Final Report: NAG5-11017

NASA Astrophysics Data Program 2000

"A Search for Early High-Energy Afterglows in BATSE Gamma-Ray Bursts"

Effective Date: 06/15/2001
Expiration Date: 01/14/2003
Extension Date: 04/28/2003

Dr. Timothy W. Giblin
Department of Physics & Astronomy
The College of Charleston
58 Coming Street
Charleston, SC 29424

(843) 953.5061
giblint@cofc.edu

Timothy W. Giblin
6/30/03

30 June 2003

I. Project Goals

The scope of this project was to perform a detailed search for the early high-energy afterglow component of gamma-ray bursts (GRBs) in the BATSE GRB data archive. GRBs are believed to be the product of shock waves generated in a relativistic outflow from the demise of extremely massive stars and/or binary neutron star mergers. The outflow undeniably encounters the ambient medium of the progenitor object and another shock wave is set up. A forward shock propagates into the medium and a reverse shock propagates through the ejecta. This "external" shock dissipates the kinetic energy of the ejecta in the form of radiation via synchrotron losses and slows the outflow eventually to a non-relativistic state. Radiation from the forward external shock is therefore expected to be long-lived, lasting days, weeks, and even months. This radiation is referred to as the "afterglow."

Because of the transient nature of GRBs, it has been extremely difficult to decipher afterglow from the "normal" GRB emission. Owing to the limited capabilities of our observations, we know very little of how the two are related. It is not clear when the afterglow begins, relative to the GRB, or at what energy we expect the initial afterglow radiation to peak. If the Lorentz factor of the outflow is very large (~500 or higher), then more kinetic energy is available and we expect the afterglow emission to peak initially in X-rays (~10 keV), or even gamma-rays (>20 keV) for highly energetic outflows.

We have seen some evidence in X-rays from the Italian-Dutch BeppoSAX spacecraft that the afterglow can temporally overlap with the GRB. It is not clear whether the afterglow is a continuation of the GRB or if the afterglow is due to a separate mechanism (such as the external shock) that happens to be temporally coincident with the GRB. In the latter case, we would observe a GRB with two emission components. The challenge thus lies within deciphering these two emission components from each other in the data.

The BeppoSAX data also suggests that in some bursts, the X-ray afterglow may begin tens or hundreds of seconds after the "normal" GRB has apparently ceased. However these results are only from about two dozen GRBs, a small sample considering the more than ~2700 bursts recorded by BATSE from 1991-2000. Nonetheless, the X-ray data suggest diversity among GRBs and their afterglows, i.e. there is no "rule" that the afterglow begins at the same time after the burst for all GRBs. A canonical delay time between the burst and the afterglow has yet to be found. This diversity is further corroborated by prompt optical observations made only for a handful of the BeppoSAX bursts by the ROTSE project. In the case of GRB990123, an optical counterpart was observed during the GRB itself reaching a brightness of 9^{th} magnitude. However, in other cases where ROTSE was able to make an observation, no detection was made down to the ROTSE sensitivity limit of ~14^{th} magnitude.

The onset of the afterglow and its relation to the GRB remains a major missing link in the GRB puzzle. Groups of bursts with varying afterglow delay times could possibly be a signature of different classes of gamma-ray bursts.

II. Milestones

In the internal/external shock scenario, electrons are accelerated at the shock front and obey a power-law distribution of energies. We expect the decay rate of the emitted afterglow radiation to obey a power-law function. As outlined in our proposal, we performed a search through the BATSE data for bursts with extended smooth decay features in their late-time light curves. Our sample resulted in 40 bursts: 17 single-pulse (or FRED-like, Fast Rise Exponential Decay) bursts, and 23 bursts that exhibited a period of variability followed by a smooth decaying emission tail. Our temporal and spectral analysis outlined in our original proposal yielded the following results:

- **Decay features are best described by a power-law, rather than exponential.** Most GRB pulse studies have modeled pulse shape using an exponential function. We performed a detailed temporal modeling of the tail features using a power-law function and an exponential. The exponential function was only as good as the power-law fit for 12 bursts. Our results support the findings of Ryde & Svensson (ApJ 566, 210, 2002), who studied the decay phase of GRB pulses with a broad range of durations. We find a mean power-law index of ~-2. Details of our temporal study are presented in Giblin et al. (ApJ 570, 573, 2002).

- **Time-dependent color-color diagrams illustrate the spectral evolution of the tail emission and reveal some consistency with synchrotron emission expected from the external shock.** To generate a color-color diagram (CCD) that preserved the temporal evolution of the burst, we color encoded the hardness and softness ratios in the CCD to match the time history. Figure 1 illustrates the time-dependent CCD for GRB980923, an early high-energy afterglow candidate (Giblin et al., ApJ 524, L97, 1999). We also folded the expected synchrotron spectrum (both fast and slow cooling modes) through the BATSE detector response matrices for the triggered detectors to produce the expected CCD patterns. These are represented as the solid and dashed lines in the CCD. We have applied this technique to the bursts in our sample. This technique is useful because it allows us to make comparisons of spectral evolution patterns among GRBs. By comparing CCD patterns of bursts in our sample and by checking for consistency with synchrotron emission, we found that 23 of the bursts in our sample were inconsistent with the expected synchrotron emission. The right panel in Figure 2 illustrates the CCDs for four of these bursts. Interestingly, their spectral evolution patterns are very broad (in both hard and soft colors), and remarkably similar to each another. The left panel shows CCDs for four bursts that show consistency with the expected afterglow synchrotron emission. Note the similarities in their patterns. Details of this CCD analysis are provided in Giblin et al. (ApJ 570, 573, 2002).

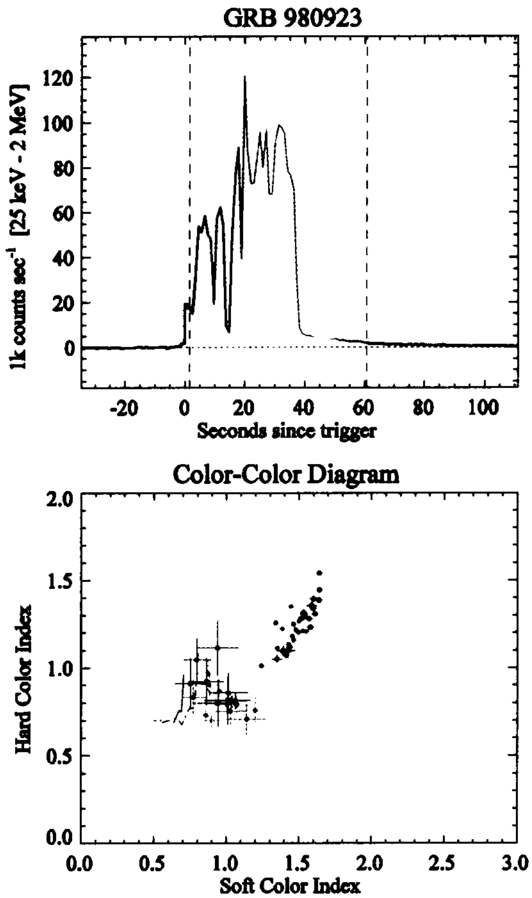

Figure 1 – Color encoded light curve and CCD for the early high-energy afterglow candidate GRB980923 reported by Giblin et al. (ApJ 524, L47, 1999). The tail emission (red and yellow) is clearly delineated from the main burst emission in the CCD. Further, it is consistent with the expected synchrotron pattern.

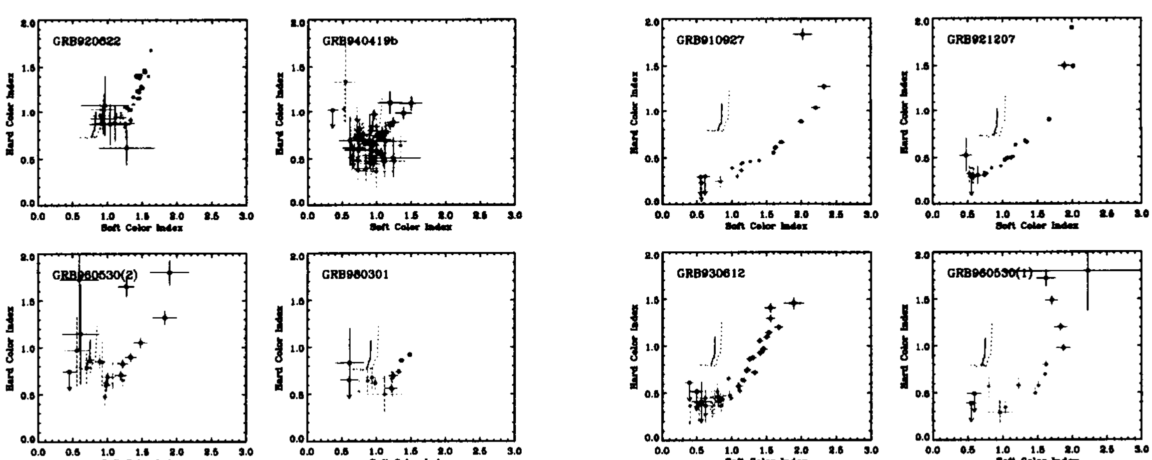

Figure 2 – (*Left panel*) A sample of burst CCDs consistent with afterglow synchrotron emission. (*Right panel*) A sample of burst CCDs inconsistent with afterglow synchrotron emission.

- **Spectral Modeling reveals nine bursts with tail emission consistent with synchrotron emission from an external shock.** Time integrated spectral fits were made to each tail using a smoothly broken power-law function for direct comparison with the predicted synchrotron spectrum, as outlined in our original proposal. Details of this analysis are provided in Giblin et al. (ApJ 570, 573, 2002).

- **Relation between temporal and spectral power-law indices indicate that some ejecta may be narrowly collimated, i.e. a jet-like geometry.** As described in our original proposal, several linear relationships exist for the temporal and spectral indices based on the geometry and position of the synchrotron break frequencies/energies. Given our model parameters, we can construct a plot of temporal vs. spectral index and plot the linear relationships for direct comparison with the fitted parameters. Figure 3 illustrates this plot for 21 bursts for which a spectrum could be reliably determined. The dashed line represents the relation expected for a jet like geometry, as opposed to spherical. Details of this comparison are provided in Giblin et al. (ApJ 570, 573, 2002).

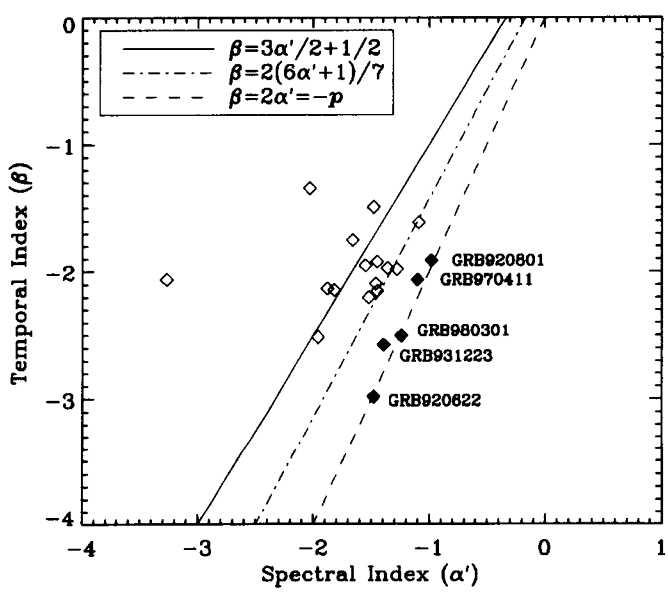

Figure 3 – Plot of temporal index vs. spectral index for 21 bursts in the sample. Filled diamonds are bursts within 1-sigma of the dashed line that indicates a jet geometry.

- **Combined results of the temporal and spectral studies give a total of 8 early high-energy afterglow candidates.** Time histories for these candidates are shown in Figure 4. Examination of these light curves indicates that in some bursts the afterglow overlaps pulses presumably due to internal shocks, suggesting that the forward external shock is initiated during the burst, not inconsistent with X-ray light curves of the bursts observed by BeppoSAX.

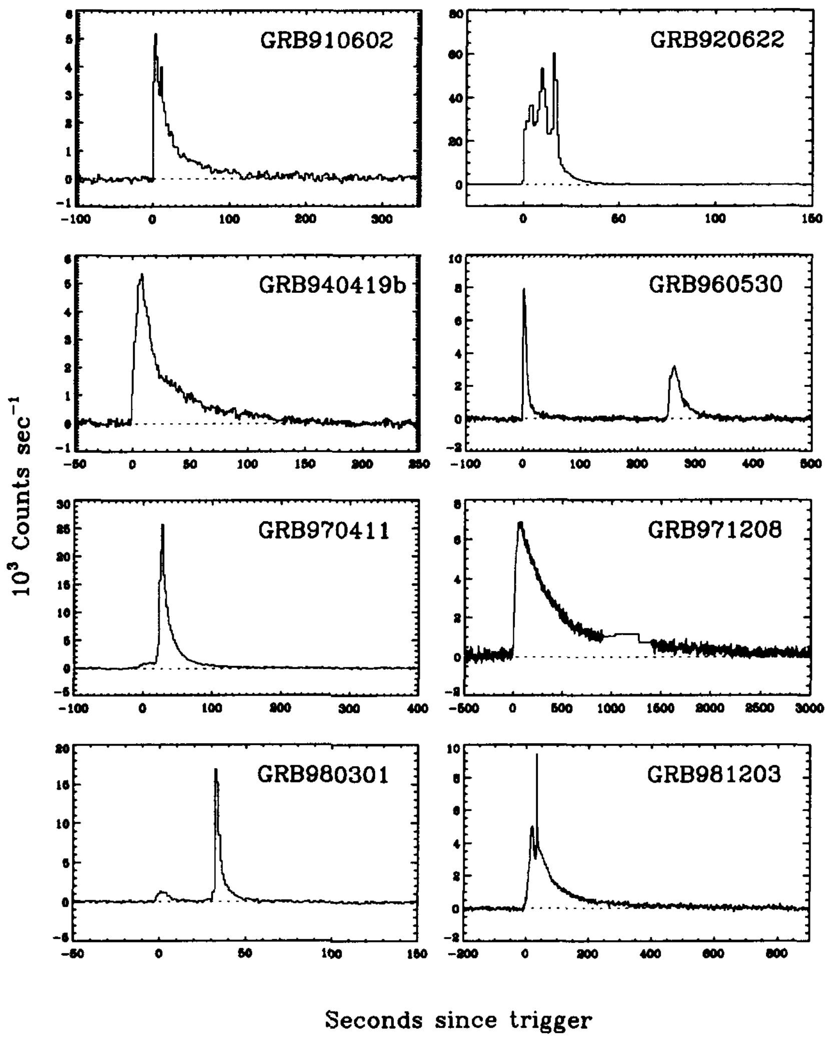

Figure 4 – Time histories for the 8 early high-energy afterglow candidates. Note that for the smooth single-pulse bursts, the early high-energy afterglow manifests itself as the actual GRB. *If this is indeed the case, then this prediction can be directly tested by the multi-wavelength capability of the upcoming NASA MIDEX Swift mission (to be launched in December 2003). The prediction can be made because the emission will be long-lived and persist for days and weeks as the synchrotron break frequency falls to lower and lower values, eventually passing through the optical and infrared.*

- **Quiescent GRBs may hold an important clue in finding the GRB/afterglow missing link.** In Figure 4, the light curve of GRB960530 displays a gap between the first and second episodes. It is the second episode of this burst that resembles the characteristic afterglow emission, not the first. Bursts that display this gap, or "quiescent" period where the burst seems to be "quiet," are referred to as quiescent GRBs. For example, the BeppoSAX X-ray light curves for GRB970228 exhibit a gap between the "prompt" burst emission and the onset of the afterglow. It is possible then, if the afterglow synchrotron frequency peaks initially in gamma-rays, that this resurgence of emission could appear late in the GRB light curve. We would expect the light curve of the second episode to be smooth, rather than variable like the prompt GRB emission from the internal shocks.

We initiated a study of quiescent gamma-ray bursts (GRBq) in the winter/spring of 2003. This study became a senior project for graduating physics major Thomas M. Freismuth at the College of Charleston under his advisor, Dr. Timothy Giblin. We combed the BATSE database once again, this time for quiescent GRBs. Our search resulted in a sample of 64 GRBqs. CCDs were constructed for each episode of each burst. We modeled the CCD pattern of each episode with a power-law function to search for trends in the data. We refer to this index as the spectral-evolution index. To build a comparison dataset, we constructed CCDs for 50 of the brightest GRBs. Histograms showing the distributions of spectral evolution indices for each set are shown in Figure 5.

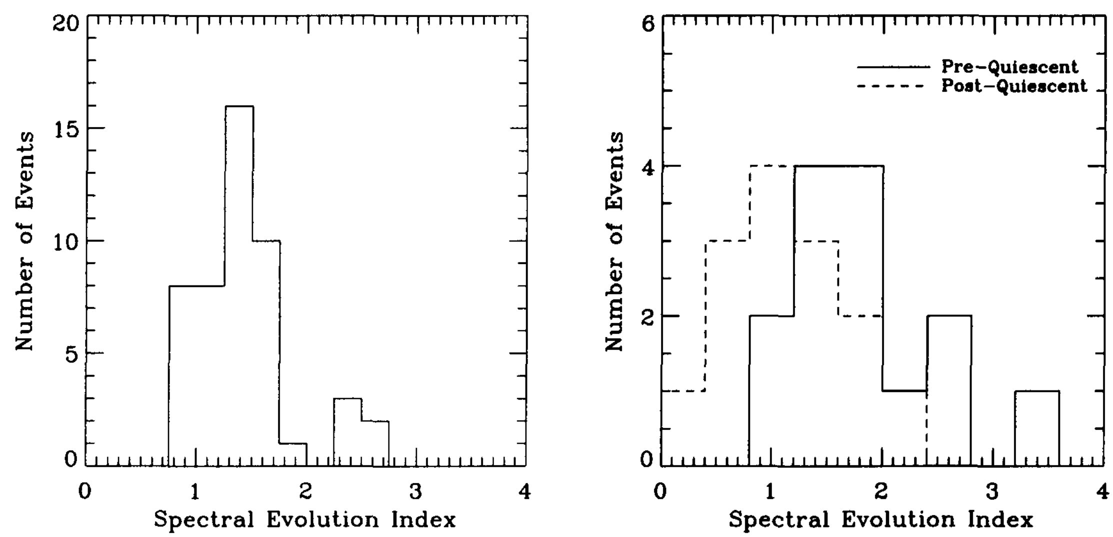

Figure 5 – (*Left Panel*) Distribution of spectral evolution indices for 48 bright GRBs with a weighted mean 1.55±0.01 and variance 0.20. (*Right Panel*) Distribution of spectral evolution indices for pre- and post-quiescent emission. Pre-quiescent distribution has a weighted mean of 1.63±0.01 and a variance of 0.43. Post-quiescent distribution has a weighted mean of 1.16±0.03 and a variance 0.31.

Considerable overlap is observed in the pre- and post-quiescent distributions; however, the means of the distributions are significantly different, as indicated by the student T-test. The post-quiescent spectral evolution is, therefore, generally softer (as indicated by a shallow spectral evolution index). About 50% of the GRBq's are consistent with synchrotron emission. Figure 6 shows the CCD(s) for the quiescent burst GRB980125 – note that the post-quiescent episode is consistent with synchrotron emission.

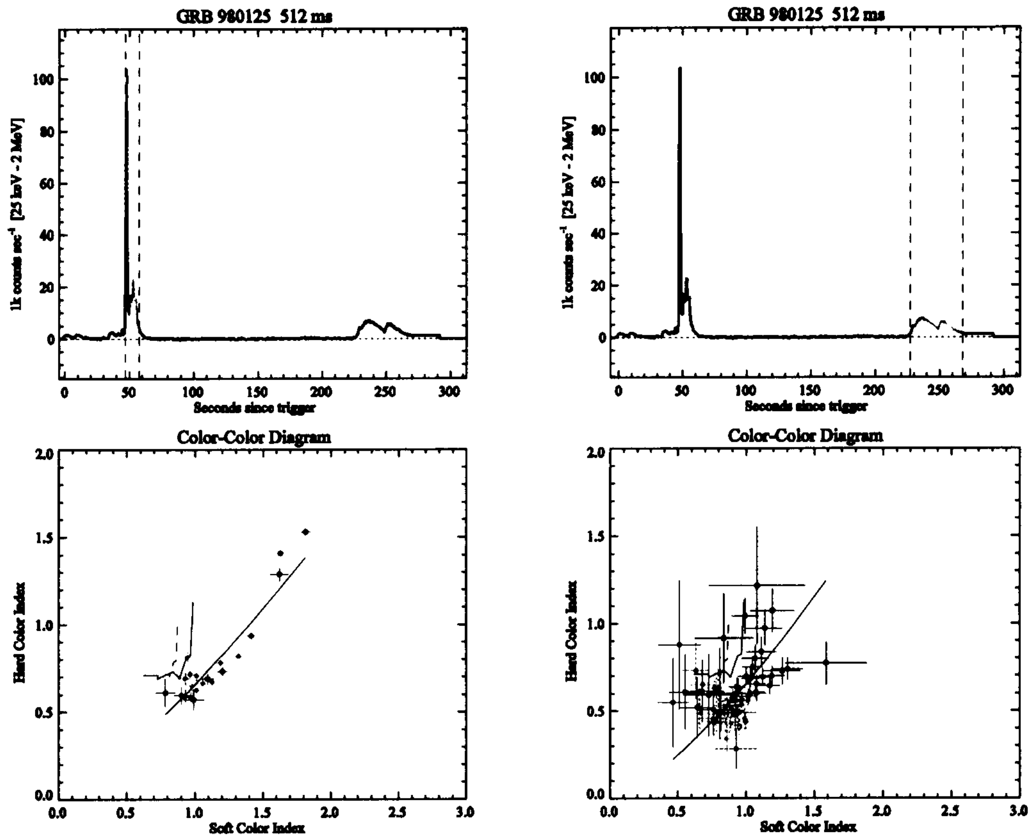

Figure 6 - CCDs for a GRBq: The pre-quiescent emission (*left*) exhibits a significant deviation from the synchrotron model, not unlike "normal" GRBs. The post-quiescent emission (*right*), however, is consistent with the synchrotron model, not unlike afterglow emission from an external shock.

We further note that when comparing the distribution of indices for bright bursts with the pre-quiescent distribution, we find a T-test probability of 0.16, indicating that the means are not that significantly different. This result is not surprising. Ramirez-Ruiz & Merloni (MNRAS 2001) studied a handful of bright GRBq's and concluded that the internal shocks may reach a metastable configuration, resulting in stored energy for an additional energy dissipation episode. Our results do not reject this hypothesis, *but also suggest that some quiescent bursts may be the result of an additional "non-burst-like" mechanism, possibly the onset of the GRB afterglow (i.e., the external shock).*

III. Future Studies

Under the auspices of this NASA ADP funded grant, our studies have definitively shown that a diverse range of behaviors between the prompt and afterglow emission exists in gamma-ray bursts. In particular,

(1) Apparently, not all GRBs display an early high-energy afterglow.
(2) In some events, the burst itself appears to be due to an external shock (i.e., no internal shocks)
(3) GRBs can contain two emission components - one due to the internal shocks, and one due to the external shock.
(4) The two emission components may overlap one another in time, making them difficult to decipher in the observed light curve (i.e., the delay time may be very short).
(5) GRBs may be highly collimated (as supported by long wavelength afterglow observations).
(6) The external shock emission component may appear at a later time, after the internal shocks have dissipated (producing a "quiescent" GRB).
(7) If quiescent bursts are some indication of the early high-energy afterglow component, then the afterglow may begin at very late times and at lower frequencies, rendering itself undetectable in the BATSE data. (This would explain point #1 above.)
(8) The external shock emission may deviate from a power-law time profile – that is, some variability may be observed initially (i.e., not all afterglows exhibit a "smooth" power-law decline in their light curves).

Our results have spawned new questions as to the nature of GRB emission, and the temporal and spectral properties of the very early afterglow. This has led to additional research projects that are currently being carried out at The College of Charleston in conjunction with an NSF funded research program. These projects focus on searches for two emission components within GRBs.

While our studies have produced some interesting and tantalizing results, early afterglow statistics from a large sample of bursts observed with the same instrument are still needed. Key issues in making this happen are: (i) increases sensitivity to lower flux levels, and (ii) broad (and simultaneous) spectral coverage from gamma-rays through low-energy X-rays. These types of observations will be provided by NASA's MIDEX *Swift* spacecraft set for launch in December 2003. In the Fall of 2003, our team will submit a Swift Guest Investigator Cycle 1 Proposal to begin analysis of the Swift data to verify our findings and perhaps make new discoveries of the transition between the GRB and the afterglow.

Invited Talks

"The BATSE View of the Transition From Prompt to Afterglow Emission", Timothy W. Giblin, invited talk at the 3rd Workshop: "GRBs in the Afterglow Era" in Rome, Italy, 2002.

Conference Presentations & Proceedings

"Extended Power-Law Decays in BATSE Gamma-Ray Bursts: Signatures of External Shocks?" Timothy W. Giblin, Valerie Connaughton, Jan van Paradijs, Robert D. Preece, Michael S. Briggs, Chryssa Kouveliotou, Ralph A. M. J. Wijers, and Gerald J. Fishman, *Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission*, Woods Hole , MA. AIP 662, eds. Ricker, G. R., and Vanderspek, R. K., pp. 273-275 (2003)

"Spectral Properties of Post-Quiescent Emission of Gamma-Ray Bursts", T. M. Freismuth, T. W. Giblin, J. Hakkila, *202nd Meeting of the American Astronomical Society*, Nashville, TN. BAAS 45.03, (2003)

Journal Publications

"Extended Power-Law Decays in BATSE Gamma-Ray Bursts: Signatures of External Shocks?" Timothy W. Giblin, Valerie Connaughton, Jan van Paradijs, Robert D. Preece, Michael S. Briggs, Chryssa Kouveliotou, Ralph A. M. J. Wijers, and Gerald J. Fishman, *The Astrophysical Journal*, 570, pp. 573-587 (2002)

Press Release

202nd AAS Meeting, Nashville, TN. May, 2003

FOR RELEASE: 10:00 am CDT, May 28, 2003

Media Contact:
Mike Robertson
Director of Media Relations
College of Charleston
Charleston, SC 29424
E-mail: robertsonm@cofc.edu
Phone: 843-953-5667

Science Contact:
Dr. Tim Giblin
Physics & Astronomy Department
College of Charleston
Charleston, SC 29424
E-mail: giblint@cofc.edu
Phone: 843-953-5061

Some Gamma-Ray Bursts, Once Turned Off, Blast Back Into Action

Scientists at the College of Charleston have found a rare subset of gamma-ray bursts that, once turned off, can turn back on full blast. By bringing into sharp focus a sometimes-overlooked but perplexing problem associated with gamma ray bursts (GRBs), the findings pose a challenge to the leading theory about the origins of these explosions, the most energetic in the Universe.

The findings are presented today at the 202nd meeting of the American Astronomical Society in Nashville, Tenn.

Shining with an energy exceeding a million trillion Suns, gamma-ray bursts are exceedingly distant, fleeting flashes of gamma ray light occurring nearly daily from random directions in the sky that are often followed by an "afterglow" of fading, less energetic light lasting hours, days, or even weeks.

Focusing on the little-known phenomena of "post-quiescent" emissions, the scientists say underscores just how much we have yet to learn, most notably about the "missing link" between the burst itself and the afterglow.

"The missing link refers to the distinction between the gamma-ray burst and the afterglow emission component," said Tucker Freismuth, who studied one of the largest GRB data sets recorded during a nine year period by the now-defunct Burst and Transient Source Experiment (BATSE). The study was Freismuth's senior thesis toward his just-completed Bachelors of Science degree in physics with astronomy concentration.

Freismuth explained that the only way to figure out this missing link is to have enough observations to produce a set of statistics on the distribution of time delays between the gamma-ray burst and the afterglow. This, in turn, would let astronomers figure out whether post-quiescent emissions represent a continuation of the burst or a rare especially energetic type of afterglow.

"We aren't saying that every gamma-ray burst with a delay between the burst and afterglow therefore has a quiescent episode," Freismuth said. "But it is also true we are not certain that the peak frequency of the afterglow is always less than the burst itself."

Working with his advisor Dr. Tim Giblin and Dr. Jon Hakkila, both faculty members of the college's department of physics and astronomy, Freismuth examined 2,704 gamma-ray bursts recorded by BATSE, the all-sky detector that flew aboard the Compton Gamma-Ray Observatory from 1991 - 2000. He was looking for bursts that, having shut off or gone "quiescent," suddenly flared again at gamma-ray energies.

They were looking for bursts whose quiescent episodes were as long or longer than the initial burst. The resurgence of gamma-ray emission they dubbed the "post-quiescent emission" since it comes after the quiescent component.

Analyzing the BATSE database, they found 23 GRBs showing a post-quiescent emission strong enough to analyze, although many more showed at least some evidence of such emissions.

Freismuth's advisor, Dr. Giblin, said it is important to understand the nature of these post-quiescent emissions in order to figure out if they are part of the burst or part of the afterglow phenomena. Such information would help refine the theoretical models involving GRBs, the chief one of which is the so-called "collapsar/fireball" model. This model attributes the burst phenomenon to the cataclysmic explosion of a highly energetic supernova (dubbed a "hypernova") that marks the deaths of especially massive stars and the afterglow phenomena to the collision of exploding stellar material with gas and dust in the surrounding interstellar medium.

Establishing that the post-quiescent emission is actually part of the afterglow component would mean, at least in some cases, its peak energy could occasionally be at gamma-ray levels rather than, as long predicted by theory, at the somewhat lower X-ray levels. This, in turn, would require at least some fine-tuning of the collapsar/fireball model.

Under this model, which has met with a good measure of success in describing both the characteristics of the burst itself and the afterglow, the burst is initiated as the dying star's core collapses into a black hole. This core collapse triggers a pressure wave that blasts out of the star in a particular direction as a fireball of heated stellar material.

Blobs of stellar material moving at different relativistic speeds inside the elongated fireball collide with each other, setting up internal shock waves that result in the release of the most energetic type of energy, gamma rays. The afterglow occurs as the blobs collide with gas and dust existing in the region around the star (the interstellar medium), creating external shock waves. These collisions are not as energetic, releasing X rays, and thereafter, as the fireball dissipates, the energy released drops down to visible light and even microwaves before disappearing entirely.

"The post-quiescent emissions may be originating in the shock wave as a result of variations in speed and density of plasma blobs being ejected by the star," Giblin said. "Or it may be we are seeing after some bursts the onset of the afterglow at gamma-ray energies. This would happen if the plasma blobs slammed into the interstellar medium at very high speeds."

Based on the spectral properties of the post-quiescent emission light curves, the team has found evidence that, in at least some cases, the post-quiescent emissions look suspiciously like those produced during the afterglow phase.

"We are fortunate to have seen a few cases in the BATSE data where the afterglow appears to overlap the GRB in time," Freismuth said. "Therefore, it is possible that in some cases we may see the afterglow begin some tens or hundreds of seconds after the burst, thus producing the observed quiescent period."

Freismuth, who will be attending graduate school at the University of Iowa in the fall physics, said many more observations are needed in order to build up a set of statistics.

"We need simultaneous GRB detection at as many wavelengths as possible, and we need high time-resolution data at as many wavelengths as possible in order to be able to answer these questions."