Gamma-Ray Bursts: An Overview

GERALD J. FISHMAN

Space Sciences Laboratory, Code ES-81, NASA-Marshall Space Flight Center, Huntsville, Alabama 35812
Electronic mail: fishman@ssl.msfc.nasa.gov

ABSTRACT. A history and overview of the observed properties of gamma-ray bursts are presented. The phenomenon of gamma-ray bursts is without precedent in astronomy, having no observed property that would be a direct indicator of their distance and no counterpart object in another wavelength region. Their brief, random appearance only in the gamma-ray region has made their study difficult. The observed time profiles, spectral properties, and durations of gamma-ray bursts cover a wide range. All proposed models for their origin must be considered speculative. It is humbling to think that even after 25 years since their discovery, the distance scale of gamma-ray bursts is still very much debatable.

1. INTRODUCTION AND BRIEF HISTORY

Gamma-ray bursts will be recorded as one of the outstanding new phenomena discovered in astronomy this century. The story is not yet complete; we are only in the middle of it—as evidenced by this debate. The general public has yet to appreciate the significance of gamma-ray bursts. However, astronomers worldwide recognize the significance of what is being observed, even though it is as yet unexplained. About once per day, a burst of gamma rays appears from a random direction on the sky. Often, this burst outshines all other sources of gamma rays in the sky, *combined*. It disappears without a trace, and as yet there is not a conclusive counterpart in the optical or radio regions or any other wavelength region.

Astrophysicists are understandably excited about gamma-ray bursts. They are among the most luminous of any object in the sky in any wavelength region. They may come from neutron stars in the most distant reaches of our galaxy or they may represent an entirely new class of objects near the edge of the observable Universe. If the former is true, then we are seeing a major constituent of the distant parts of the Galaxy that is presently unobservable by any other means. If the latter is true, then gamma-ray bursts could help us to understand the form and evolution of the Universe as a whole; they would be a new observational tool for cosmologists. We are in a no-lose situation: the resolution of this debate in the next few years would result in a major breakthrough for astronomy as we come to the close of the twentieth century.

Seventy-five years ago, almost to the very day, in the Baird Auditorium, a debate ensued on the nature of the then-mysterious spiral nebulae and on the distance scale of the Universe. As Professor Trimble noted, the eventual resolution of that debate changed forever the way in which we see our place in the Galaxy and the Universe. An understanding of the gamma-ray burst distance scale could well have similar results.

The history of gamma-ray bursts is tied closely to that of the space program and to the cold-war activities of the 1960's. In order to observe gamma rays from distant objects in space, detectors needed to be placed on platforms above the Earth's atmosphere. The space age opened up high-energy astronomy in the late 1960's. When this new window on the Universe opened, entirely new types of objects were found and new properties of familiar objects in astronomy were also discovered.

At about the same time, the cold war was near its peak. The U.S. Defense Department became worried that the Soviet Union or China could explode nuclear weapons in space, hidden from other countries, in violation of the test-ban treaty. The immediate response by the U.S. was to deploy a large variety of sensors on a series of spacecraft, the *Vela* satellites, to detect clandestine nuclear explosions above the atmosphere. After a consideration of factors affecting detection efficiency, these spacecraft were launched and operated in pairs with two identical satellites on opposite sides of a circular orbit 250,000 kilometers in diameter (about a 4 day orbit). One advantage of this configuration was to provide nearly complete, simultaneous line-of-sight coverage of all space with a minimum of spacecraft (Singer 1965).

The instrumentation onboard the *Velas* included X-ray and gamma-ray detectors designed and built by teams at the Los Alamos Scientific Laboratory (now Los Alamos National Laboratory), and Sandia Laboratories of Albuquerque NM, who were specifically assembled and commissioned for the task. The researchers were aware that detonating a nuclear bomb in space behind a thick shield or on the far side of the moon could hide the initial explosion from the satellites' view. The onboard gamma-ray detectors offered the opportunity to look for delayed hard gamma-radiation from the resulting radioactive blast cloud which could not be so easily shielded (Dickinson and Tamarkin 1965).

Of course, clandestine nuclear explosions were not found, but occasional bursts of gamma rays were seen coming from random directions in space. Later, it was determined that nearly coincident bursts were detected by multiple spacecraft. The timing of these bursts at widely separated spacecraft was consistent with that expected from sources far from the Earth and they could not be associated with the Sun or any other part of the solar system. These first observations of gamma-ray bursts were not classified, but they required extensive data reduction and analysis with limited resources before the researchers, headed by Ray Klebesadel of Los Alamos, were confident that the bursts being observed were
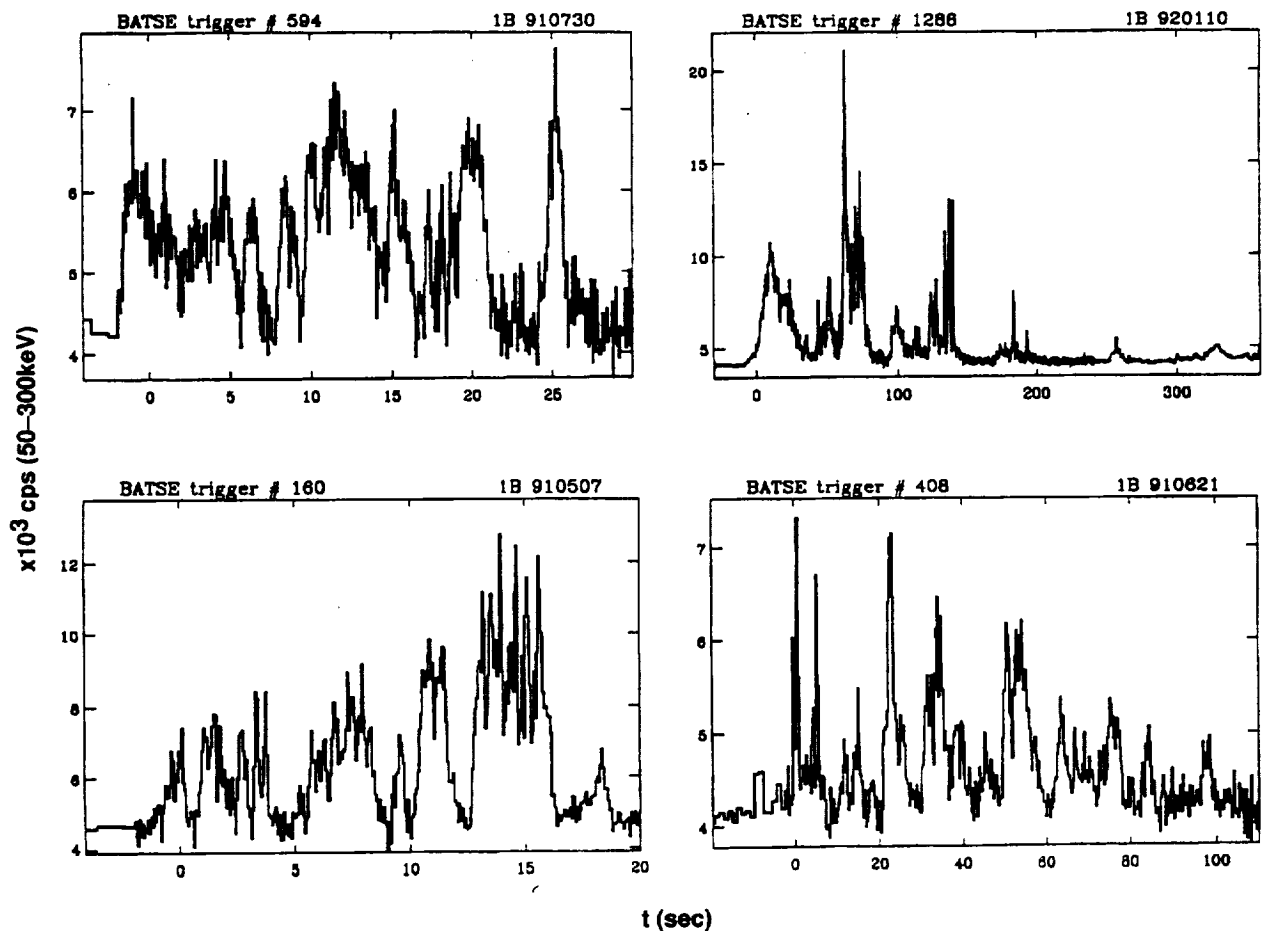
FIG. 1—Examples of several gamma-ray bursts, showing very chaotic temporal structures.

of cosmic origin. The paper announcing the discovery of gamma-ray bursts was published in *The Astrophysical Journal* in 1973 (Klebesadel et al. 1973). In the first years after their discovery, gamma-ray bursts were observed at the rate of 10 to 20 per year. Now, with more complete coverage and larger detectors, gamma-ray bursts are detected at the rate of over 300 per year.

Over two thousand observational and theoretical papers have been written about gamma-ray bursts in the past 25 years (Hurley 1994), yet they remain perhaps the least understood of all objects that have been observed in the Universe. Described in the following sections are some of the observed properties of gamma-ray bursts, obtained primarily by the BATSE experiment on NASA's *Compton Gamma Ray Observatory*. Two comprehensive gamma-ray burst catalogs from the BATSE experiment on the *Compton Observatory* have been released (Fishman et al. 1994; Meegan et al. 1994) and a third catalog is expected to be released in the summer of 1995. That experiment has been in operation since April 1991 and it is planned to continue operating at least until 2001. Some of these observations are controversial and subject to differing interpretations. Unfortunately, space does not permit a detailed description of these analyses, interpretations, and controversies in this paper; some of them will become evident during the debate.

The field of gamma-ray bursts has undergone a rapid, dramatic, and to many, a surprising change over the past three years. This has resulted primarily from more sensitive observations of the gamma-ray burst intensity and sky distributions (Meegan et al. 1992). Prior to these observations, the source of gamma-ray bursts was considered by most workers in the field to be relatively nearby neutron stars in the Galactic plane (cf. Higdon and Lingenfelder 1990).

2. TEMPORAL AND SPECTRAL CHARACTERISTICS

Perhaps the most striking feature of the time profiles of gamma-ray bursts is the diversity of their time structures and the wide range of their durations. Coupled with this diversity is the inability to place many gamma-ray bursts into well-defined types, based on their time profiles. This difficult task is hampered by bursts with multiple characteristics, bursts that are too weak to classify, and a lack of *a priori* knowledge of the number of classes and sub-classes to employ in the classification scheme.

Some burst profiles are chaotic and spiky with large fluctuations on all time scales (Fig. 1), while others show rather simple structures with few peaks (Fig. 2). However, some bursts are seen with both characteristics present within the same burst. No persistent, strictly periodic structures have been seen from gamma-ray bursts. At higher energies, the
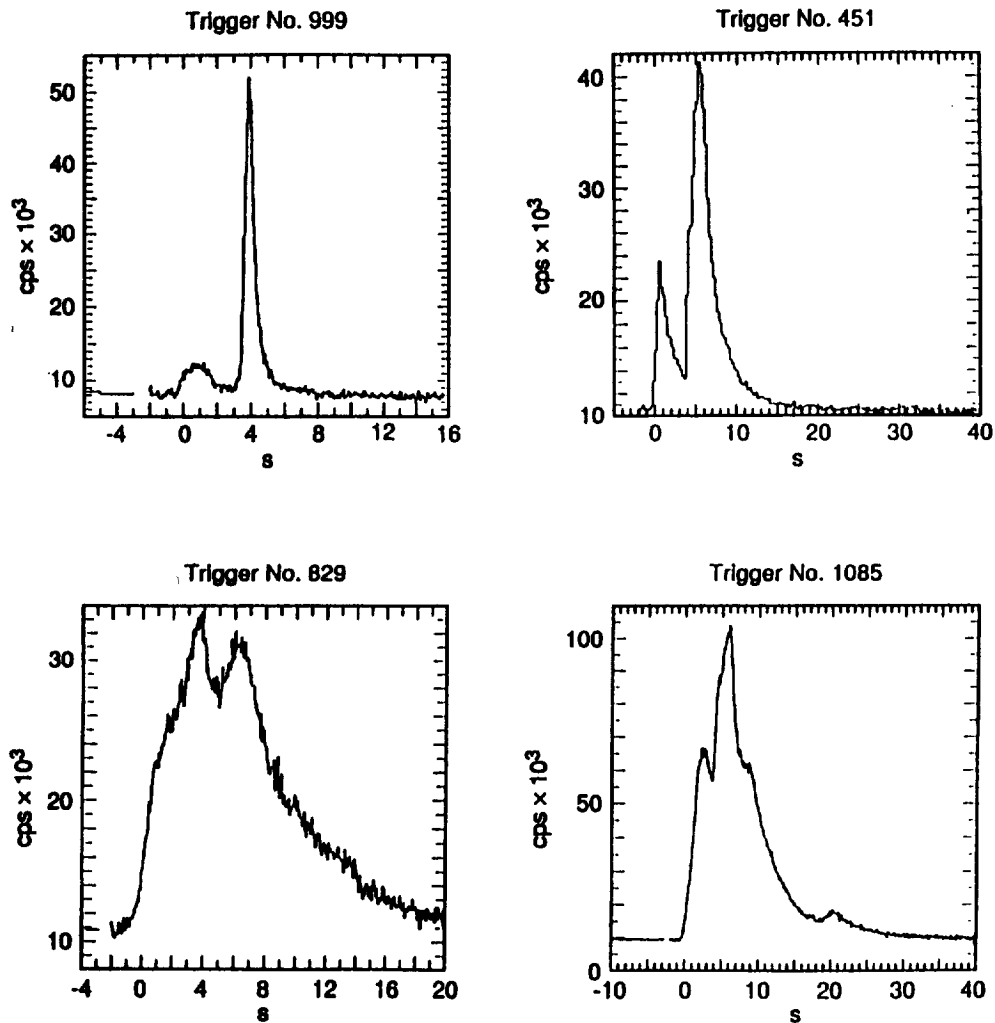
FIG. 2—Some gamma-ray bursts, such as these, have very little structure in their time profiles.

overall burst durations are shorter and sub-pulses within a burst tend to have shorter rise-times and fall-times (sharper spikes). Most bursts also show an asymmetry, with the leading edges of shorter duration than trailing edges. This applies to both the overall burst as well as to sub-structures within a burst.

The durations of gamma-ray bursts range from about 30 ms to over 1000 s. However, the duration of a gamma-ray burst, like the burst morphology, is difficult to quantify since it is dependent upon the sensitivity and the time resolution of the experiment. The "tip of the iceberg" effect tends to cause weaker bursts to be observed as being shorter, since only the higher parts of the peak emission are observable. A recent observation of delayed high-energy gamma-ray emission from a gamma-ray burst was reported in 1994. The EGRET experiment on the *Compton Observatory* detected very high-energy (200 MeV–20 GeV) photons from an intense burst on 1994 February 17 (Hurley et al. 1994). At the lower photon energies, characteristic of that observable by the BATSE and *Ulysses* detectors, this gamma-ray burst lasted 180 s. Following this emission there were additional photons, with energies up to 20 GeV, as long as 5700 s after the start of the burst.

A unique feature of gamma-ray bursts is their high-energy emission: almost all of the power is emitted above 50 keV. Most bursts have a rather simple continuum spectrum which appears somewhat similar in shape when integrated over the entire burst and when sampled on various time scales within a burst. An integrated spectrum from the strong burst GRB 910503, using data from all four GRO experiments is shown in Fig. 3 (Schaefer et al. 1994).

3. INTENSITY AND SKY DISTRIBUTIONS

The most direct evidence of the spatial distribution of the sources of gamma-ray bursts comes from the observed intensity and sky distributions. The angular (sky) distribution provides two of the dimensions of the spatial distribution, while the intensity distribution is a convolution of the unknown luminosity function and the radial distribution. Even though the luminosity function is unknown, the intensity distribution can still provide constraints on the allowable spatial distributions of gamma-ray burst sources.

If the sources are distributed homogeneously in Euclidean space, i.e., the density and luminosity function are independent of position throughout the volume of space observed,
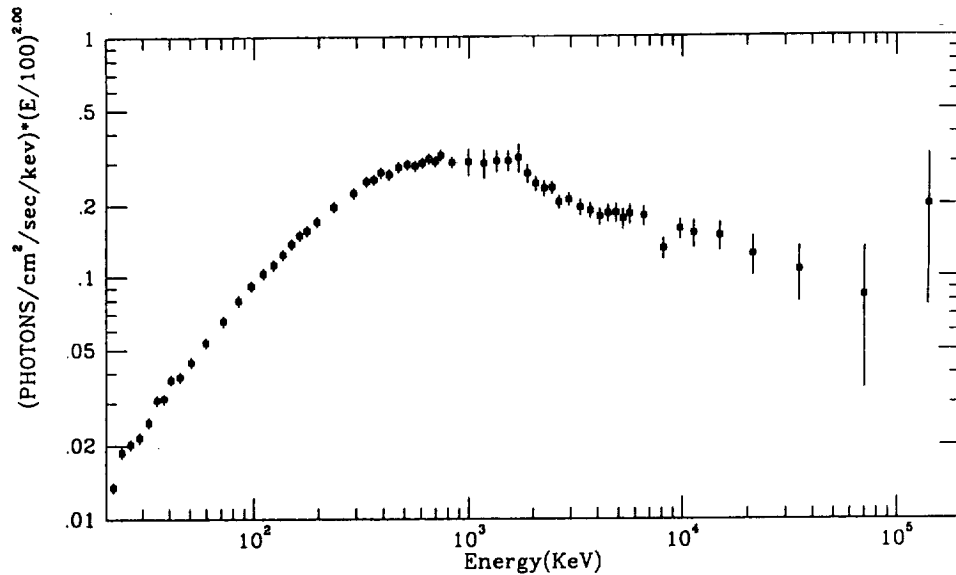
FIG. 3—Example of the very broad, smooth spectrum of a gamma-ray bursts over four decades in energy, obtained by the experiments of the *Compton Gamma Ray Observatory.*

then the integral intensity distribution will be $N(>P)$ $= P^{-3/2}$. From Fig. 4, a significant deviation of the observed intensity distribution from this $-3/2$ power law (shown as a dashed line) is evident. This clearly indicates an inhomogeneity in the region of space being sampled. Further insight into the brightness distribution was provided by Fenimore et al. (1993), who combined data from BATSE and the *Pioneer Venus Orbiter* (*PVO*) burst experiments. Though less sensitive than BATSE, *PVO* operated for approximately 14 years, yielding data on the rarer, more intense bursts. The higher intensities observed by *PVO* are seen to be consistent with

homogeneity, and the agreement between the experiments in the overlap region is excellent.

Since the launch of the *Compton Observatory*, burst locations have been available for a large sample of weak bursts. BATSE determines directions to burst sources by comparing the count rates on individual detectors, whose response varies approximately as the cosine of the angle to the detector normal. The systematic error of these locations is presently about 4 deg, as determined by using hard solar flares and bursts with locations known via interplanetary timing. Improved BATSE locations, in the range 1.5 deg for strong bursts, are now attainable and older data are being reprocessed. The statistical error is around 13 degrees near the BATSE threshold.

The distribution in galactic coordinates of 1121 bursts observed by BATSE is shown in Fig. 5. The BATSE results (Briggs et al. 1995) show that this distribution is consistent with isotropy, in a statistical sense, and that this isotropy extends to the weakest bursts, those that lie below the break from the $-3/2$ slope in the intensity distribution. It is inter-
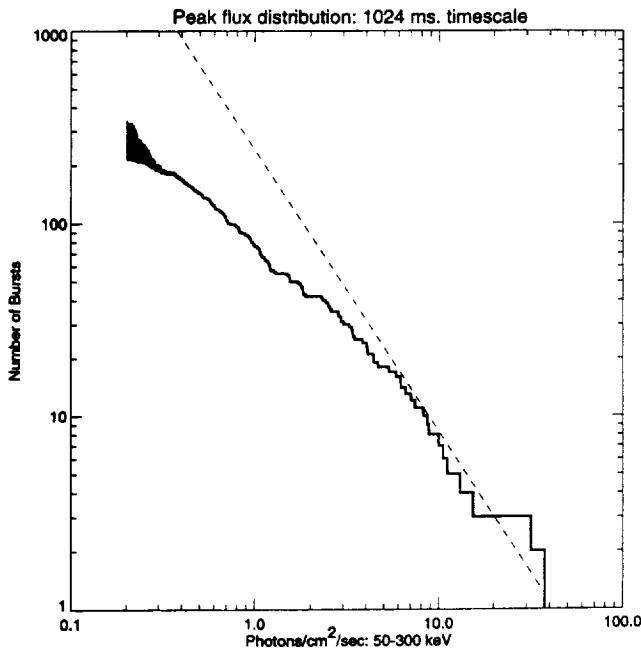

FIG. 4—The intensity distribution of gamma-ray bursts, showing the clear deviation from the $-3/2$ power law expected if the gamma-ray bursts were homogeneously distributed in Euclidean space.
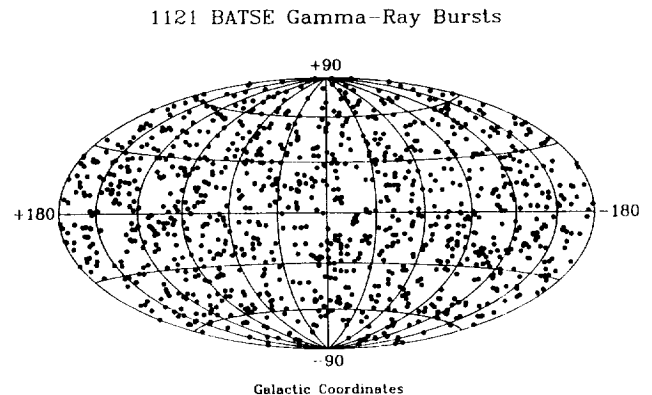

FIG. 5—The sky distribution of 1121 gamma-ray bursts, from the BATSE experiment on the *Compton Gamma Ray Observatory.*

esting to note that observations of weak bursts far from the Galactic plane had been noted prior to the BATSE results, but from a very limited number of bursts (Wilson et al. 1982; Hurley 1992). In all galactic disk models, a deviation in slope below $-3/2$ is necessarily accompanied by a strong concentration of sources in the galactic plane.

4. SEARCHES FOR BURST COUNTERPARTS

Ever since the initial discovery of gamma-ray bursts, there has been a quest to discover a counterpart to a gamma-ray burst in another wavelength region before, during, or after the gamma-ray event. These searches have concentrated on the optical region, although virtually all electromagnetic wavelength regions, and other, more esoteric radiations, have been searched.

The searches for counterparts have taken many forms, including searches for statistical associations of known objects with bursts with poorly known locations as well as searches of archival plates and other data bases for transient or unusual objects within the error boxes of well-determined burst locations. Attempts have also been made to obtain a chance observation of a counterpart with wide-field patrol cameras. These attempts have not yet proven to be unambiguously successful. There have been several claims of candidate objects as counterparts, but these have generally been discounted because of low statistical significance, controversial instrumental effects or the spurious, one-time occurrence of a claimed counterpart which could not be independently confirmed by a second instrument. A recent review of the present status of correlated gamma-ray burst observations in all wavelength regions is given by Schaefer (1994).

The pioneering efforts of Kevin Hurley, Tom Cline, and others to establish and operate an interplanetary network (IPN) of spacecraft to precisely locate gamma-ray bursts began in the late 1970's and continue today. These locations for gamma-ray bursts are the best that are available. Their accuracy, and the response time in providing them, have been continuously improving over the years. Currently, the *Ulysses* spacecraft and near-Earth detectors serve as the only two interplanetary baseline nodes. This unfortunate circumstance will persist until the Russian *Mars '96* spacecraft becomes part of the network. Typical IPN location accuracies are in range of 1 to 10 arcmin. In the past, with a network of three or more spacecraft, error boxes of 10 square arcmin were not uncommon. The large-diameter, narrow width error annuli derived from the two-spacecraft *Ulysses-Earth* network observations can be used with coarser locations from single-experiment location determinations to restrict greatly the error boxes of many bursts. A moderately strong gamma-ray burst is required for observation by the relatively small detectors of the IPN spacecraft. The *HETE* spacecraft, to be launched in 1995 (Sec. 7) will become the first gamma-ray burst experiment to provide accurate ($\sim$0.1 degree) single-spacecraft locations over a wide field-of-view (Ricker et al. 1992).

BATSE has had a quick-alert capability since 1991 that was developed to provide burst locations within several hours, under favorable conditions. A joint BATSE–

COMPTEL capability also exists that is able to provide even more accurate ($\sim$1 deg) locations within several hours for those gamma-ray bursts which also happen to be within the COMPTEL field-of-view (about 10 percent of the sky). A new, near-real-time burst location system utilizing BATSE data, called BACODINE (BAtse COordinates DIstribution NEtwork) (Barthelmy et al. 1994), is also underway. The BATSE-BACODINE system can provide gamma-ray burst locations to external sites within about 5 seconds of their detection by BATSE. When BACODINE is linked to a rapid-slewing optical telescope, it opens the exciting possibility of obtaining optical images of burst regions while the burst is in progress.

5. CONTROVERSIES REGARDING GAMMA-RAY BURST OBSERVATIONS

The reported observation of spectral line features in gamma-ray bursts, and their interpretation as cyclotron lines produced in the intense magnetic fields of neutron stars (cf. Harding 1991) has been a primary reason for associating gamma-ray bursts with neutron stars. A search for line features (either absorption or emission features) with the detectors of BATSE-*Compton Observatory* has thus far been unable to confirm the earlier reports of spectral line features from gamma-ray bursts.

The question of burst repetition remains controversial. Models of nearest-neighbor clustering using BATSE data have concluded that burst repetition, if present, accounts for less than about 20% of the observed bursts (Strohmeyer et al. 1994; Meegan et al. 1995).

Renewed interest in cosmological models of gamma-ray bursts has led to a search for a more direct means of determining their distance scale. In particular, considerable attention has been placed on the observation of time-dilation effects in gamma-ray bursts. Because of their finite, relatively short duration, gamma-ray bursts at cosmological distances would exhibit time-dilation effects unobservable from other astronomical objects. In accordance with standard cosmology, the more distant bursts are fainter and they are receding faster. Thus they would show a larger time dilation than the nearer, more intense bursts. The entire burst would be "stretched" so that the fainter (and presumably farther) bursts would be, on the average, longer. In addition, individual pulse structures within bursts and the time intervals between these pulse structures would be similarly stretched. Finally, the spectra of the fainter, more distant bursts would be redshifted, which, in essence, is a time dilation of the wavelength of emission in the observer's frame.

Due to the complexity of the gamma-ray burst time structures and the wide range of their durations, any dilation effects can only be tested in a statistical sense. Initial work in these efforts has proceeded and a positive result was announced by a group at NASA/Goddard, using BATSE data (Norris et al. 1994). Other workers have not confirmed this result and it remains somewhat controversial. If the result is confirmed, it would be consistent with a cosmological origin, but not a proof, since other effects could conceivably cause an intensity-duration correlation.

6. MODELS OF GAMMA-RAY BURSTS

A theoretical understanding of gamma-ray bursts will comprise several components: a site, an energy source, and an emission mechanism. The sites must be consistent with the observed isotropy and inhomogeneity, the energy source must be sufficient to produce the observed intensities for the distances assumed, and the emission mechanism must be able to reproduce the time scales and the spectra observed in bursts. Satisfying even these minimal observational prerequisites has proved difficult.

While there have been over a hundred theoretical papers proposing a wide range of scenarios for gamma-ray bursts (Nemiroff 1994), none provide a complete theory. That is, none have provided complete details specifying the site, the energy source, and an analysis of the energy emission processes. The final step, deriving the observed burst properties from considerations of the energy transport, has been the most difficult. The paucity of X rays, for example, presents difficulties for processes occurring near the surface of a neutron star. The intense gamma radiation would be expected to heat the neutron-star surface, producing an intense thermal X-ray component, which has not been observed.

7. FUTURE OBSERVATIONS

Two spacecraft containing gamma-ray burst instruments will soon be producing new gamma-ray burst observations. The TGRS (Transient Gamma-Ray Spectrometer) is an experiment on the US *WIND* spacecraft launched in 1994. The detector is a high-resolution, passively cooled germanium detector. The *WIND* spacecraft also contains two Konus detectors which are similar to the spectroscopy detectors of BATSE.

The *HETE (High Energy Transient Explorer)* satellite is a small satellite mission dedicated to the study of gamma-ray bursts. The prime objective is the precise localization and rapid follow-up observation of gamma-ray burst locations by on-board UV detectors and observatories on the ground. Burst localization to 0.1 degree can be achieved by the X-ray detectors and to 3 arcsec by the CCD, if there is concurrent, detectable UV emission. Data can be forwarded in near real-time to a large number of primary and secondary receiving sites for rapid follow-up observations. *HETE* is scheduled for launch in late 1995.

The last successful interplanetary probe launched with a gamma-ray burst detector was *Ulysses* in 1990. The Russian *Mars-96* spacecraft will carry several detectors for gamma-ray burst observations. It will become an important component of the Interplanetary Network (IPN) of gamma-ray burst detectors. G. Ricker/MIT (private communication) also proposes an array of miniature spacecraft with accurate timing capability, spaced around the Earth's orbit to establish a significant enhancement to the IPN.

Plans are being made for new, powerful ground-based optical CCD camera systems for burst counterpart searches. These rapidly slewing camera systems, when coupled to BATSE-BACODINE or to other near realtime burst-locating spacecraft such as *HETE* will provide unprecedented sensitivity in the magnitude range 15–17. A successor to the GROCSE camera system (Akerlof et al. 1994) is being planned. Similarly, a very sensitive, dedicated wide-field rapid-response camera for burst studies is being proposed by a European consortium as part of the European Southern Observatory (M. Boer, private communication).

The hypothesis of an extended halo of gamma-ray burst sources surrounding the Galaxy can be tested by the observation of a similar population around other nearby galaxies, notably M31. A sufficiently sensitive future detector system ($\sim 10\times$ BATSE sensitivity) pointed toward the M31 may be able to detect the faint gamma-ray bursts that might be emanating from the M31 halo. This sensitivity may be attainable by a combination of large detector area, background reduction, and collimation of the field. Such detector systems are currently under study (F. Harrison, C. Meegan, private communications).

8. THE ESSENCE OF THE DEBATE

In the past few years, gamma-ray burst research has switched from a field with sparse data and detailed theoretical models to one of much data and models with little or no detail. The consensus opinion of the locale of the sources of gamma-ray bursts has changed from a fraction of a galactic scale height to either an extended galactic halo or to cosmological distances. The gamma-ray burst enigma appears to be as great now as it was twenty years ago (Ruderman 1975). A wealth of new data on time profiles, spectral characteristics, and burst distributions has thus far failed to provided conclusive evidence on the distance scale, central object(s) or emission mechanism(s) for the classical gamma-ray bursts. The isotropy and inhomogeneity of the bursts shows only that we are at or near the center of the apparent burst distribution. For the galactic halo models, the apparent isotropy of observed bursts requires that the distribution radius be significantly greater than the distance between Earth and the Galactic Center, and it also limits the amount of the central condensation (core) of an extended halo (Hakkila et al. 1994). On the other hand, the failure to observe an excess of bursts from M31 places upper limits on the extent of this halo. The conclusion is that extended halo models require typical distances to sources of order 100 kpc, regardless of the details of the radial distribution. At these distances, the required source luminosity is of order 10^{42} ergs s^{-1} (for isotropic emission).

The observed isotropy is a necessary requirement of cosmological models. The apparent inhomogeneity would result from redshift effects, and possibly source evolution. Satisfactory fits can be found using standard candle luminosities, standard cosmologies, and no source evolution. The weakest bursts originate from sources that are at redshifts of about $z \sim 1$ to 2 and the luminosity is of order 10^{50} to 10^{52} erg s^{-1}, assuming isotropic emission.

These two, greatly divergent distance scales for gamma-ray bursts—the galactic halo distances and cosmological distances, have become the subject of the second "Great Debate" in astronomy, which now follows.

The author is grateful to Robert Nemiroff, Jerry Bonnell, and the other organizers of the Great Debate II. Members of the BATSE team in Huntsville contributed significantly to the material used in this paper.

Note: Some sections of this paper were derived from a review article on gamma-ray bursts for the *Annual Reviews of Astronomy and Astrophysics, Vol. 33* (Fishman and Meegan 1995). A more comprehensive set of references than those given here may be found in that paper.

REFERENCES

Akerlof, C., et al. 1994, in AIP Conf. Proc. 307, ed. G. Fishman, J. Brainerd, and K. Hurley (New York, AIP), p. 633

Barthelmy, S., et al. 1994, in AIP Conf. Proc. 307, ed. G. Fishman, J. Brainerd, and K. Hurley (New York, AIP), p. 643

Briggs, M. S., et al. 1995, ApJ (in press)

Dickinson, H., and Tamarkin, P. 1965, Proc. IEEE, 53, 1921

Fenimore, E., et al. 1993, Nature, 366, 40

Fishman, G., Brainerd, J., and Hurley, K., eds., 1994, Proc. Gamma-Ray Burst Workshop, Huntsville, AL, AIP Conf. Proc. 307 (New York, AIP)

Fishman, G., et al. 1994, ApJ, 92, 229

Fishman, G., and Meegan, C. 1995, ARAA, 33, 415

Hakkila, J., et al. 1994, ApJ, 422, 659

Harding, A. K. 1991, Phys. Reports, 206, 327

Higdon, J., and Lingenfelter, R. 1990, ARAA, 28, 401

Hurley, K. 1992, in Gamma Ray Bursts, ed. C. Ho, R. Epstein, and E. Fenimore (Cambridge, Cambridge University Press), p. 183

Hurley, K. 1994, in AIP Conf. Proc. 307, ed. G. Fishman, J. Brainerd, and K. Hurley (New York, AIP), p. 726

Hurley, K., et al. 1994, Nature, 372, 652

Klebesadel, R., Strong, I., and Olsen, R. 1973, ApJ, 182, L85

Meegan, C., et al. 1992, Nature, 355, 143

Meegan, C., et al. 1994, The Second BATSE Gamma-Ray Burst Catalog (electronic form) avail. GROSSC:NASA/GSFC

Meegan, C., et al. 1995, ApJ (in press)

Nemiroff, R. J. 1994, Comm. Astrophys., 17, 189

Norris, J. P., et al. 1994, ApJ, 424, 540

Ricker, G., et al. 1992, in Gamma Ray Bursts, ed. C. Ho, R. Epstein, and E. Fenimore (Cambridge, Cambridge University Press), p. 288

Ruderman, M. 1975, Ann. N. Y. Acad. Sci., 262, 164

Schaefer, B. 1994, in AIP Conf. Proc. 307, ed. G. Fishman, J. Brainerd, and K. Hurley (New York, AIP), p. 382

Schaefer, B., et al. 1994, in AIP Conf. Proc. 307, ed. G. Fishman, J. Brainerd, and K. Hurley (New York, AIP), p. 280

Singer, S. 1965, Proc. IEEE, 53, 1935

Strohmeyer, T. E., Fenimore, E. E., and Miralles, J. A. 1994, ApJ, 432, 665

Wilson, R., Fishman, G., and Meegan, C. 1982, in Gamma-ray Transients and Related Astrophysical Phenomena, ed. R. Lingenfelter, H. Hudson, and D. Worrall, AIP Conf. Proc. No. 77 (New York, AIP), p. 67