THE GAMMA-RAY BURST MYSTERY

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Gamma-ray bursts are transient events from beyond the solar system. Besides the allure of their mysterious origin, bursts are physically fascinating because they undoubtedly require exotic physics. Optical transients coincident with burst positions show that some, and probably all, bursts originate at cosmological distances, and not from a large Galactic halo. Observations of these events’ spectral and temporal behavior will guide and constrain the study of the physical processes producing this extragalactic phenomenon.

1 Introduction

The mystery of gamma-ray bursts and its possible solution are textbook examples of the scientific method. These flashes of gamma-rays originating outside the solar system were attributed after their discovery to an impulsive release of energy on nearby neutron stars. This hypothesis had testable consequences, which the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory was built to verify. But BATSE found the predictions were wrong, falsifying the hypothesis. Two new hypotheses were formulated: bursts originate in a large halo surrounding our galaxy, or at cosmological distances. These hypotheses also had testable consequences, and in May, 1997, a clear signature of the cosmological origin of at least one burst was discovered. Other predictions of the simplest cosmological model appear to be invalid, indicating that the phenomenon is more complicated, and therefore more interesting, than previously thought.

Gamma-ray bursts were discovered by the Vela spacecraft. Between 1963 and 1973 the United States launched these satellites whose mission was, among other purposes, to characterize the space environment in which future detectors would attempt to verify that the Soviet Union and other nuclear powers were not detonating nuclear weapons in space to circumvent the newly negotiated Limited Test-Ban Treaty. The Vela program consisted of pairs of satellites of progressively greater complexity. In 1969 R. Klebesadel noticed a burst of radiation had been detected by both Vela 4 satellites on July 2, 1967, verifying that this event was external to the detectors; inspection of the data from subsequent Vela satellites revealed additional bursts. Since these events did not have the signature of nuclear explosions, the existence of the phenomenon was never classified. However bursts were not reported to the astrophysical community until 1973 after later Vela satellites demonstrated that the sun was not the source. A variety of progressively more sophisticated burst detectors have flown since, and the analysis techniques have advanced accordingly.

I write this review at a time of great change in the study of bursts. I joined the BATSE instrument team just before BATSE was placed in orbit, when we “knew” that bursts occurred on the surface of local neutron stars. Within a few months BATSE showed that this was incorrect and for six years we debated whether bursts were merely on the outskirts of our galaxy, or at the edge of the universe. Since the beginning of 1997 the Italian-Dutch X-ray satellite Beppo-SAX has localized a number of bursts to small error boxes (less than an arcminute in radius) within
hours, resulting in the discovery of a few transients in other wavelength bands. As I describe in greater depth below, the observations of these transients have shown nearly conclusively that some, and by Occam’s Razor probably all, bursts are cosmological. The wealth of new observational data, and the resulting understanding of the burst phenomenon, have led to a serious confrontation of theory and observation. In light of these exciting advances in the field, here I provide background information which will assist the reader in understanding these developments. As a member of the spectroscopy group of the BATSE instrument team, for the past six years I have devoted most of my research efforts to burst phenomenology, while occasionally participating directly in the great debates which have raged in the field; my research interests undoubtedly affect the emphasis of this review.

The burst literature is vast, and it is impossible in a brief review to cite properly all relevant papers. Frequently a number of scientists developed the same concept at the same time. Therefore, on a given point I reference one or two representative papers which will lead the reader into the appropriate literature. I beg the indulgence of my colleagues whose work I have neglected.

2 What Are Gamma-Ray Bursts?

Gamma-ray bursts are transient events which originate beyond the solar system. Emission has been observed during the actual burst only above $\sim 1$ keV; recently lower energy afterglows have been detected. Bursts constitute a very diverse population, with properties characterized by large dynamic ranges. Currently two types of bursts have been identified: classical bursts and Soft Gamma Repeaters (SGRs). Note that SGRs are identified by their galactic coordinates, while bursts are named by the date of their occurrence, GRB yymmdd.

Four repeating SGRs are currently known. One appears to be in the Large Magellanic Cloud (LMC) while the other three are towards the center of our galaxy. Their spectra can be described as optically-thin Bremsstrahlung with a temperature of $\sim 25 - 40$ keV, and are therefore softer (i.e., lower average photon energy) than the spectra of classical bursts (as will be discussed below).\footnote{The most extraordinary burst from an SGR was the first observed event from SGR 0525-66, which occurred on March 5, 1979;\footnote{this burst began with an intense spike and concluded with 25 cycles of an 8 second period. This SGR has been localized to the supernova remnant N49 in the LMC.\footnote{Similarly SGR 1806-20 is coincident with a supernova remnant in our Galactic plane.\footnote{On the other hand, SGR 1900+14 is outside of a supernova remnant; there are no obvious supernova remnants in the error box of the newly discovered SGR 1815-14.\footnote{Based on this small sample, an evolutionary scenario has been suggested in which SGRs are high velocity neutron stars which eventually escape the supernova remnant created by the supernova in which the neutron star was born.\footnote{While SGRs are interesting in their own right, the rest of this review will focus on classical bursts.}}}}}}\footnote{Classical bursts are known to range in duration from 4 ms to more than 1000 s; the duration distribution is bimodal, with a cusp at a duration of 2 s.\footnote{The broad spectrum usually peaks between a few 100 keV and a few MeV; generally most of the energy is emitted around an MeV, with only a few percent in the X-ray band,}}
although some events are rich in X-ray emission. As will be discussed below, the existence of line features in burst spectra is controversial. The light curves vary in appearance: some bursts are very smooth, while some are very spiky. Only one class has been defined: about 15% of all bursts are FREDs—Fast Rise, Exponential Decay. Integrating over the spectrum, the peak photon flux ranges between 0.1 and 100 photons cm$^{-2}$ s$^{-1}$, and the energy fluence has been observed between $10^{-7}$ and $10^{-3}$ erg cm$^{-2}$. Of course, a quantity’s observed distribution is a convolution of the true distribution and a given detector’s characteristics. For example, BATSE (the largest detector system flown thus far) detects bursts by an increase in the counts accumulated in 64, 256 and 1024 ms bins; consequently BATSE becomes progressively more insensitive as the burst duration decreases below 64 ms. Nonetheless, it is clear that burst properties are characterized by large dynamic ranges.

Bursts are interesting for many reasons. Of course, their unknown origin challenges and entices us to solve the mystery. Furthermore, the phenomenon must involve exotic physics. Somehow gamma-rays are emitted efficiently with little low energy radiation, at least during the burst. The rapid time variability (on scales of less than a millisecond) indicates a small source size (tens of kilometers) yet the large distance to the source requires a large energy release (more than $10^{51}$ ergs if radiated isotropically at cosmological distances); consequently, the energy density must be enormous. Finally, if bursts originate in distant galaxies, as appears to be the case, then they may probe the evolution of the universe. Burst repetitions and temporal structure within bursts may reveal gravitational lensing by intervening structure. Bursts may trace the star formation history of galaxies soon after they formed. Thus cosmological bursts are intimately tied to the evolution of matter in the universe. Therefore, the allure of gamma-ray bursts should not be diminished by the conclusion that they are cosmological as opposed to Galactic.

3 The Mystery Of Burst Origin

Before the launch of CGRO with its BATSE detectors in April, 1991, bursts were thought to originate on local (closer than 200 pc) neutron stars: bursts were explained as magnetospheric activity on such stars, and the absorption lines reported between 15 and 100 keV implied $10^{12}$ gauss fields, comparable to the fields observed on pulsars (spinning neutron stars). This hypothesis was built on a variety of arguments which were persuasive but hardly definitive.

The primary observations regarding the gamma-ray burst distance scale has been their spatial and intensity distributions; until recently there had been no definitive signatures in the observations of individual bursts. Because the observed intensity $f$ is proportional to the inverse square of the distance $d$ to the burst, $f \propto d^{-2}$, and the volume out to this distance is proportional to the cube of the distance, we expect the number of bursts with an intensity greater than $f$ to be $N(> f) \propto f^{-3/2}$ if the burst sources are distributed uniformly in three-dimensional Euclidean space. The argument holds for various types of bursts with different intrinsic intensities since each population contributes a power law distribution $N(> f) \propto f^{-3/2}$. Thus as long as the source distribution is uniform, the cumulative intensity distribution will be a -3/2 power law. Note that this argument applies to any intensity measure
which varies as \( d^{-2} \); thus \( f \) can be the energy or photon fluence (total flux integrated over time) or the maximum energy or photon flux over any particular energy band. Burst detectors trigger on the number of photons detected in a given energy band over one or more accumulation timescales. Therefore the intensity measure most closely related to the detection process is the peak photon flux \((\text{ph s}^{-1} \text{ cm}^{-2})\) in this energy band.

The spatial distribution of bursts on the sky reveals the geometry of the source population. For example, a Galactic population is expected to favor the Galactic plane or center when bursts can be seen to distances of more than a few 100 pc, a typical scale height (i.e., the distance over which the density of a given constituent of the Galactic disk decreases perpendicular to the disk). Because it is very difficult to focus gamma-rays into images, other methods must be used to locate bursts. BATSE localizes bursts by comparing the rates in detectors with different orientations. The uncertainty of the resulting localization is typically 5° or more \((\sim 2°)\) systematic error and a statistical uncertainty which decreases as the burst intensity increases \(17\), which is nonetheless sufficient to determine whether the bursts are isotropic or favor the Galactic plane or center. Strong bursts can be localized to arcminute uncertainties by comparing the arrival times of the burst signal at detectors spread throughout the solar system;\(18\) thus far three interplanetary networks (IPNs) have operated over the past 25 years. Two detectors localize bursts to an annulus, three detectors to two points mirrored through the plane of the detectors, and four detectors can not only localize the burst to a point but can also set lower limits on the burst’s distance. Since bursts were expected to be a Galactic phenomenon, the spatial distribution is typically quantified by moments (primarily dipole and quadrupole) in Galactic coordinates (although other coordinate systems, and coordinate-free moments have been considered) \(20\).

Before BATSE, bursts were observed to be distributed isotropically, and the intensity distribution was the -3/2 power law expected for a homogeneous source population. This was consistent with the hypothesis that bursts originate on neutron stars in our immediate vicinity; according to this hypothesis detectors before BATSE were detecting bursts only out to distances less than the neutron star population’s scale height. Balloon flights with prototype BATSE detectors showed that BATSE would find a cumulative intensity distribution flatter than the -3/2 power law at the faint end \(19\). The prediction was that the faint (and therefore distant) bursts would occur preferentially either in the Galactic plane or towards the Galactic center. This is analogous to observing an isotropic sprinkling of stars in the bright night sky above a city, and discovering the Milky Way in the dark countryside sky. What did BATSE actually observe?

The cumulative intensity distribution of the BATSE bursts can be approximated by two power laws, one with an index -3/2 at the bright end, and the other with an index of -0.8 at the faint end (see the left hand side of Figure 1); BATSE has definitely seen beyond the region where bursts are distributed uniformly. However, contradicting the hypothesis that bursts originate in the Galactic plane, the spatial distribution is still consistent with isotropy (see the right hand side of Figure 1) \(15,16,17\). We are at the center of a bounded spherical source population.

Three explanations were advanced based on possible spheres centered on the
Figure 1: Cumulative intensity distribution (left) and spatial distribution (right) of the bursts of the 3rd BATSE Catalog. The intensity is the peak photon flux accumulated over 1024 ms in the 50-300 keV energy band. The dashed line on the intensity distribution is a -3/2 power law with a normalization chosen to coincide with the bright portion of the data. The dot-dashed curve below 0.3 photon cm\(^{-2}\) s\(^{-1}\) corrects for the variable detector threshold. The spatial distribution is shown in Galactic coordinates.

earth. A very few scientists suggested bursts are a solar system phenomenon, perhaps occurring in the Oort Cloud. However, some preference for the orbital plane is expected, and no convincing mechanism was ever advanced.

A minority of those studying bursts proposed a population of sources in the Galactic halo. The scale of this halo distribution would have to be large enough to make our offset of 8.5 kpc from the Galactic center unobservable (1 kpc= 3.1 \times 10^{21} \text{cm}). Assuming the sources emit isotropically, the halo population cannot be too large or we would observe bursts from nearby galaxies (e.g., the Andromeda Galaxy, M31) which presumably also are surrounded by burst sources. While this hypothesis keeps bursts in the Galaxy, the distance scale is a thousand times greater than for the local disk hypothesis, the energy requirement has increased by a factor of a million, and all the pre-BATSE theories were essentially invalidated.

Finally, the majority of those who were willing to commit themselves placed bursts at cosmological distances. Since the universe is isotropic in the standard cosmology, this explanation automatically results in an isotropic burst distribution. The curvature of space very naturally produces the apparent decrease of burst sources at large distances without invoking an evolving source population (although the population undoubtedly does evolve). The distance scale is now 10 million times greater than for the pre-BATSE theories; the energy is therefore 100 trillion times greater. The required energy is of order 10^{51} \text{ergs}, or somewhat greater, which is about the binding energy of a neutron star. The favored scenario was the merger of two neutron stars, a cataclysmic event which destroys the source.

The burst distribution was shown to be isotropic yet homogenous within about half a year of BATSE’s launch. Over the subsequent six years various controversies raged which were surrogates for the debate over the bursts’ distance scale. For example, Wang and Lingenfelter found that five bursts appeared to be clustered in time and space, while Quashnock and Lamb found an excess of bursts
with small spatial separations; these two analyses suggested that bursts repeat. Because the amount of energy required for a cosmological origin almost necessitates a cataclysmic event which destroys the source, it is highly unlikely that cosmological sources would repeat. Also, since the sources are probably in galaxies, it seems implausible that only a small number of sources would be active at any time. Subsequent analysis disputed the significance of the observational evidence for repeaters; an improvement of BATSE’s burst localization algorithm revised the burst positions and eliminated the apparent repetition signal. An improvement of BATSE’s burst localization algorithm revised the burst positions and eliminated the apparent repetition signal.

If bursts are cosmological then their spectra should be redshifted and their lightcurves should undergo time dilation. Faint bursts are presumably further, and therefore should be more affected by these relativistic effects. The difficulty is that burst properties generally vary by orders of magnitude whereas the cosmological signatures are factor of 2 or 3 effects. In addition, intrinsic correlations between burst properties could mimic the cosmological signatures, and at most the observations can be shown to be consistent with the cosmological effect. That faint bursts have softer (lower average photon energy) spectra, consistent with a cosmological redshift, is uncontroversial. The debate has raged over the presence of time dilatation, with small and improperly defined samples plaguing the analysis by both those who find an effect and those who do not. Initially Norris et al. found a strong time dilation signature; Mitrofanov et al. reported that this signature was absent in their analysis. Fenimore and Bloom showed that the apparent time dilation of bursts at a given $z$ is diminished by spectral redshifting: temporal structure is “narrower” at high energy (i.e., spikes last longer at low energy as a result of spectral evolution), and the observed time dilation is reduced when this narrower structure is redshifted into the observed energy band. Using a variety of techniques, Norris and his colleagues continue to observe time dilation, although the effect is smaller than their initial report. Using a larger sample than before, Mitrofanov and his colleagues also find time dilation. It is currently not clear whether all the studies which find apparent time dilation are consistent.

A great deal of discussion focused on observations which could solve the mystery by testing the predictions of the various hypotheses. If bursts indeed occur outside of the Galactic plane where most of the absorbing gas is found (the K-shells of “metals” such as oxygen in the interstellar medium absorb X-rays below 1 keV), then bursts’ X-ray spectra should have a low energy cutoff (assuming the intrinsic spectrum can be estimated). If bursts arise in large Galactic halos, then detectors about an order of magnitude more sensitive than BATSE should detect an excess towards nearby galaxies such as Andromeda. However, the greatest hope was placed in linking bursts with known astrophysical phenomena, primarily by finding a counterpart in another wavelength band. To that end, systems were developed to monitor the sky continuously (e.g., the Explosive Transient Camera—ETC on Kitt Peak) or to respond rapidly to a burst (e.g., the Gamma-Ray Optical Counterpart Search Experiment—GROCSE at Lawrence Livermore National Laboratory). These various projects filled in the three-dimensional space of: 1) the time since the burst; 2) the wavelength searched; and 3) the depth of the search. For many years only upper limits were reported. Great hope was placed in the High Energy Transient Explorer (HETE) which had coaligned gamma-ray,
X-ray and ultraviolet detectors, the last two with spatial resolution. However, the launch vehicle failed to release \textit{HETE}, and the mission was lost; the mission is being rebuilt with a soft X-ray detector replacing the ultraviolet camera.

4 The Solution?

The Italian-Dutch X-ray satellite \textit{Beppo-SAX} has linked a number of gamma-ray bursts to counterparts in other wavelength bands, and the mystery of the burst distance scale may have been solved. This satellite includes two wide-field cameras (WFCs) perpendicular to the coaligned narrow-field telescopes which are the mission’s main instruments. These WFCs each have a field-of-view of 40°; consequently they will observe approximately 8 bursts per year. Because of this burst capability, the anti-coincidence shields surrounding the narrow-field instruments are also used as a burst detector. This array of instruments allows \textit{Beppo-SAX} to localize gamma-ray bursts, and search the region where the burst occurred for an X-ray afterglow. Within \(\sim 4–8\) hours of the burst the coordinates can be disseminated to observers in other wavelength bands, who can then search for the burst source.

The precise sequence of events is as follows: The burst detector detects a burst. When the telemetry from the time of the burst reaches the ground, images are constructed for the two WFCs using the photons detected while the burst was in progress (this maximizes the signal-to-noise ratio). If the burst was in the field-of-view of one of the WFCs, one of the images will contain an X-ray point source not present before the burst. The source in the WFC image can be localized to an error radius of 3 arcmin. The spacecraft is then reoriented (on a timescale of \(\sim 4–8\) hours) so that the narrow-field instruments point at the location of the burst, and one or more X-ray sources may be found in the burst error box. Repeated observations over the next few days may identify a variable source which is likely to be the burst’s afterglow. The narrow-field instruments can localize a source to an error radius of \(\sim 50\) arcsec. Optical telescopes can then image these small error boxes over the next few days, searching for a variable source (variability is the expected signature of the burst counterpart).

These error boxes are unprecedented in the study of gamma-ray bursts. The WFC error box is comparable to the better burst error boxes resulting from the IPNs, and the position of the X-ray afterglow is comparable to the very best error boxes previously available. And the \textit{Beppo-SAX} positions are available within hours of the burst, allowing the search for fading afterglows. The scientific bonanza resulting from the \textit{Beppo-SAX} observations has led to other methods of rapidly localizing bursts. About one burst a month falls within the field of the All-Sky Monitor on the \textit{Rossi X-ray Timing Explorer (RXTE)}: \textit{RXTE} raster-scans the resulting error box with its main detectors. Similarly, \textit{RXTE} raster-scans small BATSE error boxes at the rate of \(\sim\) once a month. Thus many afterglows, or limits on their presence, should be available over the next few years.

A number of bursts have been localized by either \textit{Beppo-SAX} or \textit{RXTE}. In some cases no afterglow was observed, in others only an X-ray variable was identified, but in two cases optical transients were found. These two optical transients have provided a wealth of data.

7
GRB 970228 was the first burst localized rapidly. Beppo-SAX’s narrow-field instruments and subsequently ASCA and ROSAT identified and tracked a fading X-ray transient. Optical observations 20 hours and 8 days after the burst found a fading optical source; this source was then observed by a large number of telescopes, including Keck and Hubble Space Telescope (HST). Both the X-ray and optical emission faded at a rate proportional to $t^{-1.1}$, which can be explained by current theoretical models (discussed below). Possibly the host galaxy, extended emission underlies the point source. This burst conforms to the expectations for a cosmological source: a fading afterglow at the location of the burst superimposed on a galaxy. Reports that the point source exhibited proper motion (i.e., moved) and that the extended source was fading, which would have contradicted these expectations, were not verified by a HST observation in September, 1997, which found that the transient had not moved, and that the extended source’s brightness was consistent with the previous observations.

GRB 970508 appears to have provided the “smoking gun” that at least some bursts are cosmological. Once again a fading X-ray transient was observed. However, for this burst the variable optical source brightened for 2 days before it began to fade. Subsequently a radio source coincident with the X-ray and optical transient was also discovered. Scintillation by our galaxy’s interstellar medium can explain the initial rapid variations of the radio flux which subsequently damped out; this implies that the radio source expanded from an initial apparent size of $\sim 10^{17}$ cm. Most significantly, absorption lines of Mg II and Fe II at a redshift of $z = 0.835$ were found in a spectrum of the optical transient; a Mg II system at $z = 0.767$ is also present. These lines consist of doublets and the line identifications are therefore extremely secure. Thus the source must be in or behind this absorption system. The absence of absorption by the Ly$\alpha$ forest indicates the source must be at a redshift less than $z = 2.1$. When the optical source faded further, an O[II] emission line at $z = 0.835$ became apparent. No extended source underlying the transient has been observed, although there are two galaxies $\sim 5$ arcsec from the optical source. The redshifts of these galaxies have not yet been determined, but 5 arcsec at a redshift of $z = 0.835$ corresponds to $\sim 30$ kpc. Various possibilities are possible: the burst progenitor at $z = 0.835$ was either in a faint, thus far undetected, galaxy or in the outer part of a halo of one of the two observed galaxies; or the line-of-sight to the source which was at $z > 0.835$ passed through a faint galaxy or the halo of one of the observed galaxies at $z = 0.835$.

The significant conclusion drawn from the absorption lines is that at least some bursts are cosmological. Occam’s Razor dictates that unless proven otherwise, we should assume that all bursts have the same origin and are thus cosmological. However, Loredo and Wasserman have shown that the data permit at least two burst populations, one of which could be cosmological and the other local.

5 Theories for Cosmological Bursts

Theories for bursts at cosmological distances developed after the BATSE observations invalidated the local Galactic neutron star hypothesis. Because the current theories are discussed in great detail elsewhere, particularly in these proceedings,
here I provide only a schematic outline.

The burst originates with the release of a large amount of energy in a small volume. The resulting processes erase most of the memory of the origin of this energy. The necessary energy release of more than $10^{51}$ ergs (if bursts radiate isotropically) suggests a source related to the binding energy of a stellar mass such as the merger of neutron star-neutron star binaries or unusual, extremely energetic supernovae ("hypernovae"). The necessary rate is approximately once per $10^5$ years per $L_\star$ galaxy (again assuming bursts radiate isotropically).

Neutron star-neutron star binaries are observed to exist and decay by gravitational radiation, and the rate per galaxy should be sufficient. Since a comprehensive calculation has not yet been feasible, it is unknown whether a neutron star-neutron star merger will release sufficient energy for an observable burst. Davies et al. used a Newtonian smoothed particle hydrodynamics code to model the merger. The merged object is close to the maximum mass for a spinning neutron star, a disk of material is left in the equatorial plane, and of order $10^{53}$ ergs is released in various forms which can be used to power the burst. Using a piecewise-parabolic hydrodynamics code, Ruffert and colleagues perform Newtonian calculations of a merger which include gravitational radiation and its back-reaction; they find that insufficient energy is released. Mathews and Wilson calculate the fully relativistic inspiral of the binary; their numerical methodology does not allow them to follow the binary to the final merger. However, they find that as a consequence of general relativistic effects, the two neutron stars collapse to black holes before the merger. But before the collapse, the neutron stars heat up and radiate a large neutrino flux ($\sim 10^{53}$ ergs) before they collapse. These various calculations include different physical processes, and thus reach divergent conclusions.

Hypernovae are currently only a theoretical construct, and can be postulated to occur sufficiently frequently. Paczyński proposed a model where a massive rotating star collapses to a black hole, leaving behind a disk of material which then accretes onto the black hole, releasing energy. Fuller and Shi suggest that the supernova of a supermassive star ($M > 5 \times 10^4 M_\odot$) may emit a large enough neutrino flux to power the burst.

The simplest models assume that binary mergers and hypernovae occur in galaxies and are endpoints of stellar evolution, and therefore a reasonable conclusion is that bursts occur in galaxies. Of course, alternatives are possible. A neutron star-neutron star binary may be ejected from the galaxy and may not burst until it has traveled a fair distance from the host galaxy. The supermassive star ($M > 5 \times 10^4 M_\odot$) which might power the burst may form outside of a galaxy.

If the gamma-ray energy density is sufficiently large, the resulting volume will be optically thick to pair creation. A pair plasma should result which will expand relativistically; the Lorentz factor $\Gamma$ of the fireball depends on the ratio of the energy to the number of baryons which are swept up by the plasma. The original fireball models attributed the gamma-ray emission to the moment when the fireball becomes optically thin. However, this should produce a single short spike with a quasi-black body spectrum, and is therefore insufficient to reproduce the observed spectra and temporal structures. In the next generation of models the "external" shocks which form when the fireball collides with the surrounding medium radiate...
the observed gamma-rays. However, the external shocks are not thought to be capable of producing the rich temporal structure unless the shocks radiate with very low efficiency. Consequently, in the current fireball model inhomogeneities within the relativistic outflow result in “internal” shocks which radiate the observed gamma-ray emission. However, the “external” shocks should radiate at lower energies on timescales much longer than the gamma-ray burst; this is the origin of the recently observed afterglows. Here I have provided only a very brief outline of the fireball model, and I encourage the reader to consult the vast literature (including the papers in these proceedings).

6 The “Minimal” Cosmological Scenario

The burst intensity distribution is the convolution of the intrinsic luminosity function and the burst rate, both as functions of the distance to the burst source. The simplest (i.e., “minimal”) model assumes that there has been no cosmological evolution in the burst rate per comoving volume or in the luminosity function. Further, the luminosity function is assumed to be a delta function for a certain intrinsic intensity measure (e.g., the total radiated energy or the peak photon luminosity), that is, all bursts are “standard candles.” The standard candle has been the same at all cosmological epochs by the no-evolution assumption. The aesthetic beauty of the cosmological scenario is that the bend in the intensity distribution can be wholly explained by the curvature of space and time dilation at cosmological distances. A consequence of the minimal model is that there is a one-to-one mapping between the burst intensity and the distance, with the distance scale given by the shape of the intensity distribution. For example, by this model the faint BATSE bursts are at a redshift of $z \sim 1$. Which intensity is the standard candle is of course uncertain. Because BATSE triggers on the count rate in the 50-300 keV band, and the BATSE bursts constitute the largest homogeneous database, the peak photon flux (corresponding to the peak photon luminosity) is often used. An intensity measure related to a detector’s trigger is favored because the low intensity threshold is best understood. However, this is a choice based on instrumental considerations and not on physics.

Many of the proposed energy sources for cosmological bursts are the endpoints of stellar evolution, and consequently a simple assumption is that bursts occur in galaxies at a rate proportional to a galaxy’s mass. Assuming a constant mass-to-light ratio, this implies that the rate is proportional to a galaxy’s luminosity. Therefore, the minimal theory predicts that the host galaxy’s luminosity function is the luminosity function for regular galaxies, weighted by one power of the luminosity.

The minimal model is based on unrealistically simplistic assumptions. The great variety of burst profiles and the large dynamic range of burst properties such as spectral hardness and time duration make the standard candle assumption suspect. Indeed, Hakkila et al. found that a standard candle cosmological model, where the peak energy flux (ergs cm$^{-2}$ s$^{-1}$) corresponds to the standard candle, does not fit the joint PVO-BATSE distribution (of course, a different intensity measure might correspond to the standard candle). Similarly, all known astrophysical phenomena have undergone cosmological evolution. Studies have constrained the cosmological
evolution of the burst rate. While it has generally been recognized that the burst population must have undergone evolution, and that bursts at any given epoch were not standard candles, most studies fitting the burst database have adopted the minimal scenario.

7 Complications with the “Minimal” Cosmological Scenario

As described above, the minimal cosmological scenario predicts that bursts should occur in galaxies, and that the distance to the burst, and therefore to the galaxy, can be calculated from the intensity. Schaefer pointed out that the small error boxes of 8 bright bursts do not contain bright galaxies; if the brightest galaxy in the error box, or the detection threshold for the box, had a brightness equal to M31 (the Andromeda Galaxy), the total burst energy must have been as large as $2 \times 10^{53}$ ergs. Fenimore et al. found that Schaefer’s data were only marginally consistent with the galaxies predicted by the minimal scenario if the brightest galaxy in each error box was indeed the host galaxy. However, the brightest galaxy could also be an unrelated background galaxy. This apparent discrepancy with the minimal scenario has been dubbed the “no host galaxy” problem. On the other hand, Larson and collaborators reported that their sample of error boxes, which were somewhat larger than Schaefer’s, had an excess of bright galaxies, although they recognized that they could not distinguish between host and background galaxies.

D. Hartmann and I realized that a more sophisticated analysis methodology was required. Therefore we use a likelihood ratio which contrasts the hypothesis that both host and unrelated background galaxies are present with the hypothesis that all the observed galaxies are unrelated background galaxies. This ratio was developed within a Bayesian framework, but it is understandable within standard “frequentist” statistics. If this ratio is much greater than 1 then a host galaxy is clearly present in each error box, while if the ratio is much less than 1 then no host galaxy is present. Finally, if the ratio is of order unity then the data are inconclusive. By construction, this methodology accounts for the unrelated background galaxies which will be detected if the error box is searched deeply enough. We include each detected galaxy in addition to the detection limit, and we permit a more sophisticated description of the error box. This methodology demonstrates that the observations of a given error box can show conclusively that the host galaxy is present only if the expected host galaxy is on average brighter than the average brightest background galaxy, which depends on the size of the error box.

Thus far we have applied this methodology to only a few datasets, but the results show that the minimal scenario is indeed too simple. We find that the likelihood ratio for the nine fields observed by Larson and McLean is 0.25, which indicates that we are unable to determine whether host galaxies are present. On the other hand, the likelihood ratio for the four error boxes observed by Schaefer et al. with the HST is $2 \times 10^{-6}$ which clearly shows that the host galaxies predicted by the minimal scenario are not present.

One would think that the optical transients resulting from the Beppo-SAX observations would produce more conclusive results than the larger error boxes previously available. The optical transient left by GRB 970228 sits on a region of
extended emission with a flux of $V = 25.7$. This extended emission appears to be the host galaxy we expected! However, when we apply our methodology, we calculate a likelihood ratio of only 0.27, not a number much greater than one. The reason for such a small value is that a galaxy with $V = 25.7$ is typically at a redshift of $z \sim 2$, not the $z \sim 0.25$ calculated from the burst’s intensity. There is no hint of extended emission underlying the GRB 970508 transient down to a magnitude of $R \sim 25.5$. Assuming the burst was at $z = 0.835$ (this is actually the lower limit, but the burst intensity was consistent with this redshift), the likelihood ratio is 0.027. Thus the two recent well-localized bursts also show that the host galaxies predicted by the minimal scenario are not present.

Consequently alternative scenarios have been suggested. The burst rate might be proportional to the star formation rate; for example, a hypernova may result from a short-lived massive star, and thus bursts will occur when and where there has been recent star formation. The universe’s star formation history has recently been determined empirically, and it shows that the rate per comoving volume increased slowly from $z \sim 5$ to $z \sim 1.2$, and has plummeted since. Using this star formation rate as the burst rate can reproduce the burst intensity distribution, with the bursts occurring at much greater distances. A surprising consequence is that the portion of the intensity distribution which is a power law with an index of $-3/2$ results not from a uniform burst density in nearby Euclidean space (as discussed in §2) but from the balance between spatial curvature and burst evolution. It has also been suggested that at moderate redshifts star formation occurred preferentially in small galaxies.

Thus the minimal cosmological scenario is too simple, as was suspected on astrophysical grounds. The development of more sophisticated cosmological theories involves issues such as star formation, and consequently the study of gamma-ray bursts will be more closely integrated with cosmology and extragalactic astrophysics.

8 Burst Phenomenology

The discovery of the likely burst distance scale, and the additional information provided by the burst afterglows, have motivated more detailed theories. Consequently, burst phenomena which were relatively unimportant for determining the distance scale have become important for revealing the physics of the burst process.

8.1 Spectrum

The burst continuum from 10 keV to 100 MeV has a very simple shape: it is curved at low energies and becomes a power law at high energy. Indeed, the spectrum over these four decades can be characterized by a four-parameter function

$$N(E) = \begin{cases} AE^{\alpha}e^{-E/E_0} & E < (\alpha - \beta)E_0 \\ A'E^\beta & E \geq (\alpha - \beta)E_0 \end{cases}$$

(1)

where $A'$ is chosen so that $N(E)$ is continuous and differentiable at $E = (\alpha - \beta)E_0$. Figure 2 shows a fit to a spectrum accumulated over a particularly intense burst. All
Figure 2: Fit to the count spectrum accumulated over the first 12 s of GRB 910503 by a BATSE Spectroscopy Detector. The solid curve is the best-fit model folded through the detector response. The detector is based on a NaI(Tl) crystal, which introduces features into the count spectrum near the iodine K-edge at 33.17 keV.

Four parameters vary within and between bursts, but typically $\alpha \sim -1$ and $\beta \sim -2$. The energy $E_p$ at which $E^2 N(E) \propto \nu F_\nu$ (the energy flux per energy decade) peaks characterizes whether a spectrum is hard or soft. If $\beta < -2$ then $E_p = (2 + \alpha)E_0$, otherwise $E_p$ is above the energy where the high energy power law rolls over (such a rollover is not included in eq. [1]). Usually $E_p$ is calculated from the low energy component, regardless of the value of $\beta$. The observed $E_p$ distribution is between 50 keV and 1 MeV, with a maximum at $\sim$150 keV; see Figure 3. The true $E_p$ distribution may be broader because the energy band over which a detector triggers introduces a selection effect; in particular, there may be a large number of bursts with a high $E_p$. The $E_p$ distribution is important since the relativistic fireball models link $E_p$ to the fireball’s Lorentz factor.

Deviations from this simple functional form are seen at high and low energies. Approximately 10% of a sample of bright BATSE bursts have low energy excesses; unfortunately this excess was discovered using a single broad low energy channel, and spectral information on this excess is unavailable. One of the 22 bursts observed by Ginga also has a low energy excess; otherwise the four parameter function of eq. (1) describes the Ginga spectra between 2 and 400 keV. The EGRET instrument on CGRO detects individual high energy photons with energies above 30 MeV with a spark chamber. Usually too few high energy photons are recorded...
to provide detailed spectral information. Nonetheless, there is a tendency for the emission at a $\sim$GeV to linger after the lower energy burst. In GRB 940217, a particularly bright burst, the high energy emission continued for $\sim$90 minutes after the 160 second burst, with an 18 GeV photon, the highest energy burst emission yet observed, detected towards the end of this 90 minute period.

8.2 Spectral Evolution

Since the observed gamma-ray burst spectrum reflects the energy content and particle distributions within the source’s emitting region, spectral variations during a burst are an important diagnostic of the nature of this region. Early studies of spectral evolution reached apparently contradictory conclusions: Golenetskii et al. reported that the intensity and spectral hardness were correlated, while Norris et al. found a hard-to-soft trend. Subsequent studies using SIGNE and BATSE spectra showed that both trends hold in general: the spectrum does indeed harden during intensity spikes, but there is a hard-to-soft trend during these spikes, and the hardness tends to peak at successively lower values from spike to spike.

This characterization of spectral evolution resulted from fitting a sequence of spectra accumulated during a burst, and comparing the time series of a hardness measure such as $E_p$ to the intensity lightcurve. Many counts are required for a good fit to a spectrum, and therefore fitting sequences of spectra is feasible only for bright, long duration bursts. Even for the brightest bursts the time necessary to accumulate a spectrum with a sufficient signal-to-noise ratio (typically more than a second) is usually longer than the time structure evident to the eye (the separation between intensity spikes is typically a second). Therefore I have been developing other techniques of studying spectral evolution.

To characterize the spectral evolution of a large sample of bursts I used the auto- and crosscorrelation functions (ACF and CCFs, respectively) of burst lightcurves in
different energy channels. BATSE provides discriminator rates in 4 energy bands (Ch. 1: 25–50, Ch. 2: 50–100, Ch. 3: 100–300, and Ch. 4: 300–2000 keV) on a 64 ms timescale during a burst. I calculated the CCFs of a fiducial energy channel, Ch. 3 (100–300 keV), with each of the 4 energy channels (the CCF of the fiducial channel with itself is that channel’s ACF). By comparing the time lags of the peaks of each curve and their relative values at different lags, as shown by the example in Figure 4, I characterized the type of spectral evolution.

I calculated the ACFs and CCFs for 209 strong, mostly long bursts. The order of the CCF peaks shows that in general high energy emission precedes low energy emission. As was known previously from comparing the ACFs of the different channels, the CCF widths indicate that high energy temporal structure is narrower than low energy structure (i.e., spikes last longer at low energy than at high). The relative order of the CCFs at different lags shows there is hard-to-soft evolution within and among spikes in ~80–90% of the bursts, and there are only a few cases of soft-to-hard evolution. The peaks of the CCFs for the high energy channels typically lead those of the low energy channels by 0.1–0.2 s. Thus this study showed that hard-to-soft spectral evolution is ubiquitous but counterexamples exist.

Liang and Kargatis found that when the logarithm of \( E_p \) is plotted as a function of the cumulative photon fluence (i.e., the photon fluence from the beginning of the burst to the time \( E_p \) is measured), the datapoints fall on a series of straight lines with the same slope for a given burst. This can be explained by an emission region with a fixed number of radiating particles which is re-energized for each intensity spike.

8.3 Spectral Lines

Spectral lines provide a great deal of information about the emitting region. Missions prior to BATSE—Konus, HEAO-1 and Ginga—detected absorption lines between 10 and 100 keV which were attributed to cyclotron resonant scattering (which scatters photons out of the line of sight) in \( 10^{12} \) gauss fields. Since neutron stars are the only known anchors for fields of this strength, these observations supported the hypothesis that bursts originate on local neutron stars.
However, BATSE has thus far not detected any lines\textsuperscript{109,110} and consequently there has been little interest in explaining spectral lines in a cosmological burst model. A large and stable (temporally and spatially over the absorption region) magnetic field is necessary to produce the narrow lines observed by \textit{Ginga}, and creating such a field configuration in a relativistic fireball will be a major theoretical challenge.

For the past six years the BATSE spectroscopy team has been searching for lines and evaluating the results of this search. The reports of the absence of a BATSE detection\textsuperscript{109,110} were based on a visual inspection of spectra. A more comprehensive computerized search has been carried out\textsuperscript{111} and promising line candidates have been identified which are now being evaluated; we expect to issue a definitive report in the next year.

The question of whether the BATSE nondetections are consistent with the detections by previous missions led me to develop a statistical methodology to study the consistency between the results of these missions.\textsuperscript{112} For this statistical analysis detailed information is required not only about the detections but also about the nondetections; such data are available from BATSE and \textit{Ginga}. This methodology can also extract other physical information, such as the likely frequency with which lines occur. The methodology requires simulations of a detector’s ability to detect lines\textsuperscript{113} and models for the occurrence of lines within a burst.\textsuperscript{114} Thus far only preliminary results have been extracted, in part because only a subset of the necessary \textit{Ginga} data has been processed.\textsuperscript{115} With various approximations, I find that the two missions are consistent at the few percent level. However, it is also clear that lines are not very common (i.e., they may be present in only a few percent of all bursts).

\section{Final Word}

An optical transient following a gamma-ray burst is superimposed on an extended source which might be the host galaxy, and the spectrum of another transient has absorption lines at $z = 0.835$. Therefore bursts are cosmological, the mystery has been solved, and the study of this phenomenon can fade into obscurity as yet another subfield of astrophysics. But has the mystery really been solved?

First, that bursts are cosmological rests on only two optical transients. The GRB 970228 transient is coincident with an extended source which has not yet been proven to be a galaxy and which is fainter than expected for the host. The $z = 0.835$ absorption lines in the spectrum of the GRB 970508 transient show that the transient is beyond this redshift, but there is no obvious host galaxy. Further, the position of the GRB 970508 X-ray transient is known to only 50 arcsec\textsuperscript{12} as opposed to the 10 arcsec uncertainty for the GRB 970228 X-ray transient\textsuperscript{15} and therefore skeptics can still claim that the optical transient in the GRB 970508 X-ray transient error box may be unrelated to the burst; the transient sky has yet to be characterized, particularly at faint optical magnitudes. In addition, even if these optical transients result from cosmological bursts, there may yet be a population of Galactic bursts. I suspect that GRB 970228 and GRB 970508 are indeed cosmological, and that by Occam’s Razor we should assume that all bursts are cosmological, but we should be aware that this conclusion is still based on only two bursts.

Second, even if we interpret the observations as demonstrating that bursts are
cosmological, the analysis of the host galaxy searches shows that the minimal cosmological model is incorrect (§7). The alternatives are that bursts do not occur in regular galaxies, or that they are further than previously thought. Thus we are uncertain about bursts’ environment and distance scale. We can hardly claim that the burst location mystery has been solved.

Third, the conclusion that the observed emission results from a relativistic fireball is based on the large energy which is released in a small volume; few observational signatures of such a fireball have been identified in bursts’ spectral and temporal behavior. Specifically, we do not know whether the observed gamma-ray radiation results from synchrotron, inverse Compton or some other emission mechanism. The observed spectral evolution is unexplained, particularly the softening of successive intensity spikes. Thus the origin of the observed emission is still a mystery.

Fourth, even if a relativistic fireball produces the observed emission, the ultimate energy source is unknown since the fireball erases almost all memory of its origin. As I discussed, the merger of a neutron star-neutron star binary has been proposed as the energy source, but the admittedly incomplete calculations carried out to date do not verify the favored scenario. If bursts originate at higher redshifts than implied by the minimal cosmological model, then the energy requirements may exceed the output of the merger of solar mass scale objects (the angular extent of the gamma-ray emission and therefore the total energy radiated are unknown). Consequently, other energy sources have been suggested, such as the supernovae of massive stars. Hence the origin of the bursts’ energy is still a mystery.

The where, how and why of the burst phenomenon remain uncertain. Further, it is clear that bursts involve extreme physics: the release of a large energy in a small volume on a short timescale, resulting in a relativistic fireball, possibly entraining substantial magnetic fields. Finally, a deeper understanding of the origin of bursts may require the history of matter on cosmological timescales; for example these events may trace the starbursts accompanying galaxy formation. Therefore, the study of gamma-ray bursts will remain an exciting and lively field for the foreseeable future.

Acknowledgments

I thank my colleagues on the BATSE team and at UC San Diego for their assistance over the past 7 years. My research on gamma-ray bursts is supported by the CGRO Guest Investigator Program and by NASA contract NAS8-36081.

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