# BATSE OBSERVATIONS OF GAMMA-RAY BURSTS

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ABSTRACT

Gamma-ray bursts are currently perhaps the most mysterious phenomenon in the universe, once thought to originate on neutron stars in the plane of our galaxy. The BATSE instrument on *CGRO* does not observe the key prediction of this hypothesis; the data favor a population of sources either at cosmological distances or in an extended galactic halo. In this review, I present the observations upon which this mystery is based and discuss the major controversies in the study of this phenomenon.

# 1 Introduction

Gamma-ray bursts are transient events lasting from less than a second to several minutes, which originate outside our solar system. The sources of this emission radiate predominantly at $\sim 1$ MeV with emission detected between 1 keV and 18 GeV, yet no simultaneous emission at energies below the x-ray band and no quiescent radiation at any energy has been observed. In the years between the announcement in 1973 of the discovery of gamma-ray bursts by the Vela nuclear verification satellites[1] and the launch of the Compton Gamma-Ray Observatory (*CGRO*) in April 1991, a consensus had developed that bursts originated on local neutron stars (see Higdon and Lingenfelter[2] for a pre-*CGRO* review of the observations and theory). The Burst and Transient Source Experiment (BATSE) was placed on *CGRO* to verify the local neutron star paradigm and study the related phenomenology. However, BATSE has not observed the predicted signatures of a local neutron star population, turning these poorly understood events into perhaps the most mysterious astrophysical phenomenon.

In this review, I summarize BATSE's discoveries and the controversies over the interpretation of the BATSE data. Since I am a member of the BATSE team specializing in burst spectroscopy, this review will emphasize the observations rather than provide a detailed discussion of the theories which have been advanced to explain these observations. Over 100 different theories have been proposed since bursts were discovered (some of these theories are developed and discussed in multiple papers),[3] and therefore, a review of the current theories is likely to be of only short-lived interest, whereas the observational facts will (hopefully) only be elaborated upon by detectors with better temporal, spectral, and spatial resolution. The literature on gamma-ray bursts is vast, with over 2000 papers since the initial discovery,[4] and therefore, I can reference only a few representative examples; I apologize to my many colleagues whose papers I have omitted. Further details can be found in recent conference proceedings[5−7] and review articles.[8,9] This review is an expanded version of a review that appears elsewhere.[10]

To express its own concepts, every field has its own vocabulary, which is regarded by the uninitiated as "jargon." I have tried to minimize the use of unusual terms and define those which I find to be necessary. Thus, a "hard" spectrum has more photons at higher energy compared to a "soft" spectrum. Our detectors count individual photons, but because of the less than perfect quantum efficiency and uncertainty in the photon's energy, a detection is called a "count" and not a "photon."

## 2 Soft Gamma-Ray Repeaters

The origin of one type of gamma-ray burst has recently been identified. Before BATSE, the only known repeating burst sources were three "soft gamma-ray repeaters" (SGRs) which generally produce short duration bursts with lower energy emissions than classical bursts (i.e., all bursts other than SGRs), although the parameter range characterizing classical bursts overlaps with that of the SGRs. In addition, the SGRs repeat whereas whether classical bursts repeat is currently controversial.

The repeater SGR 0525-66 (astronomical sources are frequently identified by their celestial coordinates) is coincident with the Crab-like supernova remnant N49 in the Large Magellanic Cloud (LMC);[11] the first event identified from this SGR was the incredible burst of March 5, 1979, which began with a sharp spike and ended with 25 cycles of an eight-second periodicity (the only definitive periodicity detected thus far). The superposition of the error box of the March 5 event on N49 suggested a physical link, although the distance to the LMC was at the time considered problematic because of the large energies the burst would then have radiated ($\sim 4 \times 10^{44}$ erg). Crab-like remnants are filled with emitting plasma which is energized by a young pulsar; the archetype is the Crab Nebula which is powered by the Crab pulsar (hence the name of this type of remnant, which is also called a "plerion"). On the other hand, the usual type of supernova remnant is a shell of radio and optical emitting shocked gas where the blast wave from the explosion collides with the surrounding interstellar medium.

Recently, the Japanese x-ray telescope *ASCA* observed an x-ray transient from a second Crab-like remnant which occurred simultaneously with a burst from the SGR 1806-20 detected by BATSE;[12] quiescent x-ray emission was also detected from this source. These *ASCA* observations appear to have definitively connected SGRs with Crab-like remnants. To complete this association, the third source, SGR 1900+14, is near two Crab-like remnants.

Thus, SGRs almost definitely originate on galactic (or near-galactic in the case of the N49 SGR in the LMC) neutron stars. Whether SGRs are an extreme of a continuum of classical burst phenomena, or whether they constitute an independent class, is currently debated (a workshop on the topic is planned). Because of this controversy regarding their relationship to classical bursts, I will not draw any conclusions about classical bursts from the phenomenology of SGRs.

# 3 BATSE and Its Operation

The BATSE detectors are NaI scintillation counters and are therefore quite simple by the standards of modern experimental high energy physics. Only reliable and well-established detector technologies are used for space-borne instruments because of the large costs and long lead times in developing and launching these instruments, and the difficulty of repairing the detectors once launched (as shown by the recent repair of the Hubble Space Telescope). In a NaI detector, the high energy photon is absorbed in the NaI crystal, which then reradiates a fraction of the absorbed energy as optical photons. Photomultiplier tubes convert the light into an electrical charge; the voltage into a photomultiplier tube fixes the gain (the proportionality between the light and the charge). Discriminators determine whether the charge exceeds certain thresholds, while pulse height analyzers measure the charge. Thus the photomultiplier tube gain sets the energy range over which the detector is sensitive.

The BATSE detectors are housed in eight modules located at the corners of the *CGRO* spacecraft (see Fig. 1).[13,14] The primary detector in each of the modules, the Large Area Detectors (LADs), were optimized for detecting transient sources and recording their time histories. By observing sources disappear and reappear from behind the Earth, the LADs are also used to monitor the low energy gamma-ray sky; this highly productive aspect of their operation will not be discussed here. Operated in the 30-1000 keV band, each LAD was built around a single thin (1.27 cm wide) NaI(Tl) crystal with an area of 2025 $cm^2$. The LADs do produce spectra with up to 128 channels, but the thin NaI crystal gives an energy resolution of 30% at 88 keV. Useful spectral information with high time resolution (e.g., 64 ms during a burst) is also provided by the rates in the four discriminator channels which cover the energy ranges 30-50 keV, 50-100 keV, 100-300 keV, and 300 to $\sim$1000 keV. In addition, the LADs report the arrival times (to $2\mu$s) and discriminator channels of 16,000 counts detected just before and after a burst triggers the detectors.

Fig. 1. The *CGRO* spacecraft (left) and a cutaway of a BATSE module (right). The LAD is shown in the upper part of the diagram, while the SD is the cylinder protruding from the base.

Each of BATSE's modules also includes a Spectroscopy Detector (SD) which accumulates a series of 192 spectra after a burst triggers BATSE. Since the duration of the burst is not known *a priori*, this series of spectra may be exhausted before the end of a burst, or may consist predominantly of background accumulated after the burst finishes. An SD consists of a thick NaI(Tl) crystal with an area of 127 $cm^2$ and a thickness of 7.6 cm. The detectors accumulate spectra with 256 pseudo-logarithmic channels covering two energy decades between 10 keV and 20 MeV, depending on the photomultiplier gain. Currently, the SDs are operated in the range 10-1500 keV to maximize the sensitivity to spectral features at low energies (see Sec. 9 on lines below). In addition to accumulating spectra, the SDs report the arrival times (to 128 $\mu$s) and energy channel of 64,000 counts from the period just before and after the trigger.

The BATSE experiment triggers on a transient event when two or more LADs detect a 5.5 $\sigma$ increase in the 50-300 keV band over the background count rate accumulated in 0.064, 0.256 or, 1.024 second integration bins. Because the threshold is a function of the background count rate, and the detectors have a strong angular dependence, BATSE's trigger threshold varies over time and space. The LADs and SDs both accumulate large quantities of data of many types for a period of four (early in the mission) or ten minutes (currently) after a trigger. In addition, BATSE notifies the other *CGRO* instruments of the event, and indeed many amazing burst phenomena have been observed by these other detectors.

With its array of eight detectors, BATSE is able to localize bursts on the sky. The geometry of the LADs gives them a $\sim \cos\theta$ angular sensitivity. A burst is localized by comparing the rates in the various detectors which observe the burst, each with a different orientation to the burst. This seemingly simple localization method is complicated by scattering off the Earth's atmosphere which can contribute ~25-30% of the incident flux, and therefore, can create a large count rate in a detector facing *away* from a burst. Currently, burst positions are plagued by a 4° systematic error and a statistical error (resulting from Poisson fluctuations of the number of counts detected by the various detectors) which is typically 13° at the detection threshold, but which drops rapidly with burst intensity.

Strong bursts are also localized by comparing their arrival times at detectors distributed throughout interplanetary space; the resulting array of detectors is called the "interplanetary network" (IPN). The uncertainty in position for a strong burst with sharp, well-defined temporal features can be as small as an arcminute. Four or more detectors localize a burst to a single point, three detectors result in two points (even a crude localization by one of the detectors eliminates the ambiguity), and two detectors constrain the burst to an arc in the sky. When *CGRO* was launched, the interplanetary network consisted of BATSE, *Ulysses*, and the *Pioneer Venus Orbiter* (*PVO*). Since *PVO* ceased operating (mid-1992), the network has continued with only two instruments.[15] In addition, strong bursts occasionally fall within the field of view of the *CGRO*'s two imaging telescopes which can localize bursts to $\sim 1°$.

Cosmic gamma-ray bursts are not the only transient events detected by BATSE. Solar flares also trigger the LADs, and indeed, many spectacular flares were observed in the summer months of 1991 immediately after the launch of *CGRO* at the height of the solar cycle. In addition, events in the Earth's magnetosphere, emergences (from behind the Earth) or fluctuations of strong astrophysical sources (e.g., Cygnus X-1), and possibly even radiation from lightning in the upper atmosphere,[16] have all triggered the instrument. While these other sources, which produce ~2/3 of the triggers, reduce BATSE's livetime for observing bursts, they are interesting in their own right.

# 4 Burst Statistics

Since there are no means of measuring the distance to gamma-ray bursts, and thus no direct method of determining their true three-dimensional distribution, indirect statistical methods must be utilized. The most conclusive arguments for burst origin are based on the intensity and spatial (i.e., projection on the sky) distributions of burst ensembles, buttressed by physical speculation. In Euclidean space, the brightness $P$ of a burst decreases as the inverse square of the distance to the source, $P \propto r^{-2}$, while the volume $V$ out to that distance increases as the cube of the distance, $V \propto r^3$. Thus, for a constant source density, the number of bursts observed above a threshold brightness varies as the $-3/2$ power of the threshold, $N(\geq P) \propto V \propto (P^{-1/2})^3$. When the brightness threshold probes a region where the density is homogenous, then the cumulative intensity distribution should be a $-3/2$ power law, and the spatial distribution should be isotropic.

Before BATSE, the intensity distribution was indeed consistent with a $-3/2$ power law. Deviations from this power law at the faint end could be attributed to incompleteness; this incompleteness was reduced when the source intensity was measured as the peak count rate, the quantity on which detectors trigger. Similarly, the spatial distribution was found to be isotropic. Thus the source density was constant out to the distances to which bursts were detected. Since the sources were thought to be a galactic disk population, it was predicted that when detectors finally observed bursts beyond the sources' scale height (the length scale over which the source density drops perpendicular to the galactic plane) the faint bursts would be found preferentially in the plane of the galaxy, and the number of detected bursts would increase less rapidly as the detection threshold decreased. BATSE was built to be the detector which would detect bursts beyond the constant density region.

The use of the burst intensity distribution as a probe of the radial source density is complicated by the unknown luminosity function and the variable detector threshold. If the source density is constant, then the true cumulative intensity distribution, $N(\geq P)$, will be a $-3/2$ power law of the intensity, regardless of the luminosity function (more generally, a power law density distribution results in a power law intensity distribution). The luminosity function is irrelevant because the bursts of a given luminosity produce a power law distribution, and the observed distribution is merely the sum of these power law distributions, all with the same power law index. However, a varying detector threshold reduces the observed intensity distribution at the faint end. To test whether an observed deviation from a power law reflects the true shape of the intensity distribution (with implications for the source density) or results from variations in the threshold (which is an instrumental artifact), the intensity can be normalized by the threshold at the time of the burst; a power law of the intensity will also be a power law of the normalized intensity. It is best to use an intensity measure appropriate to the instrument's trigger criterion, which in our case is the peak count rate. Raising the normalized intensities to the $-2/3$ power results in the quantity $V/V_{\rm max}$ which (assuming the bursts occur in Euclidean space) compares the volume in which the burst was found to the volume in which it could have been found. If the source distribution is homogeneous in three-dimensional Euclidean space, then the observed value of $\langle V/V_{\rm max}\rangle$ should be $1/2 \pm (12N)^{-1/2}$ where the uncertainty results from the finite number $N$ of events. Using 657 BATSE bursts,

$$\langle V/V_{\rm max}\rangle = 0.330 \pm 0.011, \tag{1}$$

which shows that the burst distribution is not uniform. This is also apparent from the cumulative intensity distribution shown in Fig. 2.

The spatial distribution of the bursts BATSE has detected is consistent with isotropy, as shown by Fig. 3. Quantitative measures provide the limits which any model that predicts a deviation from isotropy must satisfy. Any source model which is not strictly isotropic produces deviations on large angular scales which can be characterized by modified dipole and quadrupole moments in relevant coordinate systems such as that of the galaxy.[17] The tendency towards the galactic center is measured by $\langle \cos\theta\rangle$, where $\theta$ is the angle between a burst and the galactic center. An instrument with uniform sky exposure would observe $\langle \cos\theta\rangle = 0$ for an isotropic source distribution but because of Earth-blockage and other more subtle effects $\langle \cos\theta\rangle = -0.013 \pm (3N)^{-1/2}$ is expected ($N$ is the number of bursts in the sample). With 1005 BATSE bursts, $\langle \cos\theta\rangle = 0.004 \pm 0.018$ is observed (a $0.9\sigma$ deviation). The preference towards the galactic plane is shown by $\langle \sin^2 b\rangle$ where $b$ is the galactic latitude. For isotropy, an ideal detector would detect $\langle \sin^2 b\rangle - 1/3 = 0$ while $\langle \sin^2 b\rangle - 1/3 = -0.005 \pm (12N)^{-1/2}$ is expected given BATSE's actual sky exposure; with 1005 bursts, BATSE finds $\langle \sin^2 b\rangle - 1/3 = -0.008 \pm 0.0091$ (a $-0.4\sigma$ deviation). Therefore, these two tests which are sensitive to the signature expected for a source population in the galactic plane yield results consistent with isotropy. The isotropy of various subsets of the BATSE burst ensemble has been considered, and no significant deviations have been found.[18,19]

Thus, BATSE finds that the intensity distribution deviates from a $-3/2$ power law at the faint end but that the bursts are still distributed isotropically on the sky.[18] The Earth appears to be located at the center of a spherical (or nearly spherical) source population whose density decreases beyond some radius, and *not* in a disk-like geometry. A basic prediction of the local galactic hypothesis has failed, invalidating the hypothesis. This is the observational basis of the excitement in the field. The galactic disk hypothesis can be resurrected only if the observations are discredited (e.g., the BATSE database is extremely incomplete) or if the hypothesis is modified (e.g., bursts emit preferentially towards the galactic plane).

If the sources are not distributed homogeneously in three-dimensional Euclidean space, then how are they distributed? The intensity distribution probes the radial structure of the source population, but it involves both the burst luminosity function and the variable detector thresholds. Normalized intensities and the $V/V_{\rm max}$ statistic remove the effects of the variable threshold for tests of source homogeneity but do not recover the true intensity distribution. Therefore, these quantities are not suitable for studies of the nature of the source inhomogeneity.[20] The appropriate techniques for modeling or constraining the source density use each observed burst as well as the known distribution of thresholds.[21,22]

# 5 Implications of Isotropy and Inhomogeneity

The BATSE observations indicate that bursts are isotropic but inhomogeneous (in Euclidean space). This can be explained by a number of models:

**Cosmological bursts**:[23] bursts distributed homogeneously out to cosmological distances would be isotropic while their number would increase less rapidly with distance in curved space than in Euclidean space. If the peak photon luminosity were a standard candle, BATSE's detection limit would be at a distance of $z \sim 1$ (Ref. 24). The necessary energy could be released by the merger of compact objects such as neutron stars, and indeed, close neutron star-neutron star binaries whose orbits are decaying by gravitational radiation are known to exist. These models require the release of enormous quantities of energy in small volumes (as determined by the short burst time scales) which will be opaque to gamma-rays

Fig. 2. Cumulative peak flux distribution for 444 bursts. The dashed curve is the $-3/2$ power law expected for homogeneity in Euclidean space. The filled-in region at the faint end of the distribution indicates the range of corrections for the variable trigger threshold. The peak flux is corrected for the angle between the burst and BATSE, and for the detector response in the 50-300 keV band.

Fig. 3. Spatial distribution of 585 bursts from the second BATSE catalog[50] in galactic coordinates.

as a result of photon-photon pair production. Since the observed burst spectrum extends well above a few MeV, relativistic fireballs and powerful shocks interacting with a surrounding medium have been invoked to circumvent this opacity to gamma-rays. Most cosmological models destroy the source to produce the burst; these models need to explain how such events can produce complex time histories, particularly for bursts which consist of spikes over a number of minutes. Also, if classical bursts are shown to repeat, then models which destroy the source are ruled out. Finally, gravitational lensing has been invoked to explain complex temporal structure, although no bursts with identical profiles or spectra have been identified.

**Extended galactic halo**:[25] if the halo is large enough (e.g., $\sim 150$ kpc) then our offset from the galactic center would not be apparent and the source distribution would appear isotropic but inhomogeneous. The absence of an excess of bursts towards nearby galaxies such as M31 places an upper limit on the halo radius, a constraint which is rapidly reducing the range of permitted models.[26,27] No known sources form an extended halo, but neutron stars born in the halo have been suggested.[28] The observation of high velocity pulsars approaching the galactic plane[29] suggests that these pulsars were born in the halo, perhaps in white dwarf systems.[28] Most models with sources born in the galactic disk have a density enhancement towards the disk; however, fine tuning a model with an asymmetric galactic potential can give an isotropic burst distribution.[30]

**Comets**:[31] a spherical population surrounding the solar system could also produce bursts. However, all known classes of solar system objects are highly anisotropic; for example, the Oort cloud is predominantly in the ecliptic.[32]

# 6 Cosmological Tests

If bursts are cosmological, then redshifting of the spectra and dilation of the temporal structure should be evident. Unfortunately, there are no characteristic temporal structures which can be used to measure the time dilation, nor are there spectral features whose redshift could be observed, and therefore, the tests must rely on averages over bursts in different intensity groupings (usually the peak count rate is used as the intensity measure). The tests proposed thus far assume that bright bursts are on average closer to the observer than dim bursts, and therefore the dim bursts should be redshifted and dilated relative to the bright bursts. The quantitative analysis of the cosmological effects generally assumes that the peak photon luminosity in the energy band of interest is a standard candle. At least 11 tests have been reported thus far:

1. Total counts normalized by the peak count rate:[33] this quantity, with dimensions of time, is about twice as large for dim bursts as for bright bursts, as expected for time dilation.
2. Wavelet activity:[33] akin to a Fourier power spectrum, the activity curve shows that (as normalized) dim bursts have more power on longer time scales than bright bursts, as expected for time dilation and verified by simulations.
3. Peak alignment: Norris *et al.*[33] find that when the highest peaks are aligned, the composite time history of the brightest bursts is narrower than that of the dim bursts, again consistent with time dilation. However, Mitrofanov *et al.*[34] do not find the cosmological signature; both groups need to investigate how the differences in their methodologies result in discrepant results.
4. Hardness:[35] bright bursts are harder than dim bursts, as expected for the redshifting of spectra which are concave down.
5. Average duration:[36] bright bursts have longer durations than dim bursts, consistent with time dilation.
6. Pulse widths:[37] when the burst time histories normalized (i.e., divided) by the peak count rate are decomposed into pulses with variable widths and normalizations, the pulses for the dim bursts are broader than for the bright bursts, as expected for cosmology.
7. Counts in pulses:[37] the total number of counts in the pulses found in Test 6 is greater for dim bursts than for bright bursts. Note that the pulses were derived for burst time histories which were normalized (divided) by the peak count rate.
8. Counts above background:[37] the total number of counts above background used in the pulse decomposition in Test 6 is greater for dim bursts than for bright bursts.
9. Auto-correlations:[38] the central peak of the average auto-correlation of an ensemble of dim bursts is broader than for an ensemble of bright bursts, as expected for time dilation. The width of the central peak (i.e., at zero "lag") of the auto-correlation function is a measure of the duration of emission

events within a burst. Only data around the highest time history spike are considered and thus this auto-correlation measures the width of the spike with the highest count rate.

10. Duration distribution:[39] the duration distribution of dim bursts is consistent with dilating the distribution of the bright bursts.

11. Interpulse duration: under consideration are different methods of measuring the time between major emission events within multispike bursts. This interpulse time may be a characteristic of the emission process and should show time dilation. Preliminary results[40] are contradictory.

These tests are not all independent, nor do they necessarily probe different time scales within a burst. Tests 1, 7, and 8 are clearly the same in that they calculate the ratio between the number of counts and the peak count rate. In Test 2, the wavelet activity on time scales longer than twice the burst duration is proportional to the number of counts in the burst, and therefore this test may be the same as Tests 1, 7, and 8.[41] Both the average time history in Test 3 and the auto-correlation in Test 9 measure the width of the peak with the highest count rate. Finally, in considering the average duration of dim bursts in Test 5, Norris *et al.*,[36] show that the entire duration distribution is shifted, as found by Test 10.

The interpretation of these tests is currently an active area of inquiry.[42] Most of the time dilation tests find the dim bursts are shifted relative to the bright bursts by a factor of order two. If the bright bursts are very local and the dim bursts are at the limit of BATSE's detection distance, then this shift indicates that BATSE's detection limit is at $z_{lim} \sim 1$. However, the bright and dim burst ensembles span nonnegligible intensity ranges and therefore the bright bursts cannot be assumed to be at $z = 0$ and the dim bursts at $z = z_{lim}$. The time dilation factor between bright and dim samples is $y = (1 + z_{dim})/(1 + z_{bright})$, which means that $z_{lim} \gg 1$. In addition, the temporal width of spikes is narrower at higher energies (a consequence of spectral evolution within bursts, which will be discussed below), and therefore spectral redshifting shifts narrower time structures into the observed spectral band. The effect of this redshifting is opposite of that of time dilation for tests which consider the width of individual spikes (e.g., Tests 3, 6, and 9), and therefore the dilation factor must be even greater to produce the observed shift for these tests. The resulting $z_{lim} \sim 6$ is much greater than previously thought.

An alternative interpretation of the observed trends shown by the above tests is that they reflect intrinsic correlations between burst properties. For example, Tests 1, 7, and 8 can be explained by a distribution of peak photon emission rates (i.e., a photon luminosity function) which is uncorrelated with the total photon emission when the burst sources are inhomogeneous.[41−44] Similarly, the hardness-intensity correlation in Test 4 can result from a photon luminosity-spectral hardness correlation (e.g., harder bursts might be intrinsically brighter) with an inhomogeneous source distribution. Note that these correlations between intrinsic burst properties imply that the peak photon luminosity is **not** a standard candle; the large dynamic range of observed burst properties makes it difficult to believe there are any standard candles in this phenomenon. This explanation of the above tests requires fine tuning of the intrinsic correlations; however, the cosmological interpretation is no longer consistently giving the expected $z_{lim} \sim 1$ (Ref. 42).

# 7 Repeaters

Since almost all cosmological burst models destroy their sources (e.g., in mergers of compact objects), the unusually vigorous debate over the existence of repeating burst sources is closely related to the galactic vs. cosmological controversy. Unfortunately, detecting repeaters in the BATSE burst ensemble is difficult because of the large BATSE error boxes. Also, with the low average sky-time coverage ($\sim 34\%$), BATSE may miss repetitions of a given source. Note that the existence of repeaters will not alter the conclusion that the source population is inhomogeneous in three-dimensional Euclidean space.[45]

When the positions of the first 260 bursts of the first BATSE catalog[46] were released, R. Lingenfelter noticed that a number of bursts within a few days of each other had strikingly similar coordinates, despite the large uncertainties in their positions. Because of these large uncertainties, the significance of repetitions even with coincident positions is not convincing; consequently, Wang and Lingenfelter[47] searched for repeating bursts with small spatial and temporal separations. The most significant ($P < 2 \times 10^{-3}$) cluster consists of five bursts.

The main debate over repeaters has focused on statistical measures of spatial burst separation which do not identify specific repeating sources but test whether there is an excess of bursts with small angular separations. Quashnock and Lamb[48] found such an excess using the "nearest neighbors" statistic on the first 260 BATSE bursts; this test considers the distribution of the distance between each burst and its nearest neighbor. Using the two-point correlation function, others find a much less significant signal at small separations and a comparable signal at large separations.[49] The virtues of these statistics are debated, and various groups edit the burst list based on different criteria.

The evidence for repeaters is weaker in the recently released second BATSE catalog[50] which, including the bursts presented in the first catalog,[46] consists of 585 bursts. The repeater signature is absent from the nearest neighbor and two-point correlation function analysis.[51−53] The strongest signal which has been found is in the spatial-temporal correlations,[54,55] and not all studies have found this correlation in the second catalog.[56] However, these studies cannot rule out $\sim 20\%$ of the observed bursts coming from repeaters.[51,56] Because of instrumental difficulties during *CGRO*'s second year of operation (*CGRO*'s tape recorders failed and the real-time telemetry was not yet optimized), bursts could be observed a smaller fraction of the time for this second group of bursts compared to the first group. Thus the probability of detecting repetitions of an observed burst is smaller; whether this is sufficient to explain the weaker or absent signature of repeaters is currently debated.

Clearly, the issue of whether classical bursts repeat will remain unresolved until detectors with better spatial resolution accumulate a large enough catalog.

# 8 The Ultimate Solution

The study of the spatial and intensity distributions has established the qualitative nature of the source population. We appear to be at the center of a spherical, bounded density distribution; a departure from isotropy is possible, but must be small. Since it is the convolution of the radial density and the luminosity function, the intensity distribution is not very constraining. In addition, the search for cosmological signatures has not thus far yielded a decisive conclusion, and any results will always be explained by opponents of the cosmological model as the product of intrinsic burst correlations or of systematic effects.

Most likely, the nature of the source will be determined by discovering a counterpart to a burst. Indeed, the origin of the Soft Gamma Repeaters has been established by identifying SGR 1806-20 with a Crab-like supernova remnant (Sec. 2). There is a long history of searching the smaller burst error boxes for likely sources (see Schaefer[57] for a review). A number of major efforts are underway to find a counterpart. By monitoring the telemetry from BATSE, the BACODINE system[58] localizes the position of strong bursts and notifies observers worldwide in less than ten seconds after the trigger, while the burst may still be in progress. To be launched in mid-1995, the HETE satellite[59] will carry gamma-ray, x-ray, and ultraviolet detectors which will view the same $\sim 2\pi$ steradian region of the sky; the hope is that the x-ray and ultraviolet instruments will localize the burst, leading to the identification of a counterpart.

However, once the type of source is revealed, the phenomenon will still not be understood until detailed physical models are constructed which explain the origin of the energy, how it is released, and finally, how it is radiated. These models will be guided and constrained by the rich burst phenomenology. In particular, the temporal and spectral properties probe the emission processes and the mechanisms by which the energy is delivered to the emission region. Even in the absence of a detailed understanding of the origin of bursts, we can nonetheless accumulate observations which future theories will have to explain.

# 9 Line Features

Konus,[60] *HEAO 1*,[61] and *Ginga*[62] observed absorption lines in burst continua below 100 keV. These features were attributed to cyclotron absorption in $\sim 10^{12}$ gauss magnetic fields.[63] Since neutron stars are the only known astrophysical bodies with fields of this magnitude, these observations supported the neutron star hypothesis. Consequently, confirmation by BATSE of the reality of these absorption features will help preserve this important constraint on burst sources at a time when the neutron star paradigm is in doubt. The existence of these features is therefore perhaps the most significant burst-related observational issue which BATSE can resolve.

No definitive lines have been identified yet in the $\sim 200$ BATSE bursts searched thus far.[64] The relevant observations are from the SDs which accumulate a series of spectra during a burst; since the duration of the burst is not known *a priori*, the number of spectra spanning the burst varies. The telemetry provides data from up to four detectors which observed the burst, permitting independent confirmation of the existence of a line. In the first search by the BATSE team, each accumulated spectrum was scanned visually. Even if a line persisted for a number of these basic spectra, our assumption was that it would be visible in the individual spectra. This search has identified line candidates, but none meet our detection criteria (which are discussed below). To begin soon, our second search will be computerized, thus removing the subjectivity of the human eye. By searching progressively longer sequences of spectra, this search should find any features which persist over a number of the spectra accumulated by the detectors but which are not obvious to the eye in any individual spectrum. In addition, this search will accumulate statistics regarding the distribution of line-like fluctuations.

The detection criteria are determined by the concern that a line candidate is a statistical fluctuation. Because many spectra are searched, a detected line must have an $F$-test probability of less than $10^{-4}$ of being a fluctuation, and consistency is required among all the detectors which could have observed the line. The $F$-test calculates the probability of finding the observed improvement (as measured by $\chi^2$, the statistic which quantifies the quality of a fit) in fitting a spectrum with a continuum+line model compared to a continuum model if the line is actually a fluctuation. The probability of a false positive (i.e., considering a fluctuation to be a real feature) is the $F$-test probability times the number of "trials," the possibilities for such a feature to occur. Calculating the number of trials is a difficult methodological problem which we have not yet solved definitively. We do not require a significant detection by more than one detector, but because a burst is almost always viewed by multiple detectors, the line should be evident, if not significant, in more than one detector. We therefore demand consistency among all the detectors which could have seen the line feature.

A number of candidates have been identified, but none have met the detection criteria. Figure 4 shows a line candidate which is significant in one detector, yet is not apparent in a second detector. Thus this candidate does not meet the consistency criterion.

The absence of any detected lines has led to a number of related studies. First, we are investigating whether the SDs are operating properly. Background lines are evident in all spectra, although they are at higher energies than the expected absorption features. We observed the x-ray pulsar Her X-1 which has a cyclotron line at $\sim 36$ keV;[66] the single count spectrum studied thus far shows evidence

Fig. 4. The line candidate in GB930506.[65] On the left are the count spectrum from detector 2 (data points) and model count spectra with (solid curve) and without (dashed curve) an absorption line. The $F$-test probability for the improvement in the fit using a two-parameter line model is $P = 6.1 \times 10^{-5}$. On the right is the count spectrum for detector 7 in which no line is apparent. The burst angle for detector 7 is 56.2°, and for detector 2 it is 73.7°. Because of the inconsistency between the two detectors, we cannot consider this to be a detection.

for this line. However, the Her X-1 continuum is very steep whereas the burst continuum is relatively flat, and therefore there are aspects of the detector response which are not tested by the Her X-1 observations. A number of additional Her X-1 observations remain to be analyzed, and further observations are planned.

Second, we are evaluating the detectability of lines in our spectra. This type of study requires the underlying line distribution, but too few lines have been detected and properly reported by previous instruments to characterize this distribution reliably. Thus, most of our analysis has focused on the detectability of lines similar to those observed by *Ginga*. Line detectability as a function of various parameters (e.g., burst angle, strength of the underlying continuum) is derived by simulating BATSE observations of various incident photon spectra which include lines. Because of Poisson fluctuations, a line may be detected in only a fraction of the simulated spectra; in other spectra, the fluctuations may conspire to make the line less significant. The detection probability is the fraction of the simulations which would be considered detections; these probabilities are used to assess BATSE's line-detection capabilities and for detailed calculations comparing BATSE to other detectors. *Ginga* observed a number of features at $\sim 20$ keV and

$\sim 40$ keV; our simulations show that lines at 40 keV can be detected for most burst angles, but lines at 20 keV can usually be detected only for small burst angles (e.g., $\theta \leq 45°$).[67] In addition, the spectra often do not extend to low enough energies for the detection of lines around 20 keV, although we have been operating most of the SDs to be sensitive to the lowest feasible energies.

These simulations also demonstrate the detection capabilities of our detector array.[67] Although the search for absorption features has a high priority, two detectors are kept at low gain to observe high energy spectra, and are thus unable to detect features below $\sim 200$ keV. For instrumental reasons, the gain for a third detector cannot be pushed high enough so that the observed spectrum extends low enough for lines to be detected. Thus, five detectors can observe lines. By considering all possible directions between the burst and the detector array, we find that the probability of detecting a line is not significantly impaired by having only five detectors searching for lines, instead of all eight.

Finally, we developed methodologies to evaluate whether the absence of BATSE line detections is inconsistent with the earlier detections.[68] These comparisons require information not only about the lines which were detected but also the detectability of lines in the bursts where no line was detected. A careful analysis of the previously reported detections shows that insufficient information was provided to evaluate the KONUS line significances and the detectability of lines in the KONUS and *HEAO 1* bursts. Therefore, the comparison is between two *Ginga* detections and no BATSE detections. Definitive calculations are not yet complete, but we have performed preliminary estimates. Although many ($\sim 200$) bursts have been searched, only a few ($\sim 18$) were intense enough for the detection of *Ginga*-like lines. We have developed different measures of the consistency between *Ginga* and BATSE. We estimate a maximum probability of $\sim 3\%$ that *Ginga* would detect two or more sets of lines and BATSE none; given that there are two detections, the probability that both would be in the *Ginga* bursts is $\sim 13\%$. Bayesian comparisons between the hypothesis that lines exist and the instruments function as understood, and various hypotheses regarding instrumental deficiencies, also indicate there is no inconsistency between *Ginga* and BATSE. Therefore, the apparent discrepancy between the BATSE and *Ginga* results is not yet critical.

## 10 Burst Continua

Burst spectra can be characterized by the four-parameter functional form[69]

$$N_E(E) = AE^\alpha e^{-(E/E_0)}, \quad E < (\alpha-\beta)E_0 \quad , \qquad (2)$$
$$= A'E^\beta, \quad E \geq (\alpha-\beta)E_0 \quad ,$$

where $A'$ is chosen so that $N_E$ and its derivative are continuous. The parameters $\alpha$, $\beta$, and $E_0$ all vary, with typical values of $\alpha \sim -0.5$, $\beta \sim -2$, and $E_0 \sim 150$ keV. This parameterization is adequate for detectors with the moderate energy resolution of NaI; undoubtedly detectors with superior energy resolution will require more complicated parameterizations in the future. Since both $\alpha$ and $\beta$ vary, the energy $E_p$ of the peak of $EN_E$ is a better measure of how hard the spectrum is than $E_0$. If $\beta \leq -2$, then $E_p = (2+\alpha)E_0$. Proportional to $\nu f_\nu$, $EN_E$ is the energy flux per logarithmic energy band, and its peak indicates where most of the energy is radiated. Both $E_p$ and $E_0$ vary from burst to burst and within bursts, indicating that there are no characteristic energies.[69] Such a characteristic energy might be expected from an atomic transition or absorption edge, the transition from atomic absorption to Compton scattering, or the radiation from electron-positron annihilation. These processes may be present (pair processes may be unavoidable) but any characteristic energy must be erased by reprocessing. Figure 5 shows the distribution of $E_p$ and $E_0$.

A number of strong bursts have occurred within the field-of-view of COMPTEL and EGRET, *CGRO*'s two gamma-ray telescopes. The spectra are usually power laws with indices of $-2 \leq \beta \leq -2.5$ up to 100s of MeV;[70,71] thus the spectral form in Eq. 2 appears to be valid over four energy decades!

EGRET has detected photons with energies greater than 1 GeV, often a few minutes after the bulk of the burst emission observed by BATSE. In the recent burst GB940217,[72] EGRET detected in its spark chamber ($E \geq 30$ MeV) ten photons during the three minutes that BATSE detected emission, eight photons during the next 15 minutes, and another ten photons 90 minutes later. Since there were many gaps in the telemetry, we can assume that this high energy emission continued for about an hour and a half after the BATSE trigger! Among the spark chamber events were photons with energies of 2.5, 3, and 18 GeV; the highest burst emission yet observed, the 18 GeV photon, was detected 103 minutes after the BATSE trigger. This high energy radiation appears to be a new emission

Fig. 5. Distribution of energies which measure the spectral hardness for a sample of 54 strong bursts.[69] Two different energies are derived from fits to the average burst spectra: the break energy $E_0$ in Eq. 2 (solid histogram) and the energy of the peak of $EN_E$ (dashed histogram).

component both because it exceeds the extrapolation of the low energy spectrum to higher energies, and because it continued after the low energy emission ended.

During a burst, the spectrum changes not only in intensity but also in shape. Almost always, the spectral hardness (characterized by $E_p$, the peak of $EN_E$) rises and falls with the intensity,[73] although the two quantities are not strictly correlated, and the hardness often leads the intensity. Specifically, as in previous studies,[74] BATSE finds hard-to-soft spectral evolution both within intensity spikes and from spike to spike (see Fig. 6).[75] In general, the spectrum hardens $\sim 0.1$ second before the intensity increases, and the emission softens as the burst progresses. Bursts usually begin with very hard emission. These are general trends, but counterexamples can be found. BATSE's spectra with the highest energy resolution frequently do not have sufficient temporal resolution to characterize the spectral evolution fully.[75] Consequently, we are investigating the use of BATSE data with less spectral resolution but greater temporal resolution.

Explaining fully the observed spectral evolution is impossible before the identification of the sources of gamma-ray bursts and the construction of detailed

Fig. 6. Example of spectral evolution within the burst GB920525.[75] The solid histogram is the count rate (left-hand axis) while the diamonds are $E_p$, the energy of the peak of $EN_E$ (right-hand axis). The width of the diamonds shows the time over which the spectrum was accumulated, and the height indicates the uncertainty range of the energy.

physical models. However, the data lead to some general speculations. That the spectrum hardens at the beginning of an increase in the burst intensity suggests that the intensity increase results from an energizing event, perhaps with the higher energy particles emitting on a shorter time scale and at higher photon energies than lower energy particles. The softening of the spectrum between successive intensity spikes indicates that a single emission region "remembers" previous emission events or that multiple emission regions communicate.

## 11 Burst Classes

Bursts come in a bewildering variety of morphologies, durations, and spectral shapes, and attempts at taxonomy have generally been unsuccessful. Some bursts are single spikes while others are a complex of many spikes. Many bursts rise and fall smoothly, while others show a great deal of substructure. Others consist of a series of events with no detectable emission in between. Figure 7 provides examples of burst time histories.

One clear division among bursts has been found. Kouveliotou *et al.*[76] find that the distribution of burst durations is bimodal, with the cusp at $\sim 1.5$ seconds (see Fig. 8). Similarly, Lamb *et al.*[77] divide bursts by the sharpness of the spike with the highest count rate. Although these two studies disagree as to the more physically meaningful definition, the divisions are usually the same since the short bursts generally have sharper spikes.

## 12 Summary

In this review, I have attempted to cover the highlights of the current excitement over the nature of gamma-ray bursts. The BATSE bursts are isotropic yet inhomogeneous (in Euclidean space). Thus, we appear to be at the center of a spherical source distribution where the density decreases beyond a certain radius (which is currently unknown); deviations from isotropy are still possible but must be very small. A cosmological origin is the simplest astronomical explanation of these statistical properties, although no physical model has been proposed which explains the observed wealth of spectral and temporal detail. On the other hand, the range of permitted parameters for a galactic halo population is shrinking as

Fig. 7. Time histories of a number of bursts observed by BATSE.

Fig. 8. Distribution of burst durations.[76]

the isotropy constraint becomes more stringent and no excess towards M31 is observed; in addition, no known halo population has the correct characteristics. The energy requirements for a halo population is approximately a million times greater than for local galactic disk sources, and therefore most of the pre-BATSE models are irrelevant.

BATSE's observation of an inhomogeneous yet isotropic burst distribution has thrown doubt on the model wherein gamma-ray bursts originate on strongly magnetized neutron stars. The neutron star model was supported by pre-BATSE observations of absorption dips below 100 keV which were interpreted as cyclotron absorption in teragauss magnetic fields. To date, no definitive line features have been discovered in the BATSE spectra, but our calculations show that the apparent discrepancy between the BATSE nondetections and the detections by previous missions is not yet significant.

The origin of gamma-ray bursts may not be known until a burst counterpart is discovered. However, even when the source type is identified, the phenomenon will not be fully explained until detailed physical models are constructed. The BATSE observations of the shape of burst spectra and their evolution will guide and constrain these future models. To the spectral resolution of BATSE's NaI detectors, the spectrum can be described over four energy decades as a high energy power law $N \propto E^{\sim -2}$ with curvature below 1 MeV; this continuum favors no characteristic energies. Recent EGRET observations suggest the presence of an additional component around 1 GeV which can persist for over an hour and a half. In general, the burst spectra show hard-to-soft evolution, with a loose correlation between the increases and decreases of the hardness and the intensity.

Ironically, the BATSE observations of gamma-ray bursts have increased our knowledge about these incredible events but decreased our understanding.

## 13 Acknowledgments

I thank the BATSE team and my colleagues at UCSD for their stimulating interactions during the past four exciting and frustrating years. The research of the BATSE team members at UCSD is supported by NASA contract NAS8-36081.

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