F_E = \int_{E=30\text{keV}}^{E=2000\text{keV}} E N(E) dE$ is the BATSE energy flux (see Equation 1 of LK96).
In this thesis, we wished to avoid the assumption that $E_{\text{pk}} F_N \approx F_E$. To do this, we
directly tested the trend $-d(E_{\text{pk}})/dt = F_E/\Phi_0$ by integrating it to give

$$E_{\text{pk}}(t) = E_{\text{pk}(0)} - \mathcal{E}(t)/\Phi_0$$  \hspace{1cm} (2.13)

where $\mathcal{E}(t) (= \int_{t'=0}^{t'} F_E(t')dt')$ is the BATSE energy fluence. We emphasize that this
is not a fundamentally different trend from the form used in LK96.

The decay constant $\Phi_0^{L^K}$ also appeared to be invariant among pulses during some
bursts analyzed in LK96, suggesting that individual pulses in a burst may originate in
the same plasma. This would severely constrain the many cataclysmic GRB models
which require an explosion with several different emission sites producing the observed
pulses. Considering the implications this hypothesis could have on theoretical works, we developed a stringent test for it.

2.2.1 Confirmation of $E_{pk}$-Fluence Relation

To determine the hardness evolution of GRB pulses, we examined High Energy Resolution data collected from the BATSE Large-Area Detectors (LAD) and Spectroscopy Detectors (SDs) on board the Compton Gamma-Ray Observatory (Fishman et al. 1989). We began with the 126 bursts which appear in Preece et al. (1998a). The bursts were chosen for having a BATSE fluence (28-1800 keV) > $4 \times 10^{-5}$ erg cm$^{-2}$ or a peak flux (50-300 keV on a 256-ms time scale) > 10 photon s$^{-1}$ cm$^{-2}$. These selection criteria eliminate bursts with insufficient photons for our analysis. The counts from the detector most nearly normal to the line of sight of each burst (burst angle closest to 0) were background-subtracted and binned into time intervals each with a signal-to-noise ratio of $\sim$ 45 within the 28 keV to 1800 keV range. Such a signal-to-noise ratio has been found to be necessary in time-resolved spectroscopy of BATSE gamma-ray bursts (Preece et al. 1998a).

We deconvolved the gamma-ray spectra of each time interval using the Band et al. (1993) GRB function (Eq. 2.10) While LK96 assumed that $\alpha$ and $\beta$ were constant during the course of each burst, this has since been shown to be untrue with a larger data set. (Crider et al. 1997). We thus left $\alpha$ and $\beta$ as free parameters in our fits.

At this point, we needed to select pulses within our bursts that we could use to test Equations 2.11 and 2.13. Ideally, our pulses would not overlap other pulses and our method for choosing the time bins associated with a pulse would not be biased. Unfortunately, by forcing our time bins to have a signal-to-noise ratio $\sim$ 45 so that
spectra may be fit to them, much time resolution is lost. Pulses which would be easily separable at a higher time resolution become blurred together. In Figure 2.6, we show an example of what would likely be identified as two pulses in our coarse (signal-to-noise $\sim 45$) data. Below it, 64-ms count rate data for this same burst, obtained from the Compton Observatory Science Support Center (COSSC), is plotted. With higher time resolution, we see this burst is composed of at least 4 distinct pulses.

To avoid contaminating our sample with overlapping pulses (and to avoid biases introduced by a human in pulse selection), we used the COSSC 64-ms count rates and background fits to determine where each of our pulses began and ended. To do this, we developed an interactive IDL routine to fit the Norris et al. (1996) pulse profile to the individual pulses within these bursts. The pulse profile function for the count rate $C(t)$ can be written

$$C(t) = A \exp \left( -\left| \frac{t - t_{\text{max}}}{\sigma_{r,d}} \right|^{\nu} \right)$$

(2.14)

where $t_{\text{max}}$ is the time of maximum count rate, $\sigma_r$ and $\sigma_d$ are the count rate rise and decay time constants, and $\nu$ is the pulse "peakedness". For an exponential rise and decay, $\nu = 1$. When $\nu = 2$ and $\sigma_r = \sigma_d$ this shape describes a Gaussian.

With 64-ms resolution, we found that in many bursts pulses overlapped in a fashion making them too complex for us to fit individual pulses. Other bursts contained pulses which could be resolved, but none of their pulses lasted long enough to span at least 4 time bins with a signal-to-noise ratio $\sim 45$. For 13 of the bursts, processed 64-ms data was unavailable. We discarded bursts which fell into any of these three categories. This left us with 26 bursts. This is comparable to the 34 multi-pulse bursts used in LK96, which included several pulses which appear to be overlapping when confronted with the 64-ms data. To avoid overlap in our own analysis, we used only bins which
Figure 2.6 The time history of BATSE trigger 543 seen both in (a) the lower time resolution which allowed us to fit a spectrum to each bin and (b) 64-ms resolution. Count rate is marked in each plot as a histogram and $E_{pk}$, as determined from the data in the upper plot, is marked on both plots for convenience. While it is clear in the lower plot that there are at least 4 pulses within this burst, only two peaks in flux are evident in the upper plot. The fits of the Norris function (Eq. 2.14) to these pulses are plotted here as dotted lines. Taken from Crider et al. (1999a).
were dominated by a single pulse (at least 70% of the counts from one pulse). Within our 26 bursts, we identified 41 regions composed of at least 4 time bins dominated by a single pulse. The time bins selected for each pulse were consecutive in all but two cases (BATSE triggers 451 and 3290). The 64-ms data for each of these two bursts suggests that a short pulse occurred near the middle of a longer pulse, which forced us to fit two separate regions with a single decay law.

Our next step was to test the $E_{pk}$-fluence relations (Equations 2.11 and 2.13) with each of the selected pulses. Our motivation for emphasizing the $E_{pk}$-energy fluence relation (Eq. 2.13) as opposed to the $E_{pk}$-photon fluence relation (Eq. 2.11) is that we believe that the former represents a more physical quantity. It is possible (perhaps even likely) that the observed BATSE photon fluence is a poor representation of the bolometric photon fluence. The BATSE LAD energy window was designed to contain the peak of GRB energy spectra, not the peak of the photon spectra. By using energy fluence in place of photon fluence, we can avoid the shakier assumption that the BATSE LAD photon flux is proportional to the bolometric photon flux. LK96 had attempted this but found that statistical errors in $E$ were too large to be useful. This was a result of their fixing $\alpha$ and $\beta$ in the spectral fitting. When we fit the time-resolved spectra with variable $\alpha$ and $\beta$, we obtained much smaller errors for $E$, which made testing the $E_{pk} - E$ relation possible. Nevertheless, we also fit Eq. 2.11 to our pulses both for historical reasons and as a test of our interpretation.

We fit both the $E_{pk} - \Phi$ and the $E_{pk} - E$ relations to our 41 clean pulses using FITEXY (Press, Teukolsky, Vettering & Flannery 1992). Table 2.1 summarizes the results for each of the pulses in our sample. The first column is the BATSE trigger number. The second column is the burst name, which is also the date the burst
triggered in the format YYMMDD. The third column is the number of the LAD which was used for processing. The fourth column lists the $t_{\text{max}}$ from the Norris function fit to the pulse. The fifth column is the energy fluence within the bins selected for fitting in units MeV cm$^{-2}$. The sixth column gives the number of bins selected for fitting. The seventh column is the fitted value $\Phi_0^{L^K}$ for each pulse defined in Eq. 2.11. The eighth and ninth columns are the fitted values of $\Phi_0$ and $E_{pk(0)}$ for each pulse as defined in Eq. 2.13. Of course, $\Phi_0$ will only equal $\Phi_0^{L^K}$ if $E_{pk}F_N = E_F$. Since the latter is not strictly true, we find that $\Phi_0 \approx \Phi_0^{L^K}$. For completeness, we also show the plots of $E_{pk}$ versus $E$ and their fits in Figures 2.7 through 2.10.

From the $\chi^2$ and the number of fluence bins for each decay fit, we calculated the probability $Q$ of randomly getting a higher $\chi^2$ by chance. Thus, $Q \gtrsim 0.5$ represents very good fits, while $Q \lesssim 10^{-3}$ represents poor fits. The $Q$ values from fits of Eq. 2.13 to our pulses appear in the tenth column of Table 2.1. If $E_{pk}$ does indeed cool linearly with $E$ in all pulses selected for fitting, then when plotting the cumulative distribution of $Q$ values, we would expect 10% of the pulses to have a $Q$ less than 0.1, 20% of the pulses to have a $Q$ less than 0.2, and so on. Figure 2.11 shows the cumulative distribution of $Q$ values for our pulses with acceptable fits. An excess of pulses with very high $Q$ values would suggest a biased pulse selection process. A Kolmogorov-Smirnov test ($P = 0.18$) applied to our distribution of $Q$ values suggests that the set of 41 pulses is not too biased and roughly follows the distribution we would expect if all of them are consistent with a linear decay of $E_{pk}$ with respect to energy fluence.

By fitting the $E_{pk}$-fluence law to the full observable duration of each pulse and not just the flux decay phase, we could characterize our pulses as "hard-to-soft". None of
<table>
<thead>
<tr>
<th>BATSE Trigger</th>
<th>Burst Name</th>
<th>LAD</th>
<th>$t_{	ext{max}}$ (sec)</th>
<th>$\Delta E$ (MeV cm$^{-2}$)</th>
<th>Bins</th>
<th>$\Phi_0^R$ (cm$^{-2}$)</th>
<th>$\Phi_0$ (cm$^{-2}$)</th>
<th>$F_{p\nu(0)}$ (keV)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>451 910627 4</td>
<td>5.0 4.9 8 37±5 51±6 125±7 0.206</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>543 910717 4</td>
<td>1.1 1.5 7 17±3 12±2 255±14 0.251</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>647 910807 0</td>
<td>14.0 4.1 7 79±17 59±15 249±11 0.664</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>647 910807 0</td>
<td>3.5 3.2 7 42±5 35±5 212±8 0.299</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>973 911031 3</td>
<td>2.5 10.8 22 70±9 62±8 295±18 0.965</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>973 911031 3</td>
<td>23.7 3.6 9 29±10 24±11 285±49 0.991</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1085 911118 4</td>
<td>2.5 10.8 16 75±5 61±5 354±10 0.016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1085 911118 4</td>
<td>6.3 2.3 4 564±569 446±462 139±3 0.714</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1085 911118 4</td>
<td>9.0 8.1 14 96±3 96±4 121±2 0.992</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1085 911118 4</td>
<td>20.2 1.1 3 87±144 140±241 41±9 0.537</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1709 920718 7</td>
<td>0.7 2.0 5 130±118 58±49 271±21 0.024</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1974 921003 2</td>
<td>1.2 1.9 6 42±6 67±10 91±3 0.775</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1974 921003 2</td>
<td>4.6 1.2 5 116±43 196±83 57±2 0.747</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1974 921003 2</td>
<td>6.6 1.7 5 26±7 63±19 54±3 0.989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1989 921015 4</td>
<td>117.7 2.9 5 37±4 49±7 93±3 0.535</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2083 921207 0</td>
<td>8.5 3.0 5 86±9 74±10 125±4 0.538</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2083 921207 0</td>
<td>1.4 7.5 15 61±2 48±2 236±5 0.302</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2138 930120 0</td>
<td>78.3 7.1 4 1388±1647 812±805 169±5 0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2316 930425 1</td>
<td>4.2 4.4 9 -270±568 -250±566 136±20 0.978</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2537 930922 1</td>
<td>1.1 1.5 4 31±6 245±8 155±9 0.233</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2606 931026 7</td>
<td>69.8 3.3 5 46±21 22±12 358±54 0.955</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3003 940529 0</td>
<td>8.8 9.7 12 70±17 59±19 340±41 0.362</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3042 940623 1</td>
<td>7.8 2.1 6 32±25 20±18 383±66 0.816</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3178 940921 2</td>
<td>8.0 5.2 4 53±42 19±14 829±111 0.410</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3227 941008 5</td>
<td>8.9 3.3 13 42±8 69±16 130±8 0.777</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3290 941124 1</td>
<td>38.3 7.7 5 49±2 43±3 211±7 0.947</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3352 950111 2</td>
<td>18.1 7.3 15 141±26 114±22 227±9 0.158</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3481 950325 2</td>
<td>39.7 2.7 4 13±3 9±2 473±56 0.557</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3491 950403 3</td>
<td>7.7 10.2 18 87±6 64±4 250±7 0.283</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3491 950403 3</td>
<td>13.2 1.6 4 84±48 191±112 47±3 0.922</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3491 950403 3</td>
<td>4.7 3.0 9 -1685±41445 -259±1760 252±48 0.345</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3870 951016 5</td>
<td>0.5 2.6 7 20±8 30±17 154±35 0.780</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3870 951016 5</td>
<td>2.0 1.8 5 -66±257 -166±612 47±36 0.999</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4368 960114 0</td>
<td>18.7 15.2 6 294±69 165±46 184±19 0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5567 960807 0</td>
<td>8.7 1.3 5 24±23 21±27 210±60 0.328</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5567 960807 0</td>
<td>10.7 2.6 7 322±1680 133±706 401±48 0.982</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5621 961001 2</td>
<td>3.9 4.5 5 49±24 48±32 372±43 0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5621 961001 2</td>
<td>7.1 2.4 5 11±1 10±2 290±45 0.250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5773 970111 0</td>
<td>8.2 6.0 17 89±7 65±5 238±5 0.017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5773 970111 0</td>
<td>17.2 4.5 9 149±25 103±19 193±5 0.623</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5773 970111 0</td>
<td>3.9 3.1 6 34±4 32±5 257±10 0.132</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1  Hardness decay parameters for 41 GRB pulses selected from 26 BATSE bursts. Refer to the text for a description of each column.
Energy Fluence ($10^5$ keV cm$^{-2}$)

Figure 2.7  Refer to Figure 2.10 for a description of this figure.
Energy Fluence ($10^3$ keV cm$^{-2}$)

Figure 2.8 Refer to Figure 2.10 for a description of this figure.
Figure 2.9 Refer to Figure 2.10 for a description of this figure.
our pulses required a "tracking" classification, though many of the ambiguous pulses excluded from this study could be "hard-to-soft" or "tracking". Three of the pulses in our sample (BATSE triggers 2316, 3491, and 3870) contain pulses with negative values of $\Phi_0$. However, all three of these pulses are still consistent with a positive value of $\Phi_0$. We remind the reader here that large absolute values of $\Phi_0$ (like those in these three pulses) correspond to pulses with very little change in $E_{pk}$, where $\frac{1}{\Phi_0} = \frac{dE_{pk}}{d\ell} \approx 0$. In such cases, small statistical errors in $\frac{dE_{pk}}{d\ell}$ translate to very large statistical errors in $\Phi_0$. Even if all pulses decay monotonically from hard-to-soft, we should expect to see a few pulses to have negative values of $\Phi_0$. Since all of our pulses are consistent with a monotonic decay in $E_{pk}$, we adopt the hypothesis that all pulses behave this way for the remainder of this section and drop these three pulses from our sample to simplify our calculations.
Figure 2.11  Cumulative distribution of \( Q \) values for 41 pulses. In this plot, \( N \) is the fraction of pulses that have a \( Q \) value less than that of a certain pulse. If all of these GRB pulses cooled linearly as a function of energy fluence, one would expect the cumulative \( Q \) distribution to match the unit distribution \((N=Q)\). The Kolmogorov-Smirnov test gives a significance \( P = 0.18 \) to the assumption that this distribution is drawn from the uniform distribution. From this, we conclude that our \( E_{pk} - \mathcal{E} \) function (Eq. 2.11) adequately describes the pulses in this subset. Taken from Crider et al. (1999a).

2.2.2 Distribution of \( \Phi_0 \)

The distribution of fitted \( \Phi_0 \) values appears in Figure 2.12. It is roughly log-normal where the mean of \( \log_{10} \Phi_0 \) is \( 1.75 \pm 0.07 \) and the FWHM of \( \log_{10} \Phi \) is \( 1.0 \pm 0.1 \). This distribution likely suffers some selection effects. This becomes obvious when one realizes that \( \Phi_0 \approx -\frac{\Delta \mathcal{E}}{\Delta E_{pk}} \). We see that the smallest absolute value of \( \Phi_0 \) is limited by the minimum energy fluence which allows one to fit spectra (about \( 1 \) MeV cm\(^{-2} \) from Table 2.1) and the energy window of BATSE (max \( \Delta E_{pk} \approx 1870 \) keV). There
are no such limitations on the high side of this distribution, since $|\Delta E_{pk}|$ can be arbitrarily small and $\Delta E$ is only limited by nature.

![Graph](image)

**Figure 2.12** This is the distribution of $\Phi_0$ values based on 41 pulses selected from 26 bursts. In this plot, we show both a histogram of values and the best-fit Gaussian distribution. The distribution of $\Phi_0$ values is roughly log-normal where the mean of $\log_{10}\Phi$ is $1.75 \pm 0.07$ and the FWHM of $\log_{10}\Phi$ is $1.0 \pm 0.1$. Taken from Crider et al. (1999a).

### 2.2.3 Invariance of $\Phi_0$ within Gamma-Ray Bursts

LK96 reported that the decay constant $\Phi_0^{LK}$ sometimes remains fixed from pulse to pulse within some bursts. Such behavior would hint at a regenerative source rather than a single catastrophic event (such as Mészáros & Rees 1993). However, the intrinsically narrow distribution of decay constants mentioned above and the relatively
large confidence regions for each pulse's value of $\Phi_0$ suggest that many bursts would appear to have an invariant decay constant merely by chance.

As done earlier with a larger, but less reliable, set of pulses (Crider, Liang & Preece 1998a), we calculated three statistics for each multi-pulse burst to test the invariance of the $E_{pk}$ – fluence decay constant. We compared two of each bursts' $M$ pulses at a time using the statistic

$$X^2_{ij} = \frac{[1/\Phi_0(i) - 1/\Phi_0(j)]^2}{\sigma^2_i/\Phi_0(i) + \sigma^2_j/\Phi_0(j)}$$  \hspace{1cm} (2.15)

and then distilled the comparisons within each burst into a single statistic to represent that burst. These statistics are defined in the first column of Table 2.2. Each is tailored for different null hypotheses. The statistic $G_1$ tests if at least two pulses in a burst are similar (and thus “invariant”), while $G_2$ tests if all the pulses have a similar decay constant. $G_3$ tests for either a single good pairing or several moderately close pairings. We believe that this last statistic is the most reasonable for testing our results since it does not require that all pulses decay at the same rate (as $G_2$ does) but also does not discard information about multiple pulses repeating (as $G_1$ does). The sample of bursts in this study has fewer bursts than previous works, and hence has fewer bursts with more than one pulse. The three versions of the $G$ statistic defined above are equivalent when only two pulses appear in a burst. Thus for this sample, with only 3 of the 9 multipulse bursts having more than 2 pulses, these statistics are nearly equivalent. We also note that in our statistic in Equation 2.15, instead of directly comparing $\Phi_0$ values, we used the fitted $E_{pk} - \varepsilon$ slopes, $1/\Phi_0$, thus avoiding implicit assumptions in transforming $\sigma_{1/\Phi_0}$ into $\sigma_{\Phi_0}$.

Next, we wished to test the null hypothesis $H_0$ that pulses within a burst had the same underlying decay constant. Our alternative hypothesis $H_1$ was that the decay
constant of pulses within a burst were randomly sampled from the distribution of \( \Phi_0 \) seen among all bursts. We created 100,000 synthetic bursts first using \( H_0 \) and then using \( H_1 \). Our synthetic pulses were created based on the observed distributions of \( \Phi_0 \) and \( \sigma_{\Phi_0}/\Phi_0 \). To avoid any bias that intrinsic invariances would have on these distributions, we created them using only one pulse from each burst. Under both hypotheses, we determined for each burst the fraction \( F \) of synthetic bursts with a lower \( G_\alpha \) (i.e. more closely matching values of \( \Phi_0 \)). We combined the results of our burst statistics by comparing the distribution of \( F \) to the uniform distribution with a K-S test. From this, we found the confidence in each hypothesis for each of our \( G \) statistics. These are listed in the second and third columns of Table 2.2.

<table>
<thead>
<tr>
<th>Definition of ( G_\alpha )</th>
<th>Confidence in ( H_0 )</th>
<th>Confidence in ( H_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1 \equiv \min X_{ij}^2 )</td>
<td>( 9.5 \times 10^{-3} )</td>
<td>0.28</td>
</tr>
<tr>
<td>( G_2 \equiv \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} X_{ij}^2 )</td>
<td>( 3.5 \times 10^{-5} )</td>
<td>0.04</td>
</tr>
<tr>
<td>( G_3 \equiv \prod_{i=1}^{M-1} \prod_{j=i+1}^{M} X_{ij}^2 )</td>
<td>( 6.2 \times 10^{-5} )</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Table 2.2** The confidences in two distinct null hypotheses for three goodness-of-fit statistics \( G \). We have very low confidence that pulses within a burst have the same decay constant (\( H_0 \)). In contrast, we are unable to disprove the hypothesis that the decay constant of pulses in bursts are sampled from the distribution of \( \Phi_0 \) seen in all bursts (\( H_1 \)), suggesting that any invariance seen in the data is purely coincidental.

The low probabilities that all bursts' pulses have identical values of \( \Phi_0 \) and the high probabilities that the observed repetitions occurred by coincidence lead us to conclude that pulse decays are not invariant from pulse to pulse within bursts. Instead, we suggest that the distribution of \( \Phi_0 \) values seen in all bursts is narrow enough that
an apparent invariance of $\Phi_0$ is inevitable in some bursts. We came to the same conclusion when examining $\Phi^{L_k}_0$ (Crider, Liang & Preece 1998a).

2.2.4 Hardness Evolution of Co-added Bursts

Besides LK96, other quantitative spectral evolution trends have been reported for GRBs. The averaged temporal and spectral evolution for 32 bright GRBs has been calculated in Fenimore (1997). The averaged photon flux evolution can be described as both rising and decaying linearly with time. The hardness, as measured by $E_{pk}$ with $\alpha$ and $\beta$ held fixed, also appears to decay linearly with time during the averaged burst ($E_{pk} = E_{pk(0)}(1 - t/t_0)$). (see Figure 2.13). This is clearly not representative of all bursts since the evolution in bursts of $E_{pk}$ is often complex (Ford et al. 1995, Liang & Kargatis 1996). These trends possibly reflect the physics dictating the envelope of emission. The fact that LK96 found the $E_{pk}$-fluence trend in many mingled pulses may result from the fact that the burst envelope also evolves in this manner.

Since the hardness of this envelope appears to decay more slowly than the hardness during the pulses we observe, we might not expect to see this trend in our pulses. However, the degree of confidence of $E_{pk}$ in our fits, coupled with the fact that energy fluence is often linear in time, makes the observations of many bursts possibly consistent ($Q > 0.001$) with this decay law. Testing the distribution of $Q$ values as we did in Fig 2.11, we find a probability $P=0.001$ that the pulses are realizations of linear $E_{pk}$-time trend, compared to $P=0.18$ for the linear $E_{pk}$-energy fluence trend. While the linear $E_{pk}$-time relation does not seem to describe individual pulses as well as the $E_{pk}$-fluence relation, the results are not conclusive. More pulses are clearly needed if one is to discriminate between any two time-dependent spectral functions.
Figure 2.13  The flux and hardness evolution of 32 co-added BATSE bursts. Taken from Fenimore (1997).

2.3  The Spectral Slope Below $E_{pk}$

The observed values and variability of all three Band GRB function parameters are crucial in evaluating the wide field of proposed models of gamma-ray burst emission. For example, many models of the spectral break require $\alpha$ to stay constant (e.g. self-absorption) or to have negative values (e.g. $-\frac{2}{3}$, Katz 1994, Tavani 1996), even when $E_{pk}$ evolves. While we find hints that $\beta$ decreases over the course of some bursts, as suggested by COMPTEL (Hanlon et al. 1995) and BATSE (Preece et al. 1998a), we focus on the evolution of $\alpha$. We find $\alpha$ is not constant, but appears to roughly track
$E_{pk}$ as the burst evolves. The steep values of $\alpha$ early in many bursts are also very inconsistent with the values predicted by most GRB models.

2.3.1 Evolution of $\alpha$

To determine the evolution of the spectral shape of GRBs, we again examine High Energy Resolution data collected from the BATSE LAD on board the Compton Gamma-Ray Observatory (Fishman et al. 1989). We selected bursts that have a BATSE fluence $(28\text{-}1800 \text{ keV}) > 2 \times 10^{-5} \text{ erg cm}^{-2}$ which resulted in a set of 79 bursts. The counts from the LAD most normal to the line of sight of each burst are background-subtracted and binned into time intervals each with a SNR of $\sim 45$ within the $28 \text{ keV}$ to $1800 \text{ keV}$ range. We fit the Band et al. (1993) GRB function to each interval and thus obtained the time evolution of the three Band et al. (1993) GRB parameters which define the spectral shape. Figures 2.14 through 2.16 show sample BATSE bursts (3B) 910807, 910927, 911031, 920525, and 931126 displayed for illustrative purposes. (See Liang & Kargatis 1996 for $E_{pk}$-fluence diagrams for 911031, 920525, and 931126.) The spectra show that for these bursts, $\alpha$ generally rises and falls with the instantaneous $E_{pk}$, though exact correlation between the two parameters is not evident. In Figures 2.14 through 2.16, $\beta$ stays relatively constant throughout most of the primary pulse, while $E_{pk}$ and $\alpha$ both steadily decrease.

To determine if $\alpha$ does indeed evolve in time in a majority of bursts, we fit a zeroth ($M=0$) and first-order ($M=1$) polynomial to the $\alpha$ evolution in each burst. Assuming a null hypothesis in which $\alpha$ is constant during a burst and the time-resolved values of $\alpha$ are normally distributed about the mean, we expect the value $\Delta \chi^2 = \chi^2_{M=0} - \chi^2_{M=1}$ to be distributed as $\chi^2$ with 1 degree of freedom (Eadie et al. 1971). We calculated
Figure 2.14 Evolution of the Band et al. (1993) GRB spectral function for 3B 910927. Each line is marked with the time (in s) corresponding to the beginning of the time bin. Note that a typical statistical $\beta$ error $\sigma_\beta \approx 0.4$. The nearly linear decay of $\alpha$ throughout this burst suggests that the early high values of $\alpha$ are not statistical fluctuations. However, this burst is still consistent with $\alpha \leq +1$. [Upper inset] Evolution of $E_{pk}$ (squares, logarithmic scale) and photon flux (histogram, linear scale) with respect to fluence. [Lower inset] Evolution of $\alpha$ (circles) and photon flux (histogram) with respect to time. Error bars represent 1$\sigma$ confidence level. Taken from Crider et al. (1997).
Figure 2.15  Evolution of the Band et al. GRB spectral function of the first pulse in 3B 910807. Note that the typical statistical $\sigma_\beta \approx 0.4$. See Fig. 2.14 caption for a description of the plots.
Figure 2.16 Band et al. $\alpha$ (circles), linear $E_{\text{pk}}$ (diamonds) and photon flux (histogram) evolution in time for 3B 911031 [GRB 973], 3B 920525 [GRB 1625], and 3B 931126 [GRB 2661]. These three bursts suggest that $\alpha$ evolves in a manner similar to $E_{\text{pk}}$. Error bars represent 1σ confidence region. The vertical dimensions of diamonds represents 1σ confidence region for $E_{\text{pk}}$ and the horizontal dimensions represent the durations of the time bins. (See Liang & Kargatis 1996 for $E_{\text{pk}}$ vs. fluence of these bursts with $\alpha$ and $\beta$ fixed to the time-integrated value.) Taken from Crider et al. (1997).
for each burst the probability $Q$ of randomly drawing a value greater than or equal to $\Delta \chi^2$. Forty-six of the bursts have a $Q$ below our acceptable cutoff of 0.001, leading us to conclude that a majority of bursts in the sample show evidence for at least a first-order trend in $\alpha$.

The five sample bursts above suggest that evolution of $\alpha$ mimics that of $E_{pk}$. To see if this occurs in other bursts, we attempt to disprove the null hypothesis that $\alpha$ is uncorrelated with $E_{pk}$. To test the degree of correlation between $\alpha$ and $E_{pk}$, in each of our 79 bursts we compute the Spearman rank correlation $r_s$ (Press, Teukolsky, Vettering & Flannery 1992). For each burst with a positive $r_s$, we find the probability $P_+$ of randomly drawing a value of $r_s$ that high or higher assuming no correlation exists. For each burst with a negative $r_s$, we find the probability $P_-$ of randomly drawing a value of $r_s$ that low or lower assuming no anti-correlation. The divisions of the bursts in this way precludes the inclusion of systematic anti-correlations, which could occur given the negative covariance between $\alpha$ and $E_{pk}$ and the observed shape of our $\chi^2$ minimum contours. We next calculated the Kolmogorov-Smirnov (K-S) D statistic between the measured distribution of $P_+$ or $P_-$ and the distribution one would expect if no correlation or anti-correlation existed. We found $D=0.45$ for the 47 positively correlated bursts. The likelihood of this value, assuming no intrinsic correlation, is $2 \times 10^{-8}$. The bursts showing negative correlation, which suffer from systematics described above, are still consistent (likelihood = 0.04) with a non-correlation hypothesis. From this we conclude that a positive correlation exists between $\alpha$ and $E_{pk}$ in at least some subset of bursts.

As part of our analysis in Section 2.2.1, we found that all of our distinguishable pulses were consistent with a “hard-to-soft” behavior for their duration. We then
assumed that any pulses that appeared to be “tracking” were in fact composed of overlapping hard-to-soft pulses. This assumption did not affect the basic conclusions of Section 2.2.1 and we do not assume it here since we have yet to rigorously prove its validity. To determine if an $\alpha - E_{pk}$ relation exists in hard-to-soft or tracking pulses, we selected 18 pulses which we determine to be clearly hard-to-soft and 12 pulses which are clearly tracking from the $> 240$ pulses within our 79 bursts. Pulses were included in the hard-to-soft category if the maximum $E_{pk}$ occurs before the flux peak and is greater than $E_{pk}$ at the flux peak by at least $\sigma_{E_{pk}}$. Pulses were tracking if the rise and fall of $E_{pk}$ coincides with those of flux to within 1 time bin (typically $\sim \frac{1}{2}$ sec) and if the rise lasts at least 3 time bins. Obviously, all pulses do not fall into one of these two categories. The pulses we selected are extreme examples in a continuum of the observed evolutionary patterns in our coarse (signal-to-noise $\sim 45$) data. Following the same analysis described above on these smaller populations, in cases with positive $r_s$, I found the likelihood of these observed values of $r_s$ assuming no intrinsic correlations is 0.003 ($D=0.46$) for the hard-to-soft pulses and 0.02 ($D=0.45$) for the tracking pulses. In contrast, while 4 of the 18 hard-to-soft pulses and 6 of the 12 tracking pulses were anti-correlated, the likelihood of these randomly occurring was 0.78 for the hard-to-soft cases and 0.29 for the tracking cases, values consistent with the null hypothesis of no anti-correlation. In Figure 2.17, is a comparison of the cumulative distributions of the 14 hard-to-soft and 6 tracking pulses which are positively correlated to that of the 47 positively correlated bursts. I found that both distributions of pulses are similar to the distribution of these bursts which implies an $E_{pk} - \alpha$ correlation. This statistical evidence led me to conclude that for hard-to-soft
and, with less confidence, for tracking pulses the asymptotic low-energy power-law slope \( \alpha \) evolves in a manner similar to \( E_{pk} \).

![Figure 2.17](image)

**Figure 2.17** Cumulative distribution of the probability \( P \) of randomly drawing a value \( \geq t \) assuming no correlation between \( E_{pk} \) and \( \alpha \) for 14 "hard-to-soft" pulses (squares), 6 "tracking" pulses (diamonds), and 47 bursts (circles) with positive correlation. Applying a K-S test determines the probabilities of getting these distributions, which are, respectively, 0.003, 0.02, and \( 2 \times 10^{-8} \). The probabilities (from a K-S test) that the positively-correlated hard-to-soft and tracking pulses represent samples from the same population from which the 47 bursts are taken are, respectively, 0.21 and 0.55. Taken from Crider et al. (1997).

### 2.3.2 Steepness of \( \alpha \) at the Beginning of Gamma-Ray Bursts

Assuming that \( \alpha \) mimics \( E_{pk} \), it follows that \( \alpha \text{ decreases monotonically for hard-to-soft pulses} \), whereas it increases during the rise phase of tracking pulses. We compare the averaged values of \( \alpha \) during the rise phase for these two groups and find that those in hard-to-soft pulses are significantly higher. While none of the 12 tracking
pulses has an average $\alpha_{\text{rise}} > 0$, 7 of the 18 hard-to-soft pulses had an average $\alpha_{\text{rise}} > 0$ (see Fig. 2.18). A K-S test between the two distributions gives a value of $D=0.56$, implying a significance of 0.014 to the hypothesis that these two samples were randomly taken from the same distribution.

![Figure 2.18](image)

**Figure 2.18** Mean value of Band et al. parameter $\alpha$ for the rise phase of 18 "hard-to-soft" pulses (solid) and 12 "tracking" (dashed) pulses. Note that only hard-to-soft pulses have mean values of $\alpha_{\text{rise}} > 0$. The probability of these two samples originating from the same population is 0.014 as determined by the K-S test. Taken from Crider et al. (1997).

We next examine the highest value of $\alpha_{\text{max}}$ that occurs in our time-resolved spectra. This value serves as a valuable test for GRB emission models. In Figure 2.19, we provide the distribution of $\alpha_{\text{max}}$ found in each of our 79 bursts. We note that $\alpha$ is not the maximum low energy slope of the GRB function within the detector range, but is the asymptotic limit of the slope if extrapolated to arbitrarily low energies. For this reason, we also plot the distribution of the maximum low energy slope observed within BATSE's energy range. Only a few bursts examined so far suggest that their maximum $\alpha$ may be $> +1$. As indicated in Figure 2.19, all of the bursts with $\alpha_{\text{max}} > +1$ have large statistical uncertainties. The nearly linear decrease of $\alpha$ with respect to time in 3B 910927 suggests that its relatively high $\alpha_{\text{max}}$ of $1.6 \pm 0.3$,
found using data from the LAD most normal to the burst, is not merely a statistical fluctuation (see Fig. 2.14). Further examination reveals, however, that this burst is still consistent with $\alpha \leq +1$ for its duration. In addition, jointly fitting the data from the two LADs most normal to the burst reduces $\alpha_{\text{max}}$ to $1.03 \pm 0.15$.

We also note that fitting 3B 910927 with a broken power law instead of the Band et al. GRB function, gives the same linear decrease of the low-energy power law slope $\gamma_1$ with respect to time. and reduced-$\chi^2$ values comparable to those of the Band et al. GRB function fit. However, $\gamma_1 < 0$ throughout the burst, a value of the low-energy slope lower than that found using the Band et al. GRB function. If the GRB function better represents the underlying physics then this difference would be expected. The parameter $\gamma_1$ measures the effective average slope below $E_{pk}$ whereas $\alpha$ measures asymptotic value, allowing for the curvature of the exponential function.
Figure 2.19 Discrete cumulative distribution function (points) and continuous density function (solid line) of the maximum value of the Band et al. (1993) parameter \( \alpha \) (upper) and the maximum spectral slope (lower) within the fitted energy region for 79 BATSE bursts. The density function is calculated by summing 79 unit Gaussian functions with means and variances taken from \( \alpha_{\text{max}} \) and \( \sigma_{\alpha_{\text{max}}} \) (or \( \text{slope}_{\text{max}} \) and \( \sigma_{\text{slope}_{\text{max}}} \)). The slope (in log-log space) of the Band et al. GRB function equals \( \alpha = -E/E_0 \) when \( E \leq (\alpha - \beta)E_0 \) and equals \( \beta \) when \( E \geq (\alpha - \beta)E_0 \), where \( E_0 = E_{\text{pk}}/(2 + \alpha) \). Error bars represent the 1\( \sigma \) confidence region. Note that \( \text{slope}_{\text{max}} \) represents the maximum slope measured in each burst and does not necessarily occur at the time when the Band et al. GRB function \( \alpha \) is maximum. Also note that these are two separate distributions and the \( i \)th \( \alpha_{\text{max}} \) is not necessarily from the same burst as the \( i \)th \( \text{slope}_{\text{max}} \). Taken from Crider et al. (1997).
Chapter 3

Evaluating GRB Models with Time-Resolved Spectra

While the popular synchrotron blastwave model may explain the newly discovered GRB afterglows, they are cannot produce the prompt gamma-ray spectra unless some absorption occurs. While photoelectric or self-absorption could result in the observed low values of $\alpha$, testing these directly with the BATSE and BeppoSAX data from GRB970111, we found both mechanisms to be inadequate. We then turned to saturated Comptonization and found it consistent with the "terrace-shaped" spectra in GRB970111, as well as the BATSE+ROTSE spectra in GRB990123.

3.1 Confronting the Synchrotron Blastwave Model

GRB spectral breaks can in principle be caused by synchrotron emission with a low-energy cutoff or self-absorption. However, in the former case, $\alpha$ would always be $\leq -\frac{2}{3}$ (Katz 1994, Tavani 1996) with no evolution. While a handful of time-integrated bursts have been used to demonstrate this as a viable mechanism (Cohen et al. 1997), we have found that such a low $\alpha$ is inconsistent with many of the time-resolved BATSE bursts. For instance, in GRB910927, fitting the time bin in which $\alpha$ is maximum with an $\alpha$ fixed to $-\frac{2}{3}$ results in a $Q$ of $1.5 \times 10^{-11}$, much lower the $Q=0.35$ obtained when $\alpha$ is a free parameter. In the case of self-absorption, $\alpha$ could go as high as +1 (thermal) or +1.5 (nonthermal, power-law; Rybicki & Lightman 1979). But again, in
such models, $\alpha$ would not evolve with time, only $E_{pk}$ (which would be interpreted as the self-absorption frequency) would.

In addition to the constraints placed on the external synchrotron shock model by our spectral analyses, the "local spherical symmetry" problem introduced by Fenimore, Madras, & Nayakshin (1996) strongly precludes this model. Since the bursting material must be moving relativistically toward the observer (to avoid the pair opacity problem), the emission is beamed and only a "local" surface (within $\theta \sim \Gamma^{-1}$) contributes. The "spherical" aspect of the shell is also important, since the delay in arrival time of off-axis photons can be comparable to the pulse duration, if the shell is large enough. A single, symmetric, relativistically expanding shell should generate a GRB pulse profile that would rise quickly and decay with a power-law $T^{-\beta-2}$, where $T$ is time and $\beta$ is the photon spectral index. While some bursts have a time history like this, many bursts cannot be explained by this mechanism (Fenimore, Madras & Nayakshin 1996). This is true even if the shell is only photon active when colliding with surrounding ambient objects. Such collisions would result in a random distribution in the separation of peaks. Instead, a log-normal distribution of peak separations is observed (Li & Fenimore 1996).

3.1.1 Testing for Photoelectric Absorption

In order to investigate whether the low-energy spectra of GRBs are consistent with an optically thin synchrotron spectrum depleted by photoelectric absorption, we have fit the time-resolved BATSE spectra of GRB970111 with a Band model (with $\alpha$ fixed to $-\frac{2}{3}$) suffering photoelectric absorption in a neutral medium where the opacity is calculated using the model of Morrison and McCammon (1983).
The gamma-ray burst of January 11, 1997 was a bright burst seen by many instruments including BeppoSAX and BATSE (trigger 5773). It also had a very high photon slope $\alpha = +1.5 \pm 0.2$ below the spectral break (Crider, Liang & Preece 1998b), making it an ideal candidate for absorption studies. We began our analysis by examining HER/HERB data from BATSE (Fishman et al. 1989) LAD 0 for GRB 970111, which is publically available from the Compton Observatory Science Support Center. This detector is the most normal to the burst ($\theta = 11.576^\circ$). The burst is also $132^\circ$ away from the geocenter, which helps reduce complications from Earth scatter. Our HER/HERB data is available spanning an energy range of 24 keV to 1996 keV and time interval of 0.03 to 21.8 seconds. The burst lasted for just over 40 seconds (as seen in Figure 3.1) in the BATSE range, so that the two last pulses are excluded from our analysis.

*Figure 3.1* Time history (64 ms bins) of GRB970111 as seen by BATSE.
Our fits of the synchrotron spectra suffering photoelectric absorption result in moderate $\chi^2$ values, typically 1.5 to 2.5. There appear to be similar systematic deviations at photon energies near $E_{pk}$ in many of the time-resolved spectra (see Figure 3.2). Furthermore, there were 10 time bins for which no fit with the photoelectric-absorption model was possible at all. The resulting $\tau_0$ values as a function of time are plotted in Figure 3.3. Such an evolution is only reproducible if the metal abundances were 100 times those of our solar system (Böttcher, Dermer, Crider, & Liang 1999). Finally, our fits to BATSE spectra using this model predict zero flux in the BeppoSAX band, clearly in conflict with observations. Thus we rule out photoionization as the cause of the steep $\alpha$ observed in GRB970111.

3.1.2 Testing for Synchrotron Self-Absorption

Synchrotron self-absorption (SSA) is another possible mechanism which may explain the paucity of photons just below the spectral break. We fit the time-resolved BATSE LAD spectra of GRB 970111 again, this time with a self-absorbed synchrotron shock function approximated by a broken power law with two breaks. We fixed the photon slope below the first break to +1 (Katz 1994) and the slope between the two breaks to $-\frac{2}{3}$ (for the slope expected for single electron emission synchrotron shocks; Katz 1994). This leaves 4 free parameters. The resulting $\chi^2$ values are similar to those found when using the Band GRB function. In Figure 3.4, we show the integrated spectra during the first 5 seconds for this burst fit with our simple SSA function. The reduced $\chi^2 (\nu = 115)$ of this fit is 1.09. Fitting this function to the time-resolved spectra reveals that the lower break energy $E_{abs}$ decreases monotonically while it is within the range of the detector (see Fig. 3.5).
Figure 3.2  Fit to a time-resolved BATSE spectrum of GRB970111 using a Band model with photoelectric absorption. The spectrum is integrated from 0.029 to 2.112 s. The fit ($\chi^2_\nu = 1.46$) results in a neutral hydrogen column of $N_H = 1.83 \times 10^{26} \text{ cm}^{-2}$ (assuming solar-system abundances), corresponding to an absorption depth at the iron K edge of $\tau_K = 258$. Taken from Böttcher, Dermer, Crider, & Liang (1999).

For fully radiative shock evolution, $E_{\text{abs}} \propto t^{-3/2}$, while for fully adiabatic shock evolution, $E_{\text{abs}} \propto t^{-1/2}$ (Sari, Piran & Narayan 1998). To compare the observed decay to these predictions, we fit our data with the function

$$E_{\text{abs}} = E_{\text{abs}(0)} \left[1 + \left(\frac{t}{t_{\text{decay}}}\right)^n\right]^{-1}$$

which becomes $E_{\text{abs}} \propto t^{-n}$ when $(t/t_{\text{decay}})^n \gg 1$. We found that this function fits our values of $E_{\text{abs}}$ very well and find that $t_{\text{decay}} = 9.3 \pm 0.5$ and $n = 2.2 \pm 0.3$.

If the paucity of photons just below $E_{pk}$ is due to synchrotron self-absorption, the magnetic energy density must be extremely high. From Rybicki & Lightman (1979,
Figure 3.3  Photoelectric absorption opacity at the Fe K-edge as a function of time. Parameters: \( n_0 = 5 \times 10^6 \text{ cm}^{-3} \), \( r_{\text{max}} = 0.18 \text{ pc} \), \( \Gamma_0 = 100 \), metal abundances = 100 \( \times \) solar-system metal abundances. Data points are the values obtained from fits to the time-resolved BATSE spectra of GRB970111. Taken from Böttcher, Dermer, Crider, & Liang (1999).

Eq. 6.53) we find that

\[
E_{\text{abs}} = C(p) \tau_T^{\frac{2}{p+1}} B_p^{\frac{p+2}{p+1}}
\]  

(3.2)

(also see Liang, Smith, Kusunose & Crider 1997). For convenience, we calculate \( C(p) \) for appropriate values of \( p \) in Table 3.1. Assuming that \( \Gamma = 1000 \) (making the co-moving \( E_{\text{abs}} \approx 70 \text{ eV} \)), \( \tau_T \approx 1 \) and using the Band et al. (1993) GRB function \( \beta \) to give \( p \approx 4 \), we find that \( B = 4 \times 10^7 \text{ G} \), which constrains some GRB models. Of course the BeppoSAX WFC data (2-40 keV) for this burst may be useful in eliminating this as a possible absorption mechanism.
Figure 3.4 A simple synchrotron self-absorption model fit to the first 5 seconds of GRB 970111 ($\chi^2_v = 1.09, \nu = 115$). Taken from Crider & Liang (1999).

3.2 Saturated Inverse Comptonization

Spectral breaks can also be caused by multiple Compton scattering (Fenimore et al. 1982, Liang & Kargatis 1996). In this case, the decay of $\alpha$ in "hard-to-soft" pulses can be interpreted as the Thomson thinning of a Comptonizing plasma (Liang, Smith, Kusunose & Crider 1997) and the initial $\alpha$ can in principle go as high as $+2$, because in the limit $\tau_T$ (Thomson depth) $\rightarrow \infty$ one would expect a Wien peak.
Figure 3.5  The decay of $E_{\text{obs}}$ with respect to time fit with Eq. 3.1. Arrows represent time bins where $E_{\text{obs}}$ was undetermined and presumed to be below the low energy detector cutoff.

Several factors make it difficult to clearly measure an early low-energy power law $\sim +2$ with BATSE data alone, even if the spectral break is related to a Wien peak. The most obvious problem is that the highest $\tau_T$ would occur earliest in a "hard-to-soft" pulse, when the flux is the lowest, so that fitting a precise spectral model becomes difficult. Another problem is that even if the true GRB spectral break is Wien-like, if one had used a function other than the Band et al. (1993) GRB function (e.g. broken power law) or simply measured the slope within the BATSE range, one could get a slope flatter than +2. This is evident in Figure 2.19, in which the maximum slope for the same set of bursts appears to only approach +1.5 while $\alpha_{\text{max}}$ appears to approach +2. This is because the exponential curvature depresses the apparent slope
relative to the asymptotic power law of the Wien function. Also important is that the Band et al. GRB function does not take into account the soft X-ray upturn expected from saturated Comptonization of soft photons (Rybicki & Lightman 1979, Liang, Smith, Kusunose & Crider 1997). If the lower boundary of the fitting energy window is below the relative minimum in the saturated Comptonization photon spectrum (Pozdnyakov, Sobol’ & Syunyaev 1983), any fitted, low-energy power law, such as the Band et al. GRB function, will be flatter than the true slope for the Wien peak. Preliminary results show that moving the lower energy cutoff of the fitting region allows one to get a higher $\alpha$. However, the uncertainty in $\alpha$ increases when reducing the size of the fitting window and thus the higher value of $\alpha$ may be misleading. Evidence for the X-ray upturns in the low-energy spectra have been found by Preece et al. (1996) who found positive residuals between the BATSE data and their fitted Band et al. GRB functions in many bursts.

As an attempt to overcome the complications addressed above, we examine two bursts that exhibit steep values of $\alpha$ and have spectral information below BATSE’s observation window. These are GRB970111, for which we have the reported BeppoSAX Wide-Field Camera spectra, and GRB990123, for which we have simultaneous optical measurements. Both bursts have the common “terrace-shaped” spectra common in

<table>
<thead>
<tr>
<th>$p$</th>
<th>$C(p)$</th>
<th>$p$</th>
<th>$C(p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>$1.8 \times 10^{-3}$ eV $G^{-2/3}$</td>
<td>4.0</td>
<td>$1.4 \times 10^{-4}$ eV $G^{-3/4}$</td>
</tr>
<tr>
<td>2.5</td>
<td>$8.4 \times 10^{-4}$ eV $G^{-9/13}$</td>
<td>4.5</td>
<td>$8.9 \times 10^{-5}$ eV $G^{-13/17}$</td>
</tr>
<tr>
<td>3.0</td>
<td>$4.3 \times 10^{-4}$ eV $G^{-5/7}$</td>
<td>5.0</td>
<td>$5.9 \times 10^{-5}$ eV $G^{-7/9}$</td>
</tr>
<tr>
<td>3.5</td>
<td>$2.4 \times 10^{-4}$ eV $G^{-11/14}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Calculated values of $C(p)$ for use with Eq. 3.2. See Rybicki & Lightman 1979 for details on calculating $C(p)$. 
saturated Compton processes. Using a Monte Carlo code, we make very preliminary fits to these two bursts.

3.2.1 Monte Carlo Simulation of Inverse Comptonization

The primary code used to generate the inverse Comptonization spectra for this research is adapted by Kusunose from the algorithm of Pozdnyakov, Sobol’, & Syunyaev (1983). It simulates the propagation of blackbody photons which are both emitted and scattered by a spherical thermal+nonthermal plasma. The plasma is characterized by the temperature $kT$ of the thermal leptons, the power law $p$ of the nonthermal leptons, and the fraction of leptons which are nonthermal $\xi$. Typically one million photons are generated and scattered through the plasma following the procedure described below:

(i) A blackbody photon is placed with random position and direction somewhere within the spherical plasma. The distance $\ell$ the photon must travel in this direction before it emerges from the sphere is also calculated. It is also assigned a weight $w = 1$ for reasons discussed below.

(ii) Using the Thomson depth $\tau_T$, the mean free path $\lambda$ the photon will travel before colliding with a lepton is calculated.

(iii) At this point, the photon has a probability $P = \exp(-\ell/\lambda)$ of escaping. For computational efficiency, the photon is “divided” here into the fraction of the photon that escapes and the fraction that is scattered by the lepton. The escaping fraction is added to the emergent spectrum, weighted by $wP$. The scattered fraction is given a new weight $w(1-P)$. If $w(1-P)$ is below some
predetermined minimum weight $\varepsilon$ (typically $10^{-10}$), no further calculations are made for this photon.

(iv) Next, the distance that the photon moves along its trajectory before it scatters off of a lepton is calculated. This is $\lambda = -\bar{\lambda} \ln[1 - r(1 - P)]$ where $r$ is a pseudorandom number between 0 and 1.

(v) Here the photon is Compton scattered by a lepton with a random direction and energy drawn from the thermal+nonthermal energy distribution. The photon is then given a new direction and energy. Steps (ii) through (v) are repeated until $w < \varepsilon$.

For completeness, we show here a sample input file in303.t9h for this code.

```
'spect-sph'         'sp303.t9h'
'elect-sph'         'el303.t9h'
'amxwl'             0.99
'kTe/mc2'           0.001957
'p'                 3.50000
'gam2'              1000.0000
'Tr(keV)'           4.139e-7
'tau_es'            45
'N'                 100000
'eps'               1.00000E-12
```

Very recently, we have begun using a similar Monte Carlo code (Böttcher & Liang 1998) adapted from an earlier code written at Lawrence Livermore National Laboratory. This new code avoids the *ad hoc* assumption that the initial photons
are blackbody. Instead, the synchrotron and bremsstrahlung produced by the thermal+nonthermal plasma is the source of the soft photons which are Comptonized. Additional parameters include the average magnetic field strength and the density of the plasma. Since the resultant Compton spectrum is largely independent of the seed photon spectral shape, use of the LLNL code does not change our results significantly.

3.2.2 Comparison with BeppoSAX Time-Resolved Spectra

While the BATSE data for GRB970111 were released to the public one year after the event, the BeppoSAX Wide Field Camera spectra for GRB970111 were not reported until a GRB conference in Rome held November 3 - 6, 1998. Using our library of Monte Carlo saturated Compton spectra, we made a preliminary fit to the spectra during the first 5 seconds of GRB970111 based on BATSE LAD data alone.

Hints of the characteristic terrace shape are already evident in the lowest few BATSE channels. Overlaying the nearly contemporaneous BeppoSAX WFC spectra shows that the low-energy upturn seen by BATSE does indeed continue down to at least 3 keV (see Figure 3.6). Once completed, a joint-fitting of the two datasets should constrain the parameters of the saturated Comptonization model.

3.2.3 Comparison with ROTSE Time-Resolved Observations

On January 23, 1999, a very intense gamma-ray burst triggered several instruments, including BATSE (trigger #7343), OSSE, COMPTEL, the BeppoSAX WFC, and the BeppoSAX GRBM. The location of this burst was automatically distributed to ground-based observers over the GRB Coordinates Network (Barthelmy et al. 1998). Only 22.18 seconds after the burst had triggered, the Robotic Optical Transient Search
Figure 3.6 Combined BATSE and BeppoSAX Spectra of GRB970111 during the first four seconds. Also plotted is the saturated Compton spectra generated with our Monte Carlo code \((\tau_T = 64, \xi = 0.01, p = 3.5, kT_e = 1\ \text{keV}, kT_{\text{photons}} = 4.139 \times 10^{-7}\ \text{keV}, \Gamma/(1+z) = 30)\).

Experiment (ROTSE) at Los Alamos National Laboratory had slewed to the position of the burst and imaged the sky. ROTSE is essentially an array of 4 commercial CCD cameras (Apogee AP-10 with Thomson 2048 x 2048 \(\mu\text{m}\) imagers) with telephoto lenses (Canon 200 mm, f/1.8) mounted on a rapid slewing mount (Epoch Instruments). It saw prompt optical emission for 10 minutes, at which point the transient faded below the detectors' sensitivity. At its peak the optical transient was 9th magnitude, bright enough to be seen by a human with a pair of binoculars.
At first glance, the gamma-ray time history and early ROTSE measurements seem to be unrelated. This prompted many authors to quickly claim that the optical emission resulted from a separate mechanism than the one responsible for the gamma-rays (Sari & Piran 1999a, Fenimore 1999, Briggs et al. 1999). Using the SHER/SHERB and the low-energy discriminator DISCSP1 data, both publicly available from BATSE, we determined the gamma-ray spectra coincident with the first three ROTSE observations. By simply extrapolating the gamma-ray spectra to the optical using the Band et al. (1993) GRB function, we discovered a remarkable correlation to the ROTSE fluxes (see Figure 3.7), strongly suggesting that the two energy regimes are related.

While the SHER/SHERB data can often be statistically consistent with many spectral functions, the MER/CONT data, with approximately 10 times as many counts, is much more restrictive. During the first ROTSE time interval, the MER data suggest an upturn at low energies, with the lowest channel being inconsistent with the Band GRB function fit by 6.7σ. The SD discriminator channel corroborates the MER/CONT upturn and is inconsistent with this fit by 3.7σ. When we fit the MER+DISCSP1 data with a Compton attenuation function (Brainerd 1994), we drastically reduced the χ² from 262 to 119. The Compton attenuation function can have a "terrace" spectral shape similar to the inverse Comptonization model within the gamma-ray regime, but it differs greatly just below BATSE's energy window. The extremely high column density (N_H > 10^{25} cm^{-2}) required to produce this spectra by Compton attenuation, even for sub-solar abundances of metals, would have completely absorbed the < 10 keV X-rays (Brainerd 1994, Liang & Kargatis 1994), contrary to the BeppoSAX data (Feroci et al. 1999).
Figure 3.7 The gamma-ray and optical prompt emission of GRB990123. The gamma-ray photon flux is calculated from MER data (23.95 to 1808.4 keV) fit using a Band et al. (1993) GRB function with $\beta$ fixed to -3 (as found by OSSE). Extrapolating a Band GRB function fit to the SHER/SHERB data during each ROTSE time bin gives V magnitudes (plotted as squares). This shows a similar evolution to the ROTSE observations (plotted as circles). There are minor differences in the time intervals used due to binning constraints. Taken from Liang, Crider, Smith & Böttcher (1999).
Returning to inverse Comptonization, we again use our Monte Carlo codes (Böttcher & Liang 1998) to make a preliminary fit to the broadband observations of GRB990123. Our results appear in Figure 3.8. It is evident that this process can naturally explain both the prompt optical and gamma-ray observations with a single emission mechanism. Currently, all other proposed models require a separate site for production of the optical flux. In addition, only the inverse Compton and Compton attenuation models can explain the unique terrace-shaped gamma-ray spectra seen in Figure 3.8a. Since the latter is inconsistent with the BeppoSAX data, we conclude the former is the best candidate for interpreting the observations. As was seen in GRB970111, this burst appears to be initially Thomson thick (\( \tau_T \approx 20 \)) and to thin out as the burst progress. In Figure 3.9 we show examples of different Monte Carlo Compton spectra to illustrate how the spectral shape varies with the different input parameters. From this, we see that the prominence of the terrace is primarily correlated with the Thomson depth.
Figure 3.8 The BATSE spectra of GRB990123 (crosses) coincident with the first three ROTSE observations (circles). The dashed curves show the extrapolations of the Band function fits to the gamma-ray data. The solid histograms show our Monte Carlo inverse Comptonization spectra. The parameters used in each simulation are: (a) $\tau_T = 20$, $kT \Gamma/(1+z) = 60$ keV, $f_{NT} = 3\%$, $B = 10^2$ G, $p = 3$; (b) same parameters except $\tau_T = 6$ and $p = 6$; (c) same parameters except $\tau_T = 8.4$ and $p = 6$. Taken from Liang, Crider, Smith & Böttcher (1999).
Figure 3.9  Compton spectra from a hybrid thermal-nonthermal plasma code (a) varying Thomson depth $\tau_T = [10^{-5}(A), 1(B), 6(C), 20(D)]$ with $kT=5$ keV, $\xi=10\%$, $B=10^3$ G, and $p=6$. Note that the uncomptonized spectrum (curve A) is a superposition of synchrotron and bremsstrahlung source functions; (b) varying nonthermal fraction $\xi = [3\% (A), 5\% (B), 10\% (C)]$ with $kT=5$ keV, $\tau_T=8.4$, $B=10^3$ G, and $p=6$. Note that the spectral break moves to higher energy as $\xi$ is increased; (c) varying thermal temperature $kT=[1$ keV (A), 3 keV (B)] with $\tau_T=16$, $B=10^2$ G, and $p=3$. Note that both the spectral break moves to higher energy and the spectrum gets harder as $kT$ is increased; (d) varying nonthermal lepton index $p=[6$ (A), 2 (B)] with $\tau_T=6$, $kT=5$ keV, $B=10^3$ G, and $\xi=10\%$. Taken from Liang, Crider, Smith & Böttcher (1999).
Chapter 4

Summary and Final Remarks

It is now nearly thirty years since the first detection of a gamma-ray burst. The multiwavelength counterparts that have eluded observers for all these years have been found. We now know that most bursters are from distant galaxies. We also believe that the newly discovered afterglows, which made this determination possible, likely occur when a relativistic blastwave collides with the surrounding medium. However, it has been shown that such a blastwave cannot reproduce the lightcurve or the prompt emission. In parallel to these advances, we carried out our own detailed examination of BATSE gamma-ray burst spectra. First, using a sample of 41 pulses clearly identifiable pulses in 26 burst, we confirmed the radiative cooling trend first observed by Liang & Kargatis (1996). We also found that while Liang & Kargatis reported an invariant cooling constant within 7 of their 12 multipulse bursts, this should be expected from the narrow range of possible $\Phi_0$ values and does not imply that the underlying cooling constant is invariant within a burst. Saturated Comptonization of a thermal plus nonthermal plasma could explain both the radiative cooling and integrated burst spectra. Examining time-resolved spectra of 79 BATSE bursts, we found that the maximum value (as high at 1.6 ± 0.3) and evolution of the Band GRB function parameter $\alpha$ (i.e. the photon slope below the spectra break) strongly suggest this as the emission mechanism. This also precludes the popular optically thin synchrotron shock model that predicts $-\frac{3}{2} < \alpha < -\frac{2}{3}$. Finally, the upturn in the spectrum we predicted below BATSE’s energy range for bursts with high $\alpha$ values (and
thus high Thomson scattering depths $\tau_T \approx 20$) has been tentatively confirmed with BeppoSAX X-ray data for GRB970111 and ROTSE optical data for GRB9990123.

4.1 Applying the Spectral Evolution Results

What physical parameters of bursters can be determined from our analysis of the spectral evolution? We have calculated for several pulses a cooling constant $\Phi_0$. Assuming saturated Comptonization, we also have the Thomson depth $\tau_T$ for a few bursts. With these and some fairly simple assumptions, we can infer many properties of the bursters.

Following Liang (1997), we first recognize that the observed energy flux

$$F_E = \frac{L' \Gamma^2}{4\pi d^2} \quad (4.1)$$

where $\Gamma$ is the bulk Lorentz factor of the emitter, $L'$ is the bolometric luminosity in the frame of the emitter, and $d$ is the distance. Since the GRB energy spectrum peaks within BATSE's energy window, it approximately measures the bolometric energy flux. Assuming energy conservation, the plasma will radiatively cool such that

$$L' = -N' \frac{dE'_{pk}}{dt'} \quad (4.2)$$

where $N'$ is the number of source leptons and $E'_{pk}$ is assumed to be the characteristic energy of the plasma. If we then differentiate Equation 2.13, we find

$$\frac{dE_{pk}}{dT} = -\frac{F_E}{\Phi_0} \quad (4.3)$$

where $T$ is the arrival time of photons as measured by the detector, which we now distinguish from time $t$ in the rest frame of the detector (Fenimore, Madras & Nayakshin
Realizing that \( \mathrm{d}T = \mathrm{d}t'/(2\Gamma) \) (Fenimore, Madras & Nayakshin 1996) and \( \mathrm{d}E_{pk} = \Gamma \mathrm{d}E'_{pk} \), we can combine Equations 4.1, 4.2, and 4.3 to find

\[
\Phi_0 = \frac{N'f}{8\pi d^2}.
\]  

(4.4)

From our definition of the Thomson depth

\[
\tau_T \equiv \int_{s_{\text{(source)}}}^{s_{\text{(observer)}}} n_e(s') \sigma_T \mathrm{d}s'
\]  

(4.5)

we see that

\[
N' = \tau_T 4\pi R^2 / \sigma_T
\]  

(4.6)

Coupled with Equation 4.4, this gives us

\[
\frac{d}{R} = 10^{12} \left( \frac{\tau_T}{\Phi_0} \right)^{1/2}.
\]  

(4.7)

From our spectral analysis we can measure \( \tau_T \) and \( \Phi_0 \) and thus find the distance-to-radius ratio. In Table 4.1, we show the parameters of the burster in terms of \( \tau_T \) and \( \Phi_0 \), normalized for GRB990123, but applicable to any burst (Liang, Crider, Böttcher & Smith 1999).

### 4.2 Caveats

In any model which attempts to explain gamma-ray bursts, some assumptions must be made. Fenimore has suggested that GRB models be critiqued by the number of "tooth fairies" they invoke (see Figure 4.1). While the saturated Compton model can naturally explain the spectral evolution of bursts, it requires a tooth fairy to release \( \sim \Omega \times 10^{57} \) ergs in the form of relativistic blastwaves such that they reproduce the chaotic time histories of bursts. Arguably, a second tooth fairy must also ensure that the emitted plasma will have a thermal+nonthermal particle distribution.
Table 4.1 Parameters of the GRB ejecta shell based on the saturated Compton model (scaled to the spectral parameters of the first ROTSE interval). Here $d_9 \times 9 \text{ Gpc}$ is the distance to the burster, $\Phi_{200} \equiv \Phi_0/200$, $\tau_{20} \equiv \tau_T/20$, $T_{10} \times 10 \text{ sec}$ is the pulse rise time in the detector frame, $\Omega_{4\pi}$ is the shell angular filling factor divided by $4\pi$, $n_p/n_e$ is the ratio of ejecta protons to leptons, and $n_{\text{ISM}}$ is the ISM density in cm$^{-3}$. The thickness in the comoving frame $H$ is derived assuming that the proper pulse rise time is equal to the photon diffusion time across the shell. Adapted from Liang, Crider, Böttcher, & Smith (1999).

Our first assumption is a common one among burster models. Most modelers do not attempt to explain the mechanism behind the initial energy release since it is presumably obscured by the resulting blastwave. We note however that some theorists instead begin with known populations of sources (e.g. compact object mergers; Popham, Woosley & Fryer 1998) and attempt to determine how often these could release energy in an fashion such that gamma-ray bursts are produced.

As for our particle distribution, first-order Fermi acceleration, which results in a power-law particle distribution, has been widely used to explain observations of shocks in both space physics and astronomy (Ellison, Jones & Reynolds 1990). For instance, spacecraft observations of the Earth’s magnetosphere show evidence for a thermal+nonthermal distribution function, which is parameterized as the "Kappa
function”

\[ f(E) = N \left( \frac{m}{2E_0} \right)^{3/2} \frac{\Gamma(\kappa + 1)}{(\pi \kappa)^{3/2} \Gamma(\kappa - \frac{1}{2})} \frac{1}{[1 + E/(\kappa E_0)]^{\kappa + 1}} \]  

(4.8)

where \( N \) is the number density, \( E_0 \) is energy of the peak in the differential flux, \( \kappa \) is the exponent of the differential flux at high energies, and \( \Gamma \) is the gamma function (not to be confused with the bulk Lorentz factor here; Vasyliunas 1968). Monte Carlo calculations of first-order Fermi acceleration in relativistic shocks have also shown that resultant particle distribution can be roughly thermal+nonthermal (Ellison, Jones & Reynolds 1990). Thus, our assumed particle distribution is not unreasonable.

4.3 Future Projects

At its inception, this thesis was planned to be a straightforward continuation of its predecessor (Kargatis 1995). We could not have anticipated the discoveries we would make in the spectral evolution, all of which point towards inverse Comptonization as the emission mechanism. Of course, the revolutionary work made possible by BeppoSAX also had an impact. There are several logical research paths one could
take based on the findings in this thesis. For the benefit of those who follow, we list them here.

4.3.1 Construction of a Library of Inverse Compton Spectra

Currently, no analytical solution is known for saturated \( \tau_T \gtrsim 20 \) Comptonization spectra. While over 500 Monte Carlo spectra have been generated by our group, these are from a variety of codes and cover only sporadic volumes of the parameter space, making interpolations difficult. Clearly, a dedicated effort is needed to generate an organized library using a single code which covers the parameter space evenly. The most recent version of our code has 5 parameters: temperature of thermal leptons \( kT \), Thomson depth of scattering medium \( \tau_T \), magnetic field strength \( B \), nonthermal lepton energy index \( p \), and fraction of nonthermal leptons \( \xi \). Strictly speaking, in a straightforward interpolation, only \( 2^M \) simulations are needed, where \( M \) is the number of parameters. (Thus, for a 1-dimensional parameter space, 2 simulations would simply be averaged.) In practice, at least \( 5^M \) will likely be required. The computing expense of generating these spectra is non-negligible. The X- and gamma-ray spectra are largely independent of \( B \), so this parameter could initially be held fixed.

It is not clear yet if interpolations can reproduce the Monte Carlo runs with reasonable accuracy. In Figure 4.2, we see three spectra generated using our saturated Comptonization code with three different Thomson depths \( \tau_T = 16, 32, 64 \). We overlay the "e-mean-log" of the \( \tau_T = 16 \) and \( \tau_T = 64 \) spectra. From this, it appears that the spectrum varies exponentially rather than linearly with \( \tau_T \). Such issues must be addressed for all parameters when interpolating saturated Compton spectra.
Figure 4.2 Monte Carlo spectra with $\xi = 0.1$, $kT_e = 1$ keV, $p = 3.5$, $kT_{\text{photons}} = 4.139 \times 10^7$, and Thomson depths $\tau_T = 16, 32, 64$. The interpolated spectrum between $\tau_T = 16$ and $\tau_T = 64$ cases is plotted as the smooth, solid line.

4.3.2 Development of a Semi-Empirical Compton Function

Even with a library constructed, the number of interpolations required for spectral fitting would make its use cumbersome for other researchers. It may be more useful to create a flexible empirical function which can represent the inverse Comptonization spectra. For example, a cutoff power-law added to a Band et al. (1993) GRB function should be capable of reproducing the X- and gamma-ray inverse Comptonization spectra. Limits can be placed on the parameters of the empirical function based on our current understanding of the physics. For instance, the photon spectral slope
of the cutoff power-law will be -1 when $\tau_T \gg 1$ and will steeper when $\tau_T \lesssim 1$. In Figure 4.3, we show examples of such an empirical function fit to our Monte Carlo simulations.

![Graph](image)

**Figure 4.3** Exponentially cutoff power law plus Band et al. GRB (1993) function fit to Monte Carlo spectra.
4.3.3 Deconvolution of GRB Data with a Time-Dependent Spectral Function

As was mentioned in Section 2.2.4, more pulses are clearly needed if one is to discriminate between the proposed time-evolving spectral functions. One could simply wait for bursts to occur or for a more sensitive instrument to be built. However, it may be possible to increase the number of fittable pulses using the existing BATSE database. Fitting a time-dependent spectral function directly to higher time resolution data (or time-tagged event data) greatly reduces the number of required fit parameters. Another approach may be to analytically integrate the time-dependent spectral function and fit that to integrated spectra, as has been done by Ryde & Svensson (1999). By increasing the number of pulses, it will become possible to make more definitive statements about the evolution of prompt GRB emission and how it relates to the GRB afterglow.

4.3.4 Identification of Extragalactic SGR Outbursts

In Section 1.1.2, we noted that the March 5th event and the recent outburst of SGR1900+14 would likely be mistaken for “hard/short” bursts by BATSE if they had occurred in nearby (< 5.5 Mpc) galaxy. Given our observations of two such outbursts in 30 years and BATSE’s sensitivity, we expect approximately 30 extragalactic SGR outbursts to be in the 4B catalog. Analysis of short, single-peaked BATSE bursts may reveal either a correlation with nearby galaxies or faint periodicities after the peak emission. In fact, it is possible that the handful of bursts with observed periodicities (Schaefer & Desai 1988) are in reality extragalactic SGR outbursts.
Bibliography


Bevington, P. R., 1969, Data Reduction and Error Analysis in the Physical Sciences, (New York: McGraw-Hill)


Böttcher, M. 1999, in preparation


Catelli, J. R., Dingus, B. L., & Schneid, E. J., AIP 4


Cline, T. L., Mazets, E. P., & Golenetskii, S. V. 1998, IAUC No. 7002


Djorgovski, S. G., et al. 1999a, GCN No. 251

Djorgovski, S. G., et al. 1999b, GCN No. 189


Eadie, W. T., Drijard, D., James, F.E., Roos, M., & Sadoulet, B. 1971, Statistical Methods in Experimental Physics (Amsterdam: North-Holland)


Feroci, M., et al. 1999, IAU Circ. 7095


Heuter, G. J. 1987, Ph.D. thesis (University of California-San Diego)

Hjorth, et al. 1999, GCN No. 219


Kargatis, V. E. 1995, Ph.D. thesis (Rice University)


Li, H., Duncan, R., & Thompson, C. 1994, AIP Conf. Proc. 307, 600-604


Shaviv, N. J. 1996, Ph.D. thesis (Israel Institute of Technology)


Vasyliunas, V. M. 1968, JGR Sp. Phys., 73, 2839
