GAMMA-RAY BURSTS[1]

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ABSTRACT

The present status of gamma-ray burst research is reviewed, with an emphasis on recent observations of their temporal, spectral, and global distribution properties. The observed sky distribution of weak gamma-ray bursts constrains the allowable geometrical models to sources in either a giant spherical galactic halo or to sources at cosmological distances. Observations of time dilation consistent with the latter have been reported. Extensive searches for a counterpart to gamma-ray bursts in other wavelength regions have thus far proved negative. In spite of the abundance of new observations of gamma-ray bursts, their energy source and emission mechanism remain highly speculative. New, rapid counterpart search efforts and several new space-borne experiments may provide the needed observations to make progress in the field.

1. INTRODUCTION

Gamma-ray bursts are brief bursts of high-energy radiation that appear at random in the sky, emitting the bulk of their energy above $\sim$0.1 MeV. During their appearance, they often outshine all other sources in the gamma-ray sky combined. They are a phenomenon without precedent in astronomy, having no observed quiescent counterpart in any other wavelength region, no observations that would provide a direct measure of their distance, and no comprehensive model that can explain their origin. Furthermore, the bursts have an extremely wide variety of durations, temporal profiles, and spectral variations, which makes modeling them all the more difficult.

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In the past 25 years over 2,000 observational and theoretical papers have been written about γ-ray bursts, and yet they remain perhaps the least understood of all observed objects in the Universe. In the scientific literature, the sources of the bursts are sometimes called "γ-ray bursters," while the observed phenomena themselves are called γ-ray bursts. Often, they are referred to as the "classical" γ-ray bursts, primarily to distinguish them from the Soft Gamma-ray Repeaters (SGRs) (cf Higdon & Lingenfelter 1990). These latter phenomena are very rare (only three are known) and are quite distinct in their spectral and temporal properties (Norris et al 1991, Kouveliotou et al 1994a, Kouveliotou 1994). These three SGRs have now been identified with supernova remnants; two within the Galaxy and one in the LMC (Kouveliotou et al 1994a, Murakami et al 1994, Kulkarni et al 1994). Of the three SGRs, we consider the well-known event of 5 March 1979 to be unique among all types of γ-ray transients. Its initial single, intense pulse was followed by an 8-second periodicity, which, in turn, was followed by repeated SGR events weeks and months later. The locations of the March 5 event and the subsequent events are consistent with the supernova remnant N49 in the LMC (Cline et al 1982, Higdon & Lingenfelter 1990, Rothschild et al 1994). The SGRs are not discussed in further detail in this review.

The history, observations, and models of γ-ray bursts have been reviewed many times in the past. Hartmann (1995) has prepared a comprehensive list of these reviews in a recent paper. A selection of some of the more recent reviews, with their primary emphasis, include: Hurley (1989, 1993) (observations); Higdon & Lingenfelter (1990) (general review); Vedrenne (1991) (observations); Harding (1991, 1994) (theory); Nemiroff (1994) (list of models); Hartmann (1991, 1994, 1995) (theoretical considerations). A comprehensive bibliography of the γ-ray burst literature has also recently become available (Hurley 1994a). There have been many conferences that were devoted primarily to γ-ray bursts or that contain a large number of γ-ray burst papers. Some of those conferences in the past ten years, and their published proceedings, include: Stanford 1984—Liang & Petrosian (1986); Taos 1990—Ho et al (1992); Huntsville 1991—Paciesas & Fishman (1992); St. Louis (First Compton Symposium, 1992)—Friedlander et al (1993), and Huntsville 1993—Fishman et al (1994a).

This review concentrates on the observed properties of γ-ray bursts and their analysis and interpretation. Because the theoretical situation is quite unsettled and highly speculative at present, the descriptions of models, emission mechanisms, and central sources are rather cursory here.

1.1 *Recent Historical Perspective*

The field of γ-ray bursts has undergone a rapid, dramatic, and to many, a surprising change over the past three years as a result of new, more sensitive observations of γ-ray burst intensity and sky distributions. These observations

have been made by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* (*CGRO*) (Meegan et al 1992). At the time of the last review in this series (Higdon & Lingenfelter 1990), most workers in the field considered the source of γ-ray bursts to be Galactic neutron stars, distributed primarily in the Galactic plane. Most of the theoretical work on γ-ray bursts in the 1980s centered on modeling the details of the energy source(s) and emission mechanism(s) for these relatively nearby neutron star models. Some of these models became very detailed and elaborate [cf Harding 1991, Ho et al 1992 (TAOS)]. This paradigm for γ-ray bursts persisted for about 15 years. The majority of workers in the field have now abandoned these models, although a significant number of theorists still believe that γ-ray bursts originate from Galactic neutron stars in a very extended Galactic halo (Section 5).

The BATSE experiment on *CGRO* observes a spatial distribution of bursts unlike any known Galactic component, either disk or halo, and furthermore sees no clustering of bursts on small or large angular scales. These bursts are not associated with concentrations of mass on any distance scale (nearby star clusters, globular clusters, the LMC, M31, the Virgo Cluster,... and so on) (see Section 6). These observations, combined with the observed deficiency of weak γ-ray bursts (indicating a spatial inhomogeneity), have caused many theorists in the field to adopt a new paradigm for the origin of γ-ray bursts: sources at cosmological distances. This new paradigm is almost entirely by default—no other known distribution seems to fit the observations. The situation is rather dissatisfying; one would like to have a more direct measure of the distance scale.

1.2   *Current Observational Situation*

The four experiments aboard the *Compton Gamma Ray Observatory* (Friedlander et al 1993) are providing a major fraction of the current γ-ray burst data, although Russian, French, and Danish burst experiments are still operating. A catalog of 66 γ-ray bursts from the Russian-French PHEBUS experiment aboard the Russian *GRANAT* spacecraft has recently been published (Terekhov et al 1994). The WATCH γ-ray burst locating instrument operated on both the *GRANAT* spacecraft (Castro-Tirado et al 1994a) and on the European *EURECA* mission (Brandt et al 1994). The γ-ray burst experiment on the *Ulysses* spacecraft has been in operation since November 1990 (Hurley et al 1992, 1994d). Currently, it is the only distant node in the Interplanetary Network of burst timing/locating experiments. Two comprehensive γ-ray burst catalogs from the BATSE experiment on *CGRO* have been released (Fishman et al 1994b, Meegan et al 1994b). That experiment has been in operation since April 1991, and it is planned to continue operating at least until 1999.

2. TEMPORAL CHARACTERISTICS OF GAMMA-RAY BURSTS

Perhaps the most striking features of the time profiles of γ-ray bursts are their morphological diversity and the large range of their durations. Coupled with this diversity is our inability to classify γ-ray bursts into well-defined types, based on their time profiles. Although these characteristics were known from previous experiments, the large sensitive area of the BATSE detectors shows them well, as presented in the *First BATSE Gamma-Ray Burst Catalog* (Fishman et al 1994b). Examples of the extreme differences in burst morphologies and durations are shown in a sample page from this catalog (Figure 1).

2.1 *Burst Morphology*

Several attempts have been made in the past to categorize γ-ray burst morphologies (cf Hurley & Desai 1986, Klebesadel 1992). This difficult task is always 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 subclasses to employ in the classification scheme. In addition, there appear to be no other observational parameters (location on the sky, spectra, duration, ...) that have a distinct correlation with the temporal morphologies. (One exception, described below, is that the shorter γ-ray bursts tend to have harder spectra.) Fishman (1993) shows some of the possible classes of γ-ray burst profiles from the *First BATSE Gamma-Ray Burst Catalog*. These classes include:

1. single pulse or spike events;

2. smooth, either single or multiple, well-defined peaks (Figure 2);

3. distinct, well-separated episodes of emission (Figure 3); and

4. very erratic, chaotic, and spiky bursts (Figure 4).

The single pulse bursts have little or no additional structure. The approximate range of the duration of these events is from $\sim$30 ms to $\sim$100 s. A particular subclass of these events are the so-called FREDs (Fast Rise, Exponential Decay), in which the rise time is very much shorter than the fall time. The decaying portion is not strictly an exponential function but has a continually decreasing slope. In many FREDs, there are one or more minor increases during the decaying portion. The spectra of these γ-ray bursts almost always evolve from hard to soft, and the secondary peaks, if present, are usually much softer than the primary peak. Some of these characteristics are quantified by Bhat et al (1994a).

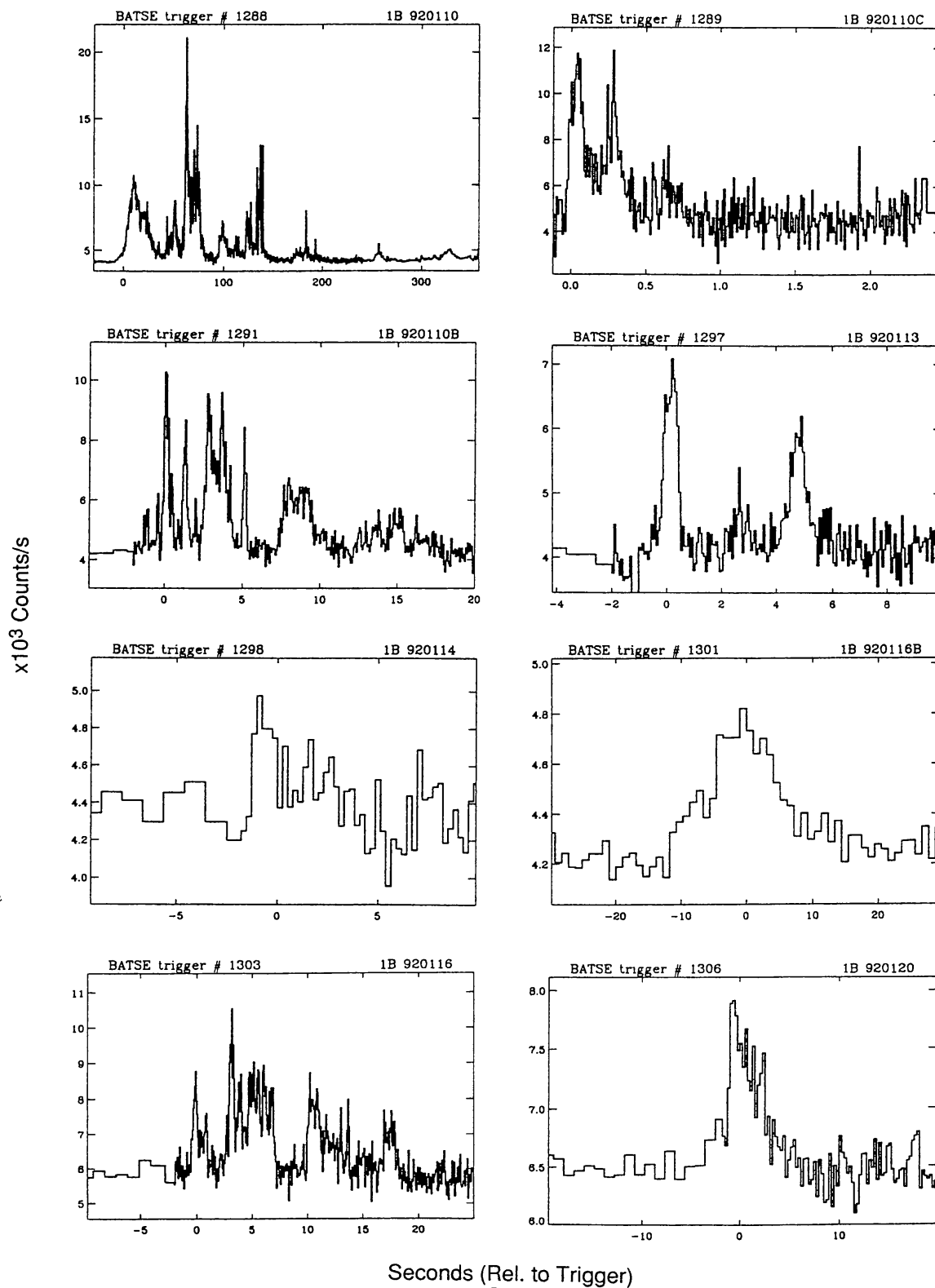In many of the smooth, multiple-peak events of class 2, the rise-times and fall-times tend to be similar.

Figure 1   Sample page from the *First BATSE Catalog of Gamma-Ray Bursts* (Fishman et al 1994b), indicating the diversity in the time profiles, intensities, and durations of gamma-ray bursts.
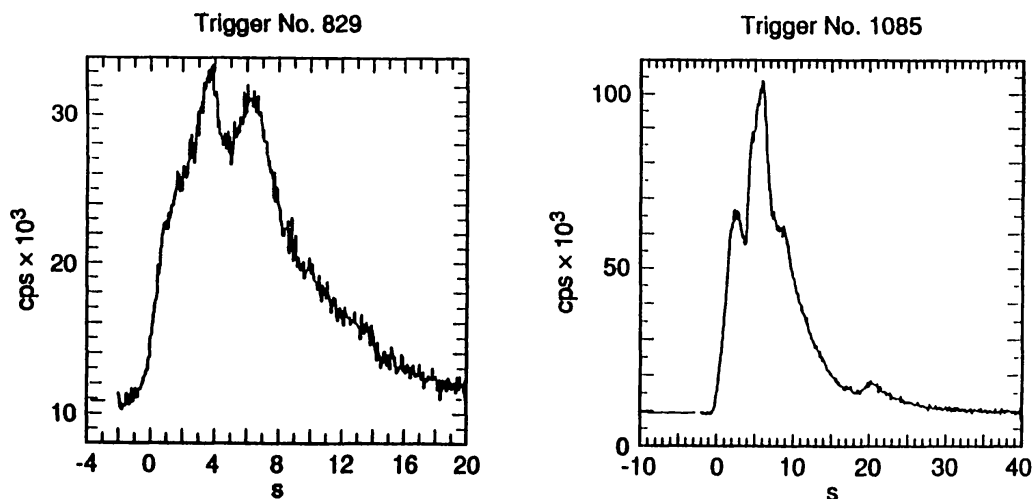
Figure 2   Examples of strong bursts that show no structures on fine time scales.

Class 3 events exhibit relatively long periods of time between peaks in which there is no detectable emission. The total time of these "gap" intervals can be much longer than that of the detectable emission. This type of burst is ill-defined in weak bursts, because there is less certainty in distinguishing periods of emission. In some strong bursts, such as 1B 910503, very low limits can be placed on the flux between emission peaks relative to the peak flux during the burst.

The majority of class 4 γ-ray bursts are highly structured, with many complex, overlapping peaks and spikes (spikes are narrow, intense peaks with durations $<\sim 0.1$ s). In many of these bursts, there appears to be an underlying "envelope" of emission from which the peaks and spikes arise.

A cursory examination of burst profiles indicates that some are chaotic and spiky with large fluctuations on all time scales, while others show rather simple structures with few peaks. However, some bursts are seen with both characteristics present within the same burst. Sub-millisecond structure has been detected in at least one burst (Bhat et al 1992). No persistent, strictly periodic structures have been seen from γ-ray bursts from a fast Fourier transform analysis of BATSE data (Kouveliotou et al 1992).

Another general property of the γ-ray burst time profiles is that at higher energies the overall burst durations are shorter and subpulses within a burst tend to have shorter rise times and fall times (sharper spikes). Most bursts also show an asymmetry, with shorter leading edges than trailing edges. This asymmetry has been quantified by Link et al (1993) and by Nemiroff et al (1994a), who argue that the bursts are caused by an explosive event rather than a sweeping, beamed event, since the latter would, in general, not show such an asymmetry. However, some bursts show no asymmetry (cf Figure 5), even when high counting rates would permit such measurements to be made.
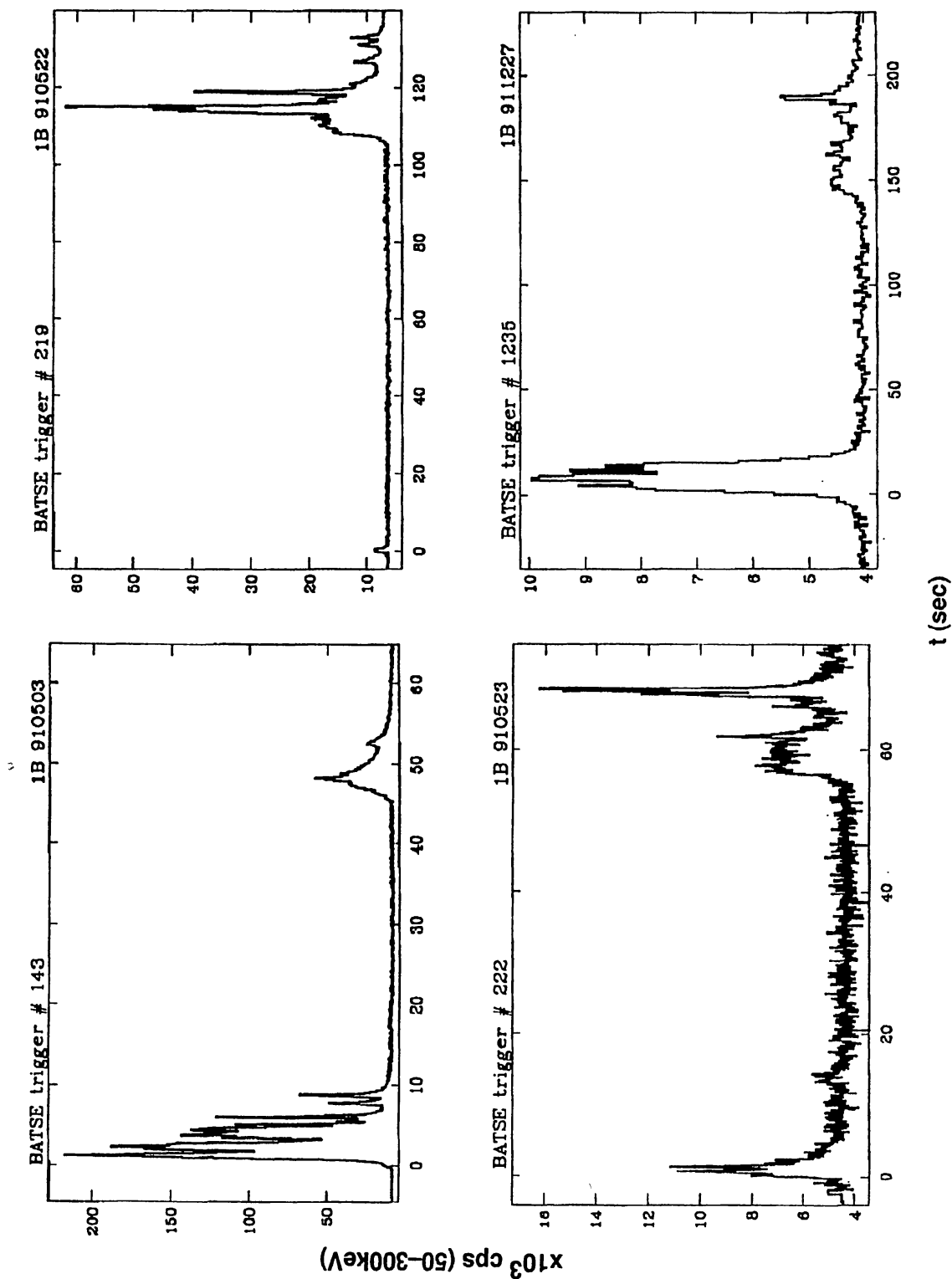
Figure 3   Some gamma-ray bursts that have distinct, well-separated episodes of emission.

In the past few years, several analytical methods have been introduced in the study of γ-ray burst temporal structures. The use of wavelets to analyze time profiles of γ-ray bursts has been described by Norris (1994) and Meredith et al (1994). The complex profiles of γ-ray bursts can be decomposed into a relatively small number of parameters through wavelets. These analyses are more appropriate than Fourier decomposition owing to the finite duration of bursts. It has been noted that models of temporal profiles based on log-normal (or Kapteyn) pulses appear to be well suited for quantitative analyses with relatively few parameters (Brock et al 1994). Similarly, Bhat et al (1994b) have also devised several new parameters for the study of the variability, complexity,
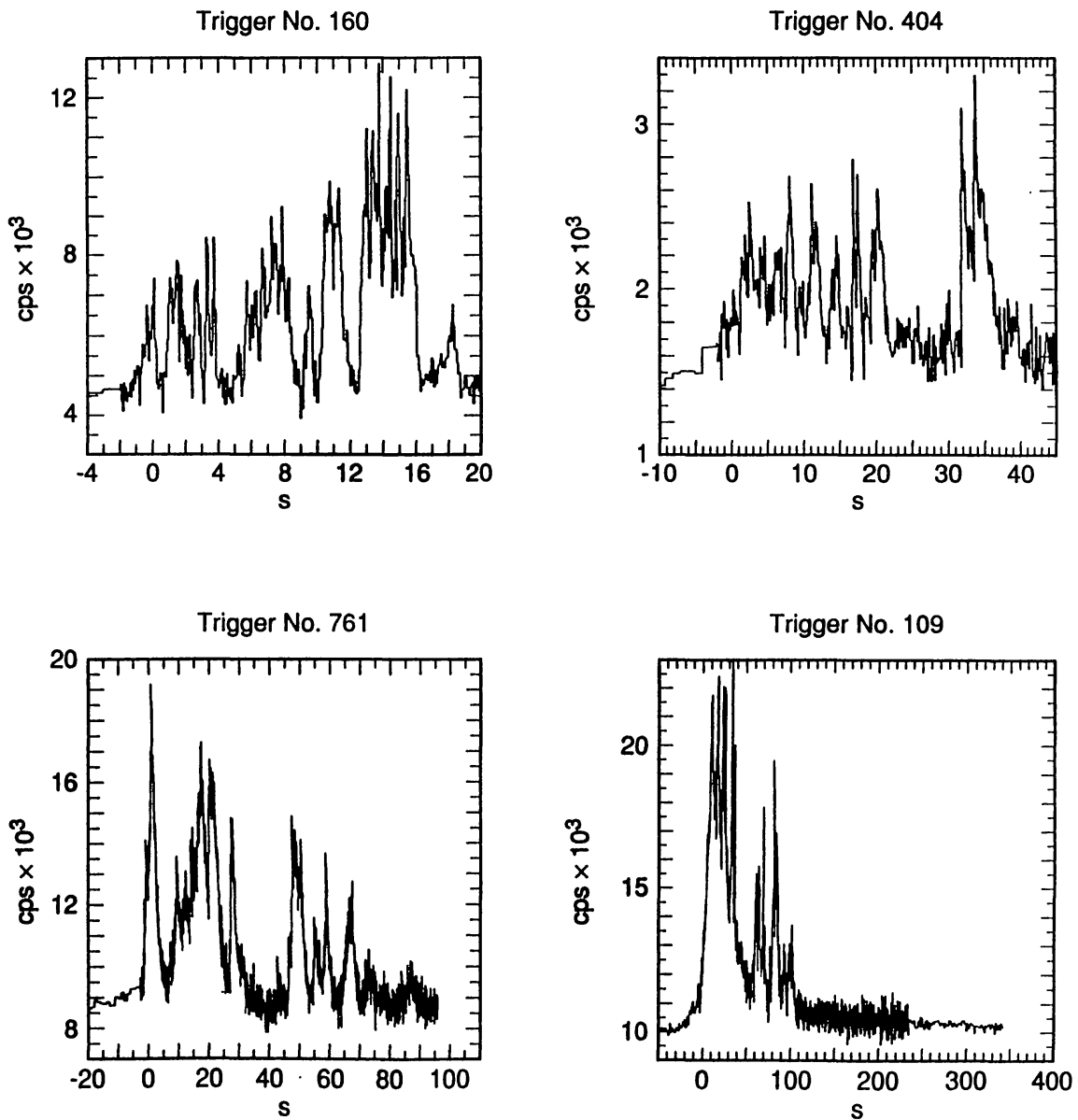
Figure 4 Examples of gamma-ray bursts with extremely complex temporal structures.
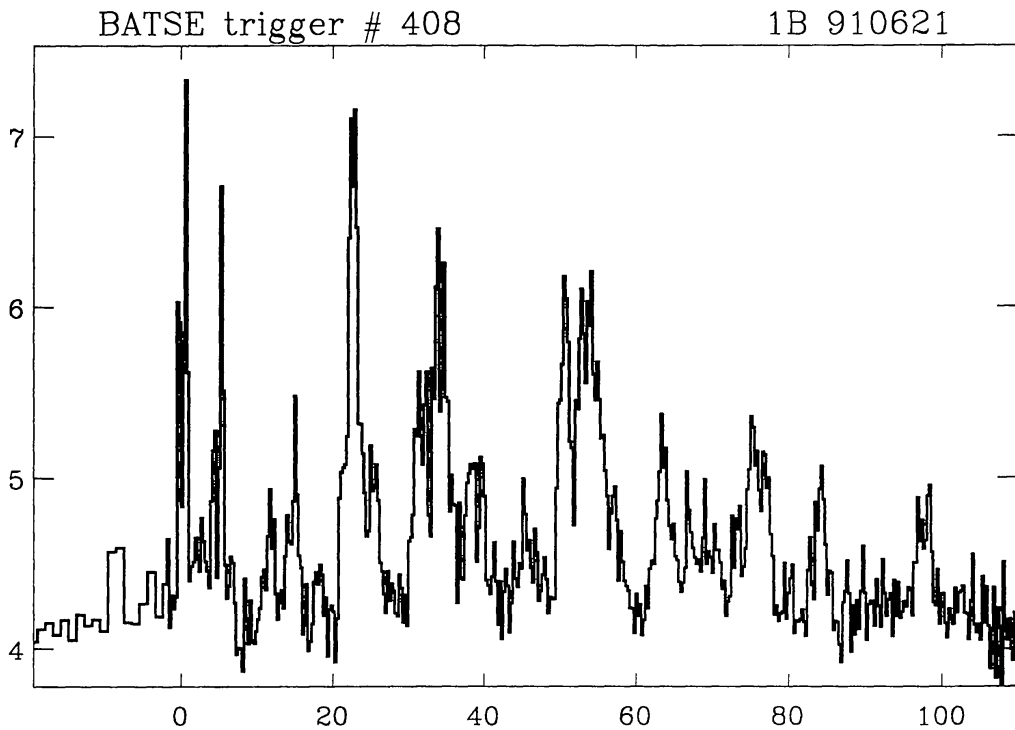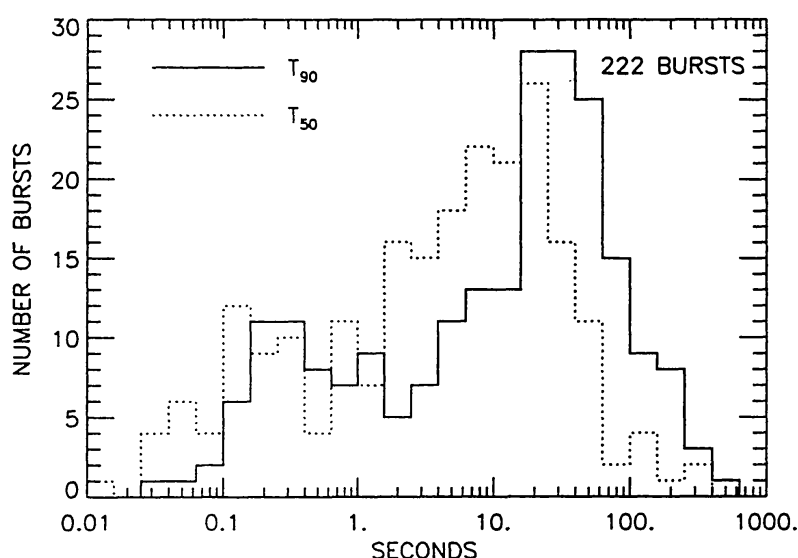
Figure 5 An example of a gamma-ray burst that shows no asymmetry in the overall time profile or in the individual peaks within the burst.

and spectral evolution of bursts, with particular application to short γ-ray bursts (<2 s). Lamb et al (1993) had developed a "variability" parameter to categorize γ-ray burst temporal morphology, from which they found two distinct morphological classes. However, that parameter was subsequently found to be biased by instrumental parameters (Rutledge & Lewin 1994, Meegan & Kouveliotou 1994). Lestrade et al (1994) and Lestrade (1994) use a variability measure based on counting rate runs up and down to quantitatively measure the "spikiness" of bursts. The use of this measure on a set of BATSE γ-ray bursts shows no indication of two separate populations (Lestrade et al 1994).

Unsuccessful searches have been made for short-duration (microsecond) flares or bunching of photons in γ-ray bursts (Schaefer et al 1993). Such bunching had been postulated by Mitrofanov (1983) and, if found, would have great implications for the physics of the burst emission process. Bhat et al (1994b) also searched for such bunching without positive results in a sample of short (<2 s) BATSE γ-ray bursts. At higher energies (>100 MeV), microsecond bursts have been searched for in the EGRET-*CGRO* spark chamber data without success (Fichtel et al 1994). These high-energy, short bursts might be expected to come from relatively nearby Galactic evaporating black holes remaining from the early Universe (Hawking 1974, Page & Hawking 1976).

2.2 *Burst Durations*

The durations of γ-ray bursts range from about 30 ms to over 1000 s. However, the duration, like the burst morphology, is difficult to quantify because it is dependent upon the intensity and background and somewhat dependent upon the time resolution of the experiment. Some definitions of duration, such as the time above arbitrary flux or significance level, introduce a strong intensity bias into the measurement of duration. The BATSE group has settled on a T-90 measure—the time over which 90% of the burst fluence is detected; this measure eliminates the initial and final 5% of the total burst emission. Such a definition yields durations that are, to first order, independent of intensity. A recent compilation of the distribution of durations is shown in Figure 6 (from Fishman et al 1994b). A bimodality is seen in the logarithmic distribution, with broad peaks at about 0.3 s and 20 s and a minimum at around 2 s, as reported by Kouveliotou et al (1993b). These distributions are well fit by log-normal distributions (McBreen et al 1994). The distribution drop-off at short durations is partially due to an instrumental bias—the minimum time scale over which the BATSE experiment can trigger on bursts is 64 ms. The shorter bursts are also seen to have harder spectra, as measured by a hardness ratio (Figure 7). A hint of the bimodal distribution of burst durations was previously described by Klebesadel (1992) from a rather limited set of burst data derived over an eight-year period from a variety of spacecraft. A spectral difference between short and long events was seen in data from the PHEBUS experiment on the *GRANAT* spacecraft (Dezalay et al 1992). Kouveliotou et al (1994b) further

Figure 6 The duration distribution of 222 gamma-ray bursts from the BATSE catalog. Two separate measures are shown, representing 50% and 90% of the total burst fluence. A bimodal distribution is seen, with a separation near 2 s. (From Fishman et al 1994b.)
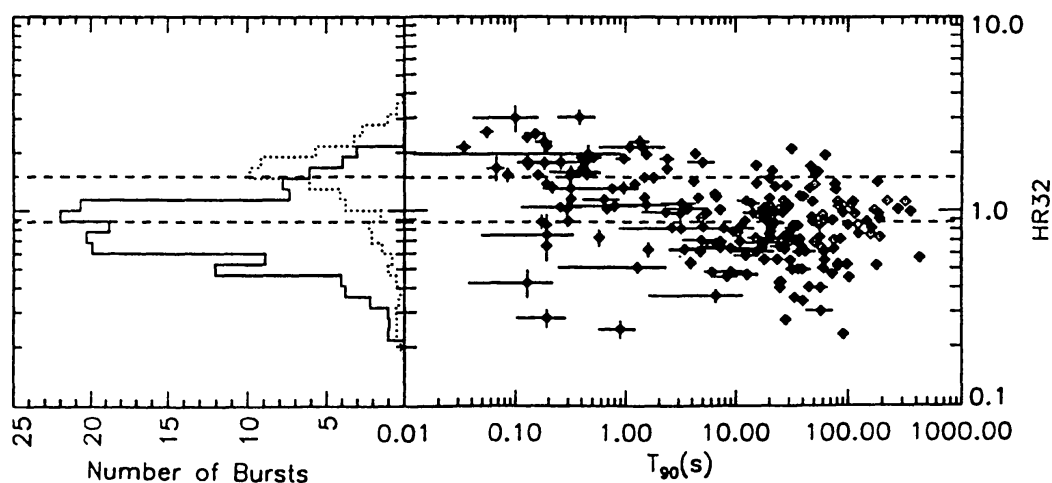
Figure 7   The hardness vs duration of gamma-ray bursts. The shorter bursts tend to have harder spectra, as measured by a hardness ratio. (From Kouveliotou et al 1993b.)

note that there are no other observed differences in the celestial distribution of these two duration subclasses of γ-ray bursts.

The duration distribution of a separate set of γ-ray bursts, from the Franco-Soviet SIGNE experiment aboard the *Venera 13* and *14* spacecraft, was analyzed by Kargatis et al (1994a). The burst trigger criteria implemented on the SIGNE experiment resulted in a bias against the shorter duration bursts and thus a bimodality in the distribution was not observable. However, for longer duration bursts, they found that this distribution was compatible with that found for the BATSE bursts (Kargatis et al 1994b).

A recent (and quite unexpected) observation of delayed high-energy γ-ray emission from a γ-ray burst was reported in 1994. The EGRET experiment on the *Compton Observatory* detected very high-energy (200 MeV–10 GeV) photons, up to 1.6 hr following an intense burst on 17 February 1994 (Hurley et al 1994a). At the lower photon energies observable by the BATSE and *Ulysses* detectors, this γ-ray burst lasted 180 s. During this time, EGRET observed about a dozen high-energy photons, with energies as high as 4 GeV. However, following this emission there were additional photons, with energies up to 20 GeV, as long as 5700 s after the start of the burst. All high-energy photons were consistent with the same burst direction. Unfortunately, a data gap and Earth occultation occurred at intermediate times, so that the full extent of the time profile at high energies could not be followed. Figure 8 shows the composite time profiles of this burst, as seen by the EGRET, BATSE, and *Ulysses* experiments. There have been five other γ-ray bursts observed by EGRET that had high-energy photons of comparable energy, but only this γ-ray burst had such long, extended emission. Extended hard x-ray and low-energy γ-ray emission from many γ-ray bursts have been searched for in BATSE data using the Earth occultation technique (Horack et al 1993, Horack & Emslie
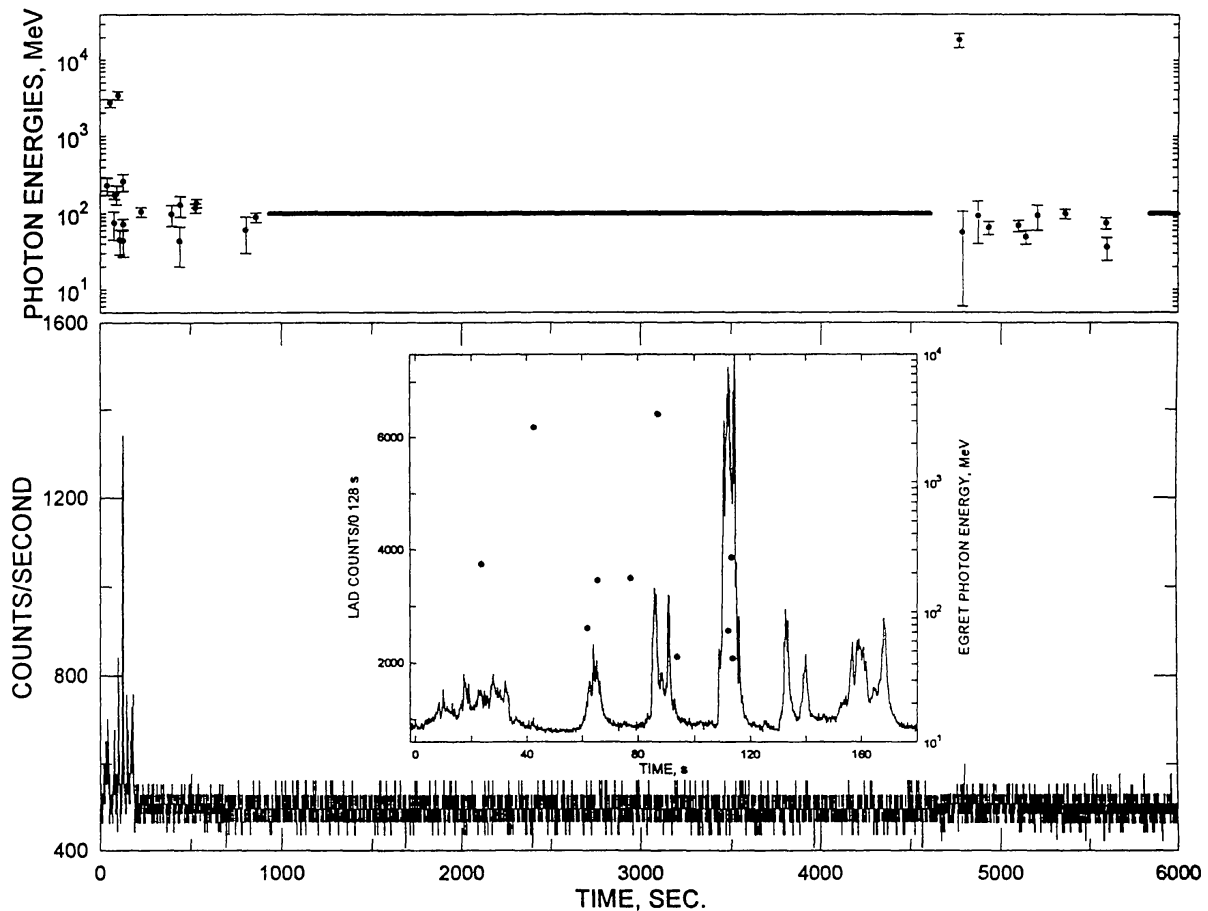
Figure 8 The amazing burst of 17 February 1994, observed to emit GeV photons up to 1.5 hr after the initial outburst, as observed by the EGRET experiment on the *Compton Gamma Ray Observatory*. This composite figure includes data from the EGRET, *Ulysses*, and BATSE experiments. (From Hurley et al 1994a.)

1994a). Such "afterglow" emission might be expected by some models. No extended, lower energy emission has been found; an upper limit of $\sim 5 \times 10^{-9}$ erg cm^{-2} s^{-1} on time scales $\gtrsim 1$ hr was found.

3. SPECTRAL CHARACTERISTICS OF BURSTS

A unique feature of γ-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 that appears somewhat similar in shape when integrated over the entire burst and when sampled on various time scales within a burst. Figure 9 shows a typical burst spectrum from 0.1 MeV to 10 MeV, with the peak power at about 600 keV (Share et al 1994). A spectrum from the strong burst GRB 910503, using data from all four *CGRO* experiments is shown in Figure 10 (Schaefer et al 1994d). The COMPTEL experiment on the *Compton Observatory*, which is sensitive to medium-energy γ rays, has observed

the peak power from many bursts to be in the MeV energy range (cf Winkler et al 1992, Hanlon et al 1994a,b). There is a growing trend to plot γ-ray burst spectra in the form of $E^2 dE$ or νF_ν vs energy, where F_ν is the spectral flux at the frequency ν. This has the advantage of making it easy to discern the energy of peak power from the burst. This suggestion has been made by many (cf Liang 1989) and is becoming a common practice in γ-ray astronomy.

3.1 *Continua Spectra*

Spectral shapes that have been fit to burst spectra include broken power laws (Schaefer et al 1992), log-normal distributions (Pendleton et al 1994a,b), and power laws joined by exponential spectra (Band et al 1993). If a single power law is fit to a relatively narrow energy range, such as that measured by the BATSE Large Area Detectors (LADs), the resulting distribution of power-law spectral indices shown in Figure 11 is obtained (Pendleton et al 1994c). Plots of the correlations between the ratios of detected counts within wide energy bands, called color-color diagrams (in analogy to similar studies in optical astronomy), have also been found to be useful in the study of the systematics of γ-ray burst spectral evolution (Kouveliotou et al 1993a).
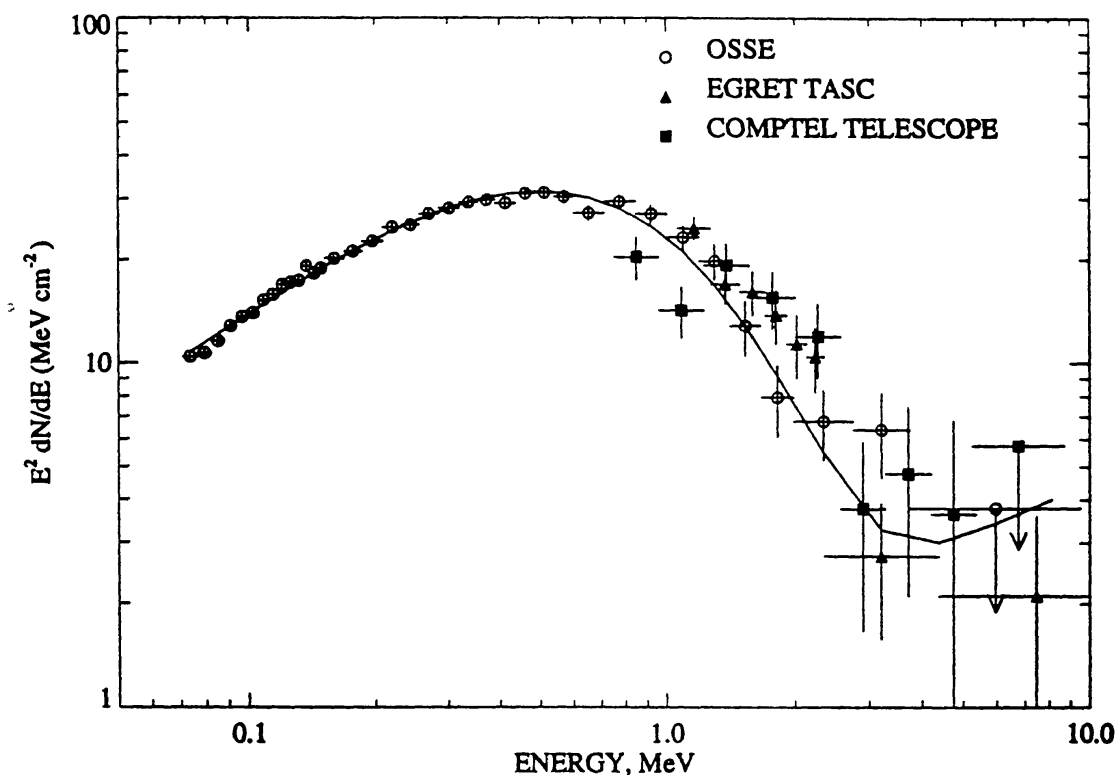

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)
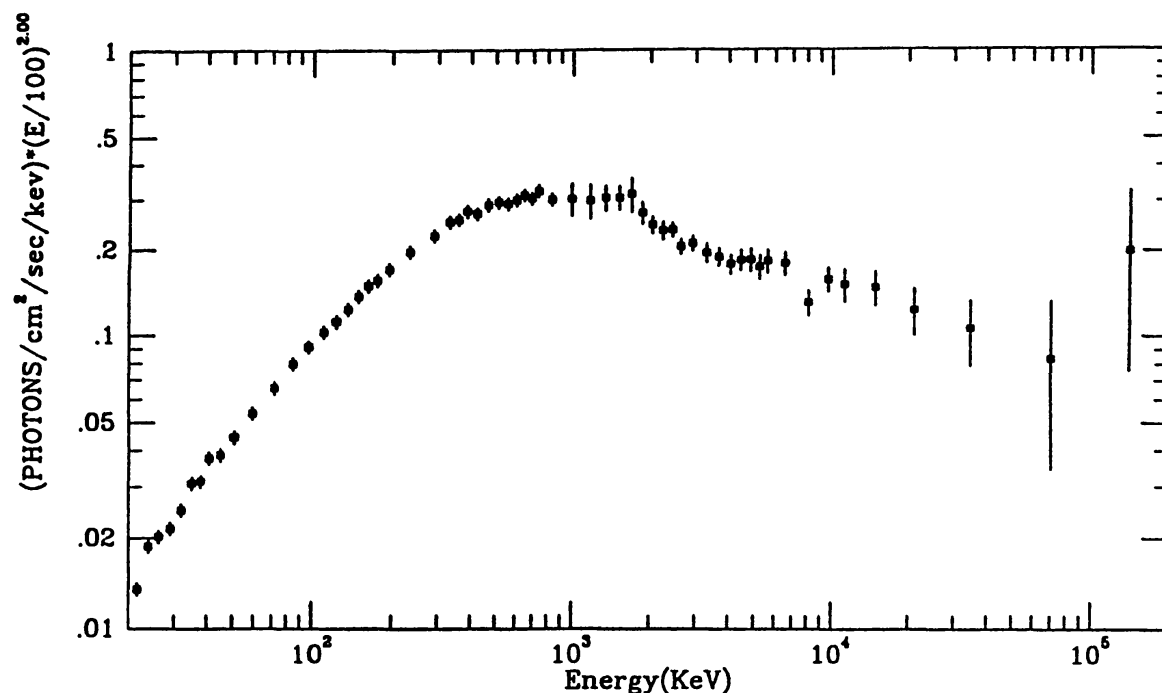
Figure 10   The spectrum of GB 910503, measured by all four experiments on the *Compton Gamma Ray Observatory* (Schaefer et al 1994d).

Although the spectral shapes of many bursts are similar, the energy at which peak power is emitted changes from burst to burst and is seen to rapidly change within a burst. Some significant changes on time scales as short as milliseconds have been observed (Ford et al 1994, 1995; Kouveliotou et al 1994b). Earlier observations by the γ-ray spectrometer on the *Solar Maximum Mission* showed that, in many bursts, the high-energy emission follows a single power law well into the MeV range (Matz et al 1985, Share et al 1992).

A comprehensive examination of BATSE spectral data has recently been performed by Band et al (1993) using the following functional form for the
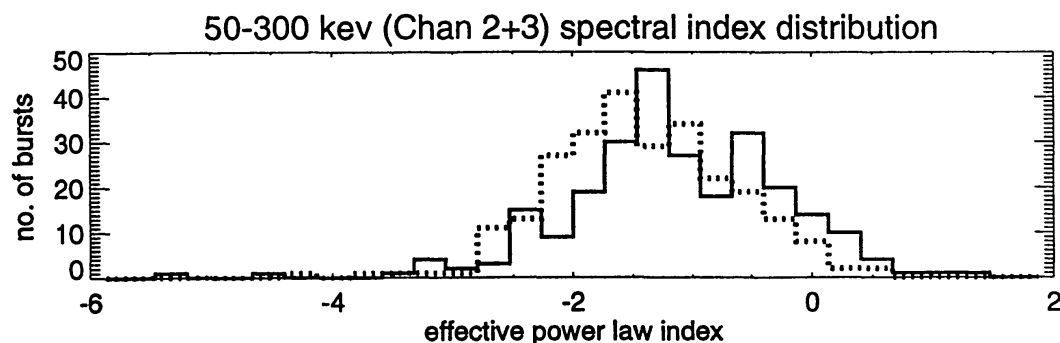

Figure 11   The distribution of power-law indices for a large number of bursts, as measured by the BATSE large-area detectors. (From Pendleton et al 1994c.)

continuum:

$$N(E) = AE^{\alpha}e^{-E/E_0}$$

for low energies, and

$$N(E) = BE^{\beta}; \quad \alpha > \beta$$

for high energies. This spectral form was found to fit the data very well over the entire energy range of these detectors, $\sim$20 keV to several MeV. Although the fits to the above form were good, the analysis showed a wide range of the parameters, i.e. a large spectral diversity. The break energy of the spectra, E_0, ranged from less than 100 keV to over 1 MeV. Brainerd (1994a) considered how Compton scattering by a thick medium might produce this distinctive spectrum found in γ-ray bursts. It is of interest that no correlations of burst spectral parameters were found with burst morphology or burst location (Band et al 1993). Thus, the separation of bursts into distinct populations by spectral classes is problematic.

Other generalizations can be made with regard to burst continuum spectra. Within most (but not all) bursts, there is a hard-to-soft spectral evolution, resulting in the lower energies peaking earlier (Pendleton et al 1994a,b; Ford et al 1994, 1995). Bhat et al (1994a,b) analyzed a particular subclass of γ-ray bursts: those that exhibit a sharp rise, followed by a relatively smooth, longer decay time. The majority of these showed the hard-to-soft spectral evolution, but their overall spectral characteristics were not different from other γ-ray bursts. Pendleton et al (1994a,b) have found several examples of bursts in which the spectra evolve very smoothly from hard to soft. In all time intervals within these bursts, the spectra are well represented by a log-normal distribution. Kargatis et al (1994a) have also analyzed γ-ray burst spectral data from 1981–1982 from the SIGNE experiments on *Veneras 13* and *14* for a systematic study of spectral evolution and other spectral characteristics. No uniform characteristics could be determined, although many showed a correlation between spectral hardness and intensity. However, they also found it significant that many bursts showed no such correlation. Previously, such a correlation had been found by Golenetskii et al (1983), and many had assumed that this was a ubiquitous property. It has also been noted (Section 2.2) that, in general, shorter bursts have harder spectra (Dezalay et al 1992, Kouveliotou et al 1993b), as shown in Figure 7. Koshut et al (1994, 1995) have performed an interesting spectral comparison between short bursts and short spikes of comparable duration that are found within longer duration events. The two have different spectral properties. There are indications that the spikes within longer bursts have a lower average photon energy than the single spike bursts.

3.2   *High-Energy Gamma Rays*

EGRET has seen significant flux and power into the GeV energy range (Schneid et al 1992, Hurley 1994a, Section 2.2, Figure 8). These EGRET spectra are consistent with a single power-law spectrum at high energies, when integrated over the burst. Typical spectral indices range between -1.7 and -2.5 for these power laws. A remarkable new observation, mentioned above (Section 2.2), is that many of these high-energy photons (>100 MeV) are delayed with respect to the bulk of the lower energy emission (Dingus et al 1994, Hurley et al 1994a). At the time of the high-energy, delayed photons, there was no emission at lower energies, as observed by the BATSE experiment (Figure 8). A 20 GeV photon was recorded from the burst direction 1.5 hours after the burst detected by EGRET. This is the highest photon energy ever recorded from a γ-ray burst. Models for the delayed GeV photons have appeared recently. These explain the high-energy photons as resulting from either π^0 muon decay (Katz et al 1994) or from delayed, reverse-shock interactions of a highly relativistic, unsteady wind with the interstellar medium (Meszaros & Rees 1994a). Plaga (1995) shows how the intergalactic magnetic field could produce such a delay.

3.3   *Low-Energy X-Ray Emission*

Some bursts show emission as low as 1 keV, but the power contained in these low-energy photons is less than 1 or 2% of the total power from the burst (Yoshida et al 1989; Murakami et al 1991, 1992). Soft x-ray precursor emission was observed in one γ-ray burst out of 17 studied. The WATCH-*GRANAT* experiment has observed extended and precursor emission at energies of about 10 keV in at least seven γ-ray bursts (Castro-Tirado et al 1994a). Liang & Kargatis (1994) model the deficiency of x rays in γ-ray bursts as absorption by thick masses of circumburster material rich in iron-group elements. Brainerd (1994a) also shows that the deficiency of low-energy photons is a natural consequence of high-opacity absorption. Li & Liang (1992) have considered the possibility of observing faint, soft x-ray emission from γ-ray bursts in a possible extended halo of burst-producing objects around M31. Thus, low-energy x-ray observations are potentially very important for γ-ray burst models, and therefore it is highly desirable for them to be placed on more firm observational grounds with future experiments.

3.4   *Spectral Lines?*

The reported observation of spectral line features in γ-ray bursts and their interpretation as cyclotron lines produced in the intense magnetic fields of neutron stars [cf Harding 1991, Ho et al 1992 (TAOS)] has been a primary reason for associating γ-ray bursts with neutron stars. While it had been dogma that spectral line features are superposed on the continuum of many γ-ray bursts (cf Higdon & Lingenfelter 1990), we now believe that is not the case. A search for line features (either absorption or emission) with the detectors of BATSE-*CGRO*

has thus far been unable to confirm the earlier reports of spectral line features from γ-ray bursts (e.g. Yoshida et al 1992, Murakami et al 1988, Fenimore et al 1988). Several recent papers from the 1993 Huntsville conference proceedings (Palmer et al 1994a, Ford et al 1994, Preece et al 1994, Schaefer et al 1994c) have discussed the preliminary BATSE line search analyses and their results. Subsequent searches for unambiguous indications of spectral line features in the BATSE data have been unsuccessful (Palmer et al 1994b). Newer searches are in progress using automated line-search software that examine each strong γ-ray burst in numerous time intervals over a large energy range (M Briggs, private communication). Although candidate line features are occasionally seen by one of the BATSE spectroscopy detectors during a portion of a burst, none of them has been verified at a high confidence level by another detector. The consistency of the BATSE negative observations with the positive observations of *Ginga* has been examined by Band et al (1994) and Palmer et al (1994b). They find that the two sets of observations are consistent with each other at the 10% confidence level. Thus, the discrepancy is yet unresolved.

One possible explanation for the false appearance of spectral features has been described. Pendleton et al (1994b) show some examples of spectra with very different continua that occur within the same burst and in nearly adjacent time intervals. Superposition of these spectra within a burst can produce "cusps" in the time-integrated spectra, leading to indications of spectral features in some BATSE γ-ray bursts.

4.   GLOBAL PROPERTIES: SPATIAL AND INTENSITY DISTRIBUTIONS

The most direct evidence of the spatial distribution of the sources of γ-ray bursts comes from their observed angular and intensity distributions. The angular distribution provides two of the dimensions of the spatial distribution, while the intensity distribution is a convolution of the unknown luminosity function and the unknown radial distribution. Even though neither distribution function is known, the intensity distribution data can still provide strong constraints on the allowable spatial distributions and luminosity functions of γ-ray burst sources.

4.1   *Observed Burst Intensity Distribution*

Several measures of burst intensity have been used to derive distributions; each have specific biases and selection effects. The most important of these effects arises from the fact that burst detection thresholds are specified in terms of count rates above background within some time and energy interval. The intensity distribution must therefore be corrected for trigger efficiency.

Earlier work used the total fluence S (erg cm^{-2}) for intensity distributions—a measurement of the total energy integrated over the duration of the burst.

This method has been largely abandoned in intensity distributions because it is virtually impossible to determine the efficiency for detecting bursts as a function of fluence, due to the wide range of temporal behavior of bursts. Consequently, $\log N$–$\log S$ distributions suffer from poorly known efficiency corrections over a large range of S, and reliable conclusions are unattainable.

Peak flux (erg cm^{-2} s or photons cm^{-2} s) is preferable to fluence because it can be more directly related to the trigger criteria typically employed by γ-ray burst detectors. To do so requires that the energy and time intervals over which counts are integrated be the same as those used for burst detection. Peak flux distributions require correction factors near the trigger threshold, since the conversion from count rate to flux will depend on the burst energy spectrum and the detector's response, including the angle of incidence of the burst to the detectors.

The maximum detected count rate C_{max} may be used as an intensity measure. Petrosian (1993) has shown how such a distribution can be corrected for variations in the trigger threshold C_{min}. Using C_{max} obviates the need to consider geometrical, detector, or spectral complications. The main disadvantage is that these same complications reappear if one wants to compare the C_{max} distribution to a theoretical model that uses physical units of intensity or to compare it to that of another experiment.

Going one step further, C_{max}/C_{min} is sometimes used for displaying intensity distributions. The threshold is always 1 by definition, and no corrections are necessary. A C_{max}/C_{min} distribution may be useful to demonstrate the deviation from homogeneity (described below); however, it is not appropriate to use such a distribution for developing physical models of spatial distributions because of its disassociation from physical units.

Given these considerations, we recommend the use of peak flux for intensity distributions. This allows comparisons among experiments and comparisons with theoretical models. It also places the burden of correcting for instrumental effects where it belongs—on the experiment team. Figure 12 (from Pendleton et al 1995) shows the differential peak flux distribution for 796 bursts observed by BATSE. The x axis is the peak flux integrated over 1.024 s in the energy interval 50 to 300 keV. The diamonds represent the actual number of bursts observed, and the crosses represent the number of bursts after correcting for trigger efficiency. The correction takes into account the varying threshold and the variations in the geometry of the burst observations. Scattering by the Earth's atmosphere is taken into account in the computation of the peak flux of each burst, but it is not included in the efficiency correction. Consequently, the corrected values are overestimates, as is evident in the lowest flux bin. Also not included in the efficiency correction is the peak counts bias, which results from statistical fluctuations of bursts near threshold (in't Zand & Fenimore 1994). Although the largest uncertainties in the intensity distribution
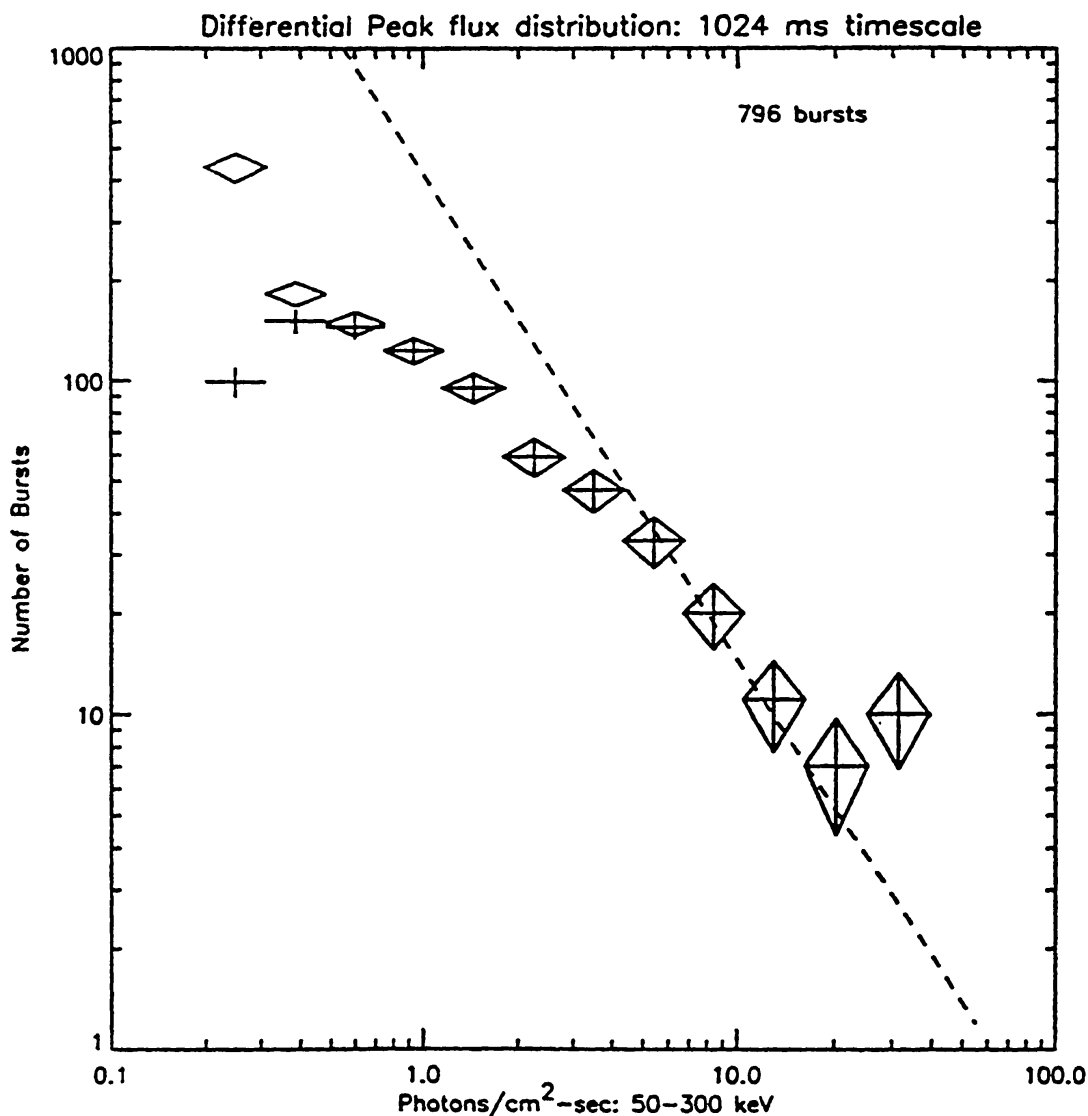
Figure 12   The peak flux distribution of 796 gamma-ray bursts observed by BATSE (Pendleton et al 1995). The flux is measured over the energy range 50–300 keV.

are concentrated just above the threshold, these are not crucial in attempts to fit models.

It is easily shown that if sources are distributed homogeneously in Euclidean space, i.e. the density and luminosity function are independent of position throughout the volume of space observed, then the integral intensity distribution will be $N(>P) \propto P^{-3/2}$. From Figure 12 it is seen that there is a significant deviation from the form expected ($-3/2$ power law, shown as a dashed line) if the bursts were distributed homogeneously. Deviations from homogeneity are also seen in plots of the peak flux integrated over 64 and 256 ms, although the effect is not as strong, presumably because BATSE is less sensitive and does not observe as deep into space on these shorter trigger time scales.

Further insight into the brightness distribution was provided by Fenimore et al (1993), who combined data from BATSE and the *Pioneer Venus Orbiter* (*PVO*). Though less sensitive than BATSE, *PVO* operated for 10 years, yielding data on the rarer, more intense bursts. Figure 13 shows the integral intensity distribution for combined BATSE and *PVO* data. 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. There are no free parameters in the fit between these two data sets.

The most direct statistical test for inhomogeneity is the V/V_{max} test (Schmidt 1968, Schmidt et al 1988). For each burst, the value $V/V_{max} = (C_{max}/C_{min})^{-3/2}$ is computed. If the burst sources are distributed homogeneously in Euclidean space, this ratio will be uniformly distributed between 0 and 1, with an average
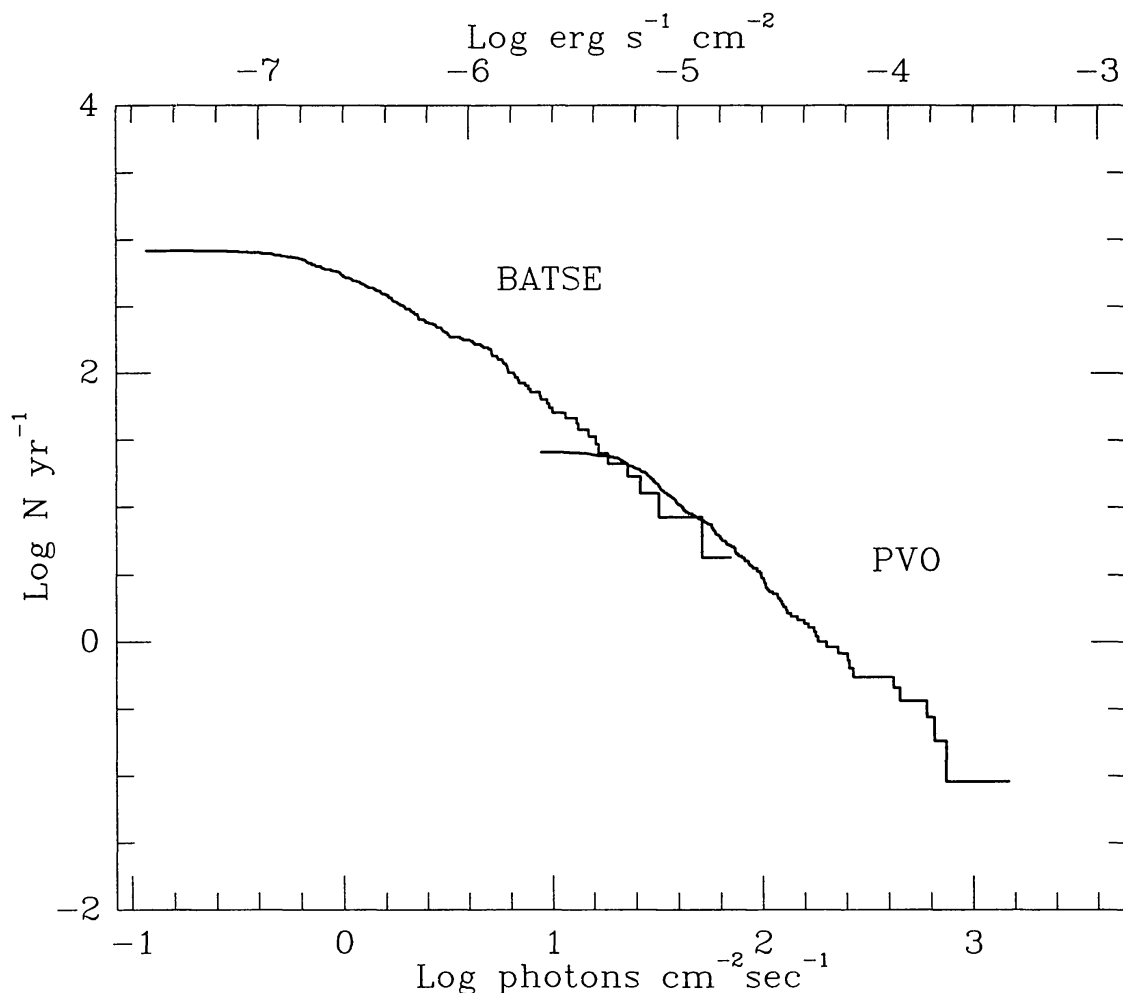

Figure 13   The $\log N$–$\log P$ distribution from combined BATSE and *PVO* data (adapted from Fenimore et al 1993). The distributions match well in the overlap region. The *PVO* data, which has recorded more strong bursts than BATSE during its long lifetime, is seen to follow a $-3/2$ power law for strong bursts.

value $\langle V/V_{max} \rangle = 1/2$. Because this test uses the count rate threshold for each burst, it avoids errors associated with varying thresholds and conversion of counts to flux. The BATSE observations yield $\langle V/V_{max} \rangle = 0.32 \pm 0.01$ for 520 bursts (Meegan et al 1994a). Measurements from the *Solar Max Mission* (Higdon et al 1992) found $\langle V/V_{max} \rangle = 0.400 \pm 0.025$. From *Ginga*, Ogasaka et al (1991) measured $\langle V/V_{max} \rangle = 0.35 \pm 0.035$, and from PHEBUS-*GRANAT*, Terekhov et al (1994) determined $\langle V/V_{max} \rangle$ to be 0.376 ± 0.017. Observations from *PVO* indicate that the less frequent, brighter bursts are consistent with homogeneity, with $\langle V/V_{max} \rangle = 0.46 \pm 0.02$ (Chuang et al 1992, Hartmann et al 1992). In summary, intensity distributions show conclusively that the distribution of sources is not homogeneously distributed in Euclidean space. The simplest interpretation of these distributions is that the source density is approximately constant nearby but decreases at greater distances.

The observed intensity distribution is a convolution of the luminosity and spatial distributions. Horack & Emslie (1994b) have shown that self-consistency analyses of integral moments are powerful tools for constraining the allowable ranges of luminosity functions and/or spatial distributions. Several recent analyses of the BATSE intensity distribution have shown that the observed bursts come from a relatively narrow range of luminosity (Horack et al 1994a, Ulmer & Wijers 1995, Ulmer et al 1995, Hakkila et al 1995).

4.2 *Angular Distribution*

Since the launch of the *Compton Observatory*, burst locations have been available for a large sample of 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. Because each burst is seen by four detectors, a χ^2 minimization technique can be used to determine the position and intensity. Some details of the localization technique are provided in Brock et al (1992). The systematic error in the first catalogs is around 4° (Meegan et al 1994b), as determined by using hard solar flares and bursts with locations known via interplanetary timing. Improved BATSE locations, in the range $\sim 1.5°$ for strong bursts, will be attainable in future catalogs. The statistical error is around 13° near the BATSE threshold (Meegan et al 1993).

The distribution in galactic coordinates (from Briggs et al 1995) of 1005 bursts observed by BATSE is shown in Figure 14. The apparent isotropy, supported by statistical analysis, has severely challenged the hypothesis that the bursts originate within the Galaxy (Briggs et al 1995). While previous catalogs (e.g. Atteia et al 1987) have also indicated an isotropic distribution, the BATSE results (Meegan et al 1992, 1994a,b; Fishman et al 1994b; Briggs et al 1994) show that this isotropy extends to the weakest bursts—those that lie below the break from the $-3/2$ slope in the intensity distribution. Observations of weak

1121 BATSE Gamma−Ray Bursts
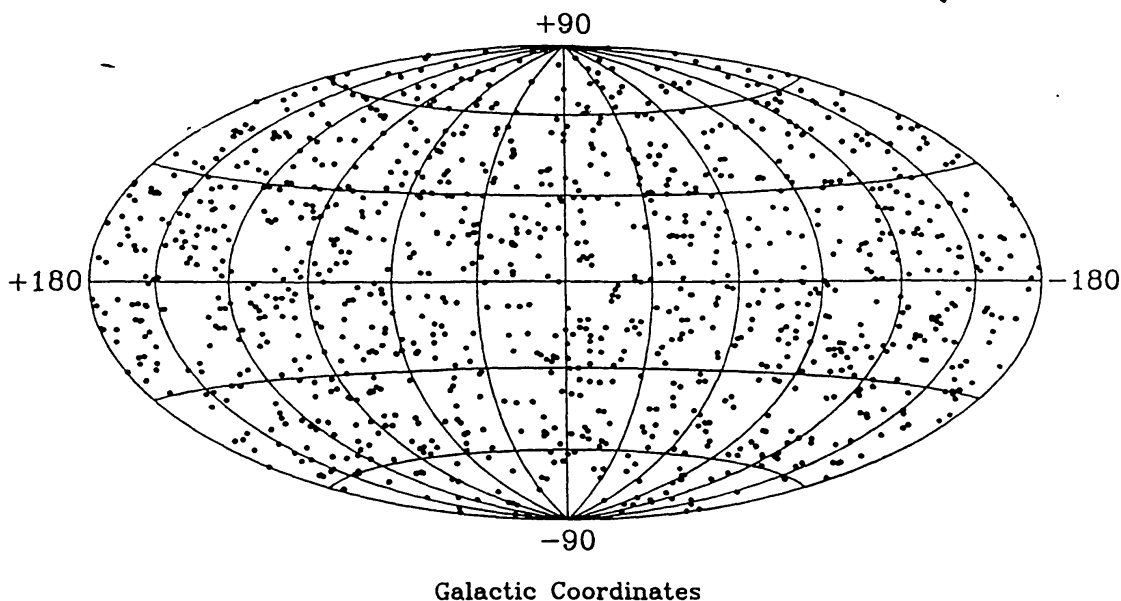

Galactic Coordinates

Figure 14   The celestial distribution of 1121 gamma-ray bursts as seen by BATSE over a three-year period, plotted in Galactic coordinates. No clustering or anisotropies are seen (Briggs et al 1995, Meegan et al 1995, Hartmann et al 1995).

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 (cf Mao & Paczyński 1992a). This conundrum will be explored further in the Section 5.

There are a number of statistics available to characterize the angular distribution and to search for anisotropy. Hartmann & Epstein (1989) determined the dipole vector and quadrupole tensor for 88 bursts observed by the Interplanetary Network (Atteia et al 1987), concluding that the distribution was isotropic to within the statistical limits. Two statistics have become standard for the comparison of burst distributions to Galactic models. The average value of $\cos\theta$, where θ is the angle between the direction to the burst and the Galactic center, measures the concentration toward the Galactic center. The average value of $\sin^2\beta$, where β is the Galactic latitude, measures the concentration toward the Galactic plane. For an isotropic distribution of sources and isotropic sampling, $\langle\cos\theta\rangle = 0$ and $\langle\sin^2\beta\rangle = 1/3$. The Bingham statistic B and the Rayleigh-Watson statistic W provide measures of the dipole and quadrupole moments that are independent of coordinate system. Briggs et al (1995) have computed these for BATSE data and have found no evidence for anisotropy. Additional statistical methods for gamma-ray burst angular distribution studies

have recently appeared (Hartmann et al 1995). Studies of the angular distribution of burst sources must take into account the nonuniform sky sampling of the observations. For the *First BATSE Gamma-Ray Burst Catalog* (Fishman et al 1994b), a sky map of exposure was computed and the distributions were corrected for this exposure.

Briggs et al (1995) also present measures of isotropy for various subsets of the BATSE data. This recent reference includes the dipole and quadrupole moments of the sky coverage. No subset of bursts shows any evidence for anisotropy. The uncorrected data show only the slight concentration toward the celestial poles that arises from the anisotropic sky coverage.

Quashnock & Lamb (1993a) noted that the medium intensity bursts in the *First BATSE Catalog* exhibited unexpectedly large dipole and quadrupole moments. This was taken as evidence for a Galactic distribution of sources, although the analysis was questioned by Strohmeyer et al (1994). The effect is not present in subsequent data (Briggs et al 1995).

4.3   *Burst Repetition*

The question of burst repetition remains controversial. Before BATSE, this issue had been addressed by Atteia et al (1985) and by Schaefer & Cline (1985). The lower limits to the repetition time scale were found to be about 10 years, if the bursts were monoluminous, but could be as short as about 0.5 years if the luminosity spread were large. In contrast, Quashnock & Lamb (1993b) found an excess of bursts with small angular separations in the *First BATSE Catalog* and suggested that a significant fraction of sources repeat on a time scale of months. This apparent excess was not seen in subsequent data, and this could in principle account for the disappearance of the apparent excess. Petrosian & Efron (1995) using an alternate statistical analysis find marginal evidence for repeating bursts from both sets of BATSE data. The failure of the *CGRO* tape recorders has resulted in a reduced efficiency for the later data, which could in principle mask the repeater signal. Nearest-neighbor tests and two-point angular correlation tests of clustering using BATSE data have indicated that burst repetition, if present, accounts for less than about 20% of the bursts observed by BATSE (Strohmeyer, Fenimore & Miralles 1994; Meegan et al 1995; Hartmann et al 1995).

Wang & Lingenfelter (1993) found that five bursts in the *First BATSE Catalog* were clustered in time as well as location. Subsequent BATSE data were examined in detail by Brainerd et al (1995) for such effects, but no evidence for repetition was found. A marginal report of a burst repetition has also been reported from COMPTEL-*CGRO* observations (Ryan et al 1994a, Hanlon et al 1994c).

In summary, there have been hints of burst repetition in the BATSE and COMPTEL data, but the evidence is not statistically compelling. Additional data, along with expected improvements in the location accuracy, will be

required to resolve this controversy. Typical upper limits on classical γ-ray burst repeaters on time scales of years are $\sim 20\%$.

5. GEOMETRICAL MODELS

We define geometrical models as models for the distribution in space of the burst sources, without considering what the sources are or how they produce bursts. This is particularly useful in the study of γ-ray bursts because the angular and intensity distributions provide significant constraints on the spatial distribution and luminosity distribution, whereas the astrophysics of the energy source and emission process in γ-ray bursts is subject to speculation at this time. The constraints arise from the combination of an isotropic angular distribution and a strongly inhomogeneous intensity distribution. This combination implies a spatial distribution centered near Earth, with a radially decreasing density (cf Wasserman 1992). The problem, of course, is relating this distribution to observed distributions of known objects. Hartmann (1994), for example, discusses the extreme range of distance scales and possible astronomical populations, from the inner solar system to cosmological distances, which have been proposed for γ-ray burst distributions.

Two complications may arise in geometrical models: beaming and source evolution. If the beaming direction is random, geometrical models are largely unaffected. The source density is scaled upward, and energy requirements are scaled downward. These effects may be important for physical models, but the spatial distribution of sources remains functionally the same. Anisotropic beaming in a Galactic frame has been proposed by Duncan et al (1993). In this case, the angular distribution of observed bursts will indeed depend on the particular beaming model.

Source evolution is an important additional parameter to be considered in cosmological models. It has been invoked in Galactic models as well (Li & Dermer 1992), since a delay in the onset of bursting appears necessary to achieve isotropy if the sources are ejected from the Galaxy.

In the following subsections, we consider a range of geometrical models that have been discussed in the recent literature. Physical models are described in Section 8.

5.1   *The Oort Cloud*

The Oort cloud provides the nearest possibility for a roughly isotropic, radially decreasing source density. Speculative models have been suggested, employing comet-comet collisions (White 1993, 1994; Luchkov 1994) and comet-primordial black hole collisions (Bickert & Greiner 1993). The geometrical and physical implications of such models were examined by Horack et al (1994 b,c), Maoz (1993), and Clarke et al (1994). It is concluded that the Oort cloud is unlikely to be the source of γ-ray bursts.

5.2   The Galactic Disk

Before the BATSE data on the distribution of weak bursts were available, bursts were considered to emanate from within the Galactic disk, most likely from neutron stars. The isotropy of the brightest bursts was interpreted as evidence that the distance to the sources was less than the disk scale height. On physical grounds, highly magnetized neutron stars are attractive candidates for generating nonthermal γ-ray spectra with rapid temporal structure (cf Harding 1991). The *Ginga* observations of absorption lines (Murakami et al 1988) were taken to be strong evidence for magnetic fields typical of neutron stars. With this disk model and typical distances of $\sim$1 kpc, burst luminosities are about 10^{38} erg/s, near the Eddington luminosity of a neutron star.

The current data, however, now convincingly rule out such models. Mao & Paczyński (1992a) have shown that even the very early BATSE determinations of the Galactic quadrupole moment and V/V_{max} were inconsistent with any disk geometry. These earlier conclusions have been strengthened by the observations of additional bursts.

5.3   The Extended Galactic Halo

A satisfactory geometrical model can be constructed from burst sources in an extended Galactic halo (e.g. Brainerd 1992, Li & Dermer 1992, Eichler & Silk 1992, Fabian & Podsiadlowski 1993, Podsiadlowski et al 1995). Isotropy of observed bursts requires a size significantly greater than the distance between Earth and the Galactic Center, and it also limits the size and fraction of the central condensation (core) of an extended halo (Hakkila et al 1994a,b). On the other hand, the failure to observe an excess of bursts from M31 places upper limits on the extent of this halo. The radial distribution and luminosity function, however, may be adjusted to reproduce the observed intensity distribution.

Hartmann et al (1993) provided insight into the required size of the halo by noting that any spherically symmetric distribution of sources can be thought of as a series of concentric shells. The dipole moment of each shell can be computed analytically. One finds that all shells with radii less than about 100 kpc have dipole moments larger than the 2-σ BATSE error bar (Briggs et al 1995). The conclusion is that extended halo models require typical (not maximum) 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} erg/s.

Hakkila et al (1994a,b) compared BATSE observations to several Galactic models, including extended halo models. Their study determined that a simple extended halo model is acceptable if the halo extends beyond about 125 kpc, but not beyond about 400 kpc. At larger distances, the lack of observed bursts near M31 provides additional constraints. It must be noted, however, that there is no

direct physical or other observational evidence for such an extended Galactic halo: Its existence is postulated specifically to solve the γ-ray burst problem. The physical models for populating such a halo are described in Section 8.

5.4   Two-Component Models

Several researchers have proposed two-component models of γ-ray bursters (Lingenfelter & Higdon 1992, Smith & Lamb 1993, Katz 1994, Higdon & Lingenfelter 1994). The rationale for such models is to have a separate subpopulation of Galactic neutron stars to serve as sources of bursts in which cyclotron lines may be observed. However, mixing two significant populations with conventional spatial distributions cannot reproduce the BATSE isotropy and inhomogeneity results. On the contrary, the presence of a disk population generally leads to more severe constraints on the remaining bursts (Paczyński 1992b). Hakkila et al (1994a,b) have examined several two-component models and find that at most about 20% of the bursts could have a Galactic disk distribution. Smith (1995) maintains that a larger fraction of a separate population of shorter and more variable bursts of disk origin is still compatible with the BATSE observations.

5.5   Cosmological Models

The observed isotropy is a necessary requirement of cosmological models. The apparent inhomogeneity would result from redshift effects and possibly source evolution. Cosmological models for gamma-ray bursts were first postulated by Usov & Chibisov (1975) and by van den Berg (1983). Cosmological distributions have been fit to the observed intensity distribution by Piran (1992), Mao & Paczyński (1992b), Fenimore et al (1993), Wickramasinghe et al (1993), Emslie & Horack (1994), Woods & Loeb (1994), and Yi (1994). Satisfactory fits can be found using standard candle luminosities, standard cosmologies, and no source evolution. In these models, the weakest sources are at redshifts z of about 1 and at luminosities of order 10^{51} erg/s. Emslie & Horack (1994) show that a narrow luminosity function of the observed bursts is required to reconcile the observations with standard cosmology. The effects of source density evolution on the observed intensity distribution, for different cosmological assumptions, has recently been modeled by Horack et al (1995). Cohen & Piran (1995) have also modeled the observed burst intensity distribution in the framework of a cosmological interpretation.

6.   OBSERVATIONAL TESTS FOR A COSMOLOGICAL ORIGIN

The new interest in cosmological models of γ-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 γ-ray bursts and on the observation of lensed events. Another signature of bursts from cosmological distances (assuming production by merging compact objects) would be the simultaneous detection of gravitational waves from these events, as discussed in Section 9.2.

6.1   *Time Dilation in Gamma-Ray Bursts*

Because of their finite, relatively short duration, γ-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 are receding faster. Thus, they would show a larger time dilation than the nearer, more intense bursts. The exact form of the dilation vs distance (and intensity) relation is dependent on the cosmological parameters, especially at the larger redshifts (cf Paczyński 1992a, Piran 1992). There are several ways in which time dilation of rapidly receding burst sources can manifest itself in an observable way. For example, 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 (e.g. Paciesas et al 1992, Dermer 1992).

Due to the extreme complexity of the γ-ray burst time structures and the wide range of their durations, any dilation effects can only be tested in a statistical sense. A group at NASA/Goddard has pursued initial work in this area, using BATSE data, and announced a positive result (Norris et al 1994, 1995). These analyses were performed by artificially weakening the stronger γ-ray bursts and introducing the appropriate background so that, all bursts could be analyzed in a consistent manner and all had the same signal-to-noise ratio. The quantitative analysis of the time profiles was made through the use of wavelets. The observed stretching of the profiles of bursts was found to be consistent with that expected from the effects of time dilation from bursts at a cosmological redshift of $z \sim 1$. A result of this analysis is shown in Figure 15. However, other effects could also be responsible for the observed dilation, such as an intrinsic luminosity-duration relation or an evolutionary effect (cf Norris et al 1994). Cosmological redshift effects have also been recently used to explain gross spectral differences observed in the continua spectra of strong and weak gamma-ray bursts (Nemiroff et al 1994b, Mallozzi et al 1995).

Davis et al (1994) performed several alternate analyses of the average temporal properties of strong and weak BATSE γ-ray bursts using pulse-fitting software and rescaling all bursts to remove noise biases in the temporal properties. They found that the width of pulse structures within strong γ-ray bursts were systematically shorter than those of the weak bursts. These results were

also consistent with a time dilation of a factor of 2 for the weakest set of γ-ray bursts or a redshift $z \sim 1$.

These recent analyses are somewhat complex, and the results have been challenged in the scientific literature. Mitrofanov et al (1994) do not detect the dilation effect in an alternate analysis, and Brainerd (1994b) notes, that special relativistic effects in a highly beamed source may mimic a dilation. Band (1994) notes that an intrinsic relation between the luminosity and duration of a burst can also mimic dilation, although Wijers & Paczyński (1994) point out that the two effects can be separated. Those authors performed an independent analysis of the duration distribution of the *Second BATSE Burst Catalog*, and they conclude that the data slightly favor a cosmological interpretation of the observed time dilation.

6.2   *Lensed Gamma-Ray Bursts*

It is possible for γ-ray bursts at cosmological distances to be lensed by intervening galaxies or other large mass concentrations (Paczyński 1986, 1987). The observation of a lensed γ-ray burst would be nearly indisputable evidence for a cosmological distance for the source. Such lensed events would occur at different times, but they would have similar time profiles (except for a scaling factor), identical spectra, and would appear to come from the same location (to within the resolution of present detection techniques). Observational considerations in the detection of lensed bursts are given by Nemiroff et al (1993, 1994c), Narayan & Wallington (1992), Wambsganss (1993), and Nowak & Grossman (1994). Estimates of the frequency of lensed events, or γ-ray burst
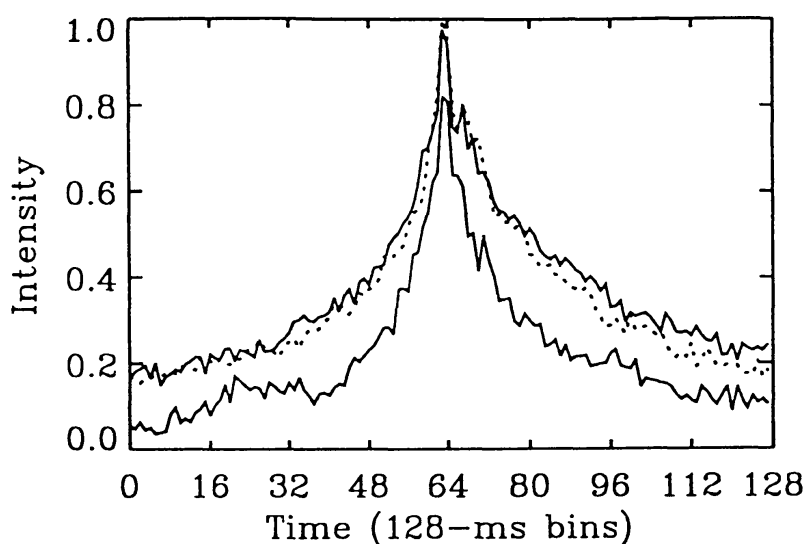

Figure 15   Average profile of pulses within a set of 131 gamma-ray bursts from the *First BATSE Catalog*. The subsets of the weaker bursts are represented by the outer two profiles, which appear stretched (dilated) by about a factor of two in comparison to the weaker bursts (inner profile) (Norris et al 1994).

echoes, under various cosmological scenarios have been made by Mao (1992) and by Grossman & Nowak (1994). Grossman & Nowak's results are not encouraging for the observation of lensed events with the current generation of detectors. Preliminary searches for lensed events from the BATSE data base of bursts have thus far been unsuccessful in identifying any credible lensed events (Nemiroff et al 1993, 1994c; Nowak & Grossmann 1994). The possible repeating burst found by COMPTEL was shown not to be a lensed candidate since the two events had different temporal and spectral properties (Hanlon et al 1994c).

7. SEARCHES FOR BURST COUNTERPARTS

Throughout the 30 year history of high-energy astronomy, it has been shown repeatedly that a deeper understanding of sources and emission processes can be attained through observations in multiple energy regions or wavelengths. A prime example is the soft γ-ray repeaters, which were shown to be plerionic supernovae remnants through the combined observations in γ-ray, x-ray, optical, and radio regions (Kouveliotou et al 1994a, Murikami et al 1994, Kulkarni et al 1994). Ever since the initial discovery of γ-ray bursts, there has been a quest to discover a counterpart to a γ-ray burst in any other wavelength region before, during, or after the γ-ray event. These searches have concentrated on the optical region, although virtually all other electromagnetic wavelength regions have been searched, while other, more esoteric radiations have been sought as well.

The searches for counterparts have taken many forms, including searches for statistical associations of known objects with bursts with poorly known locations (e.g. Howard et al 1993, Hack et al 1994). Searches have been made of archival plates (e.g. Schaefer 1990) 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 (e.g. Zytkow 1990, Greiner 1992, Greiner & Moskalenko 1994), or the spurious, one-time occurrence of a claimed counterpart that could not be independently confirmed by a second instrument. A recent review of the present status of correlated γ-ray burst observations in all wavelength regions is given by Schaefer (1994a). Hudec (1993a,b) has reviewed the present status of the optical searches for counterparts with a particular emphasis on the misidentification of optical transient counterparts. In view of the importance of the implied results, further observational evidence is needed before the claimed burst counterparts are generally accepted.

7.1   *The Interplanetary Network and*
Other Burst Location Methods

The pioneering efforts of K Hurley, T Cline, and others to establish and operate an interplanetary network (IPN) of spacecraft to precisely locate γ-ray bursts began in the late 1970s and continue today. These locations for γ-ray bursts remain the best that are available. Their accuracy, and the response time in providing them, have been continuously improving over the years. This, of course, has been subject to the availability of spacecraft with γ-ray burst detectors separated by long baselines. In recent years, the cessation of the *Pioneer Venus Orbiter* and the failure of the *Mars Observer* spacecraft have resulted in the present situation: Only the *Ulysses* spacecraft and near-Earth detectors now serve as interplanetary baseline nodes. With only two nodes, the network timing can only provide an annulus of uncertainty for the burst location—in essence, a one-dimensional error box in the shape of a thin ring on the sky. The radius of this ring or annulus depends on the burst direction relative to the line joining the two nodes, and the width of the annulus reflects the timing error of the burst. This unfortunate circumstance will persist until the Russian *Mars '96* spacecraft becomes part of the network. No other spacecraft with γ-ray burst detection capability are planned at present. Typical timing errors for the current interplanetary network result in locations in the range of 1 to 10 arc-minutes. In the past, with a network of three or more spacecraft, error boxes of 10 square arc-minutes 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 greatly restrict the error box of many bursts. A moderately strong γ-ray burst is required for observation by the relatively small detectors of IPN spacecraft. Recent experience has shown that fine temporal structure within the burst is usually not required to obtain a precise location. Hurley (1994b) has improved the IPN location methodology by utilizing cross-correlation of burst time profiles.

The unique WATCH-*GRANAT* and WATCH-*EURECA* experiments (Brandt et al 1994, Castro-Tirado et al 1994b) have established the technique of obtaining rapid and accurate single-spacecraft γ-ray burst locations through the use of a rotating modulation collimator. Error radii (3 σ) of 1° degree have been obtained by WATCH, as confirmed by the more accurate IPN locations (Hurley et al 1994b). Other recent non-IPN localizations have been made by the COMPTEL (Kippen et al 1994) and EGRET (Dingus et al 1994) experiments on *CGRO*. These two high-energy experiments can also provide burst location accuracies of the order of 1°, for strong bursts with high-energy emission that happen to be in their field of view of about one steradian. SIGMA-*GRANAT* has also provided accurate locations for bursts within its primary field or in its sidelobes (Claret et al 1994).

The BATSE-*CGRO* location uncertainties have been $\sim 4°$ in radius, for strong γ-ray bursts (Fishman et al 1994b). This systematic uncertainty will be reduced to an $\sim 1.5°$ radius as better location calibrations and techniques become available for BATSE (G Pendleton, private communication). The *HETE* spacecraft, to be launched in 1995 (Section 9.1), will become the first γ-ray burst experiment to provide accurate ($\sim 0.1°$) single-spacecraft locations over a wide field of view (Ricker et al 1992).

7.2 Recent Efforts at Counterpart Searches

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 (Kippen et al 1993, 1994) that is able to provide even more accurate ($\sim 1°$) locations within several hours for those γ-ray bursts that also happen to be within the COMPTEL field of view (about 10% of the sky). This capability has already been demonstrated for the intense γ-ray burst of 31 January 1993 (Kouveliotou et al 1994b, Ryan et al 1994b, Sommer et al 1994), when an extraordinary effort involving over 30 instruments observed the burst region within hours and days of its occurrence (Schaefer et al 1994a). Other rapid counterpart searches based on BATSE-COMPTEL locations include those of Boer et al (1994a), Barthelmy et al (1994a), and McNamara et al (1994).

A new, near-real-time burst location system utilizing BATSE data, called BA-CODINE (BAtse COordinates DIstribution NEtwork) (Barthelmy et al 1994b, Fishman & Barthelmy 1995), is also underway. The BATSE-BACODINE system can provide γ-ray burst locations to external sites within about 5 seconds from the time of their detection by BATSE. Linking BACODINE to a rapid-slewing optical telescope, opens the exciting possibility of obtaining optical images of burst regions while the burst is in progress (Section 9.1). Although simultaneous images of γ-ray burst fields have been obtained previously with sky patrol plates, these were made with very wide-field patrol cameras with relatively low sensitivity.

With the availability of rapid γ-ray burst locations, and the deepening of the γ-ray burst enigma, there have been major, renewed efforts to find a counterpart to a γ-ray burst in other wavelength regions. Those ground-based searches that can utilize the rather coarse BATSE- or WATCH-derived burst locations, such as wide-field Schmidt cameras, can now respond to these bursts more quickly than ever before possible. Some of the more recent, rapid response searches for optical or radio counterparts include those by Boer et al (1994a), Barthelmy et al (1994a), Castro-Tirado et al (1994a), Hurley et al (1994c), Krimm et al (1994), McNamara et al (1994), and Schaefer et al (1994a). Comprehensive deep searches of γ-ray burst fields have been recently reported by Vrba et al (1994).

Greiner et al (1993, 1994) described several negative searches for simultaneous optical counterparts to γ-ray bursts using a multitude of sky patrol

cameras, located primarily in Eastern Europe. The typical limiting photographic magnitude of this search was m_{pg} ~3 to 4, for an assumed optical flash of 1-second duration. A sensitive, wide-field transient optical CCD camera, the Explosive Transient Camera, has been operating for over three years at Kitt Peak in a search for burst counterparts (Vanderspek et al 1994, Krimm et al 1994).

In addition to ground-based optical emission, space-borne correlated observations of well-located γ-ray bursts have also been attempted in the EUV and XUV regions (Owens et al 1993a,b; Hurley et al 1995) and in the x-ray region (Boer et al 1993, 1994b,c; Hurley et al 1994c; McNamara et al 1994).

Sensitive radio searches for delayed radio emission from a strong γ-ray burst have been recently reported from observations made at various times and as soon as three days following the burst (Frail et al 1994, Koranyi et al 1994). The lack of observed emission is claimed to constrain cosmological fireball models of γ-ray bursts.

7.3   *Models of Expected Optical and Radio Emission*

Several attempts have been made to model the possible accompanying optical and UV emission from a γ-ray burst (see Schaefer 1994a for a review). Band & Hartmann (1992) have considered the observational consequences of and the diagnostic possibilities presented by the flash photo-ionization that should occur in the vicinity of a γ-ray burst. Models of cyclotron reprocessing have been developed that predict various amounts of IR, optical, and UV fluxes from local neutron star models of gamma-ray bursts (Hartmann et al 1988). Meszaros & Rees (1994b) have recently modeled the relativistic shock emission that might be expected from the IR to >GeV photon energies from fireball jets at cosmological distances.

Recently, several papers have appeared that would be encouraging for the observation of delayed radio emission from γ-ray bursts. Paczyński & Rhoads (1993) argue that the highly relativistic jets required in most cosmological models of γ-ray bursts would interact with surrounding material, producing strong synchrotron radio emission. The expected, delayed emission of perhaps a few days and fluxes in the milli-Jansky range may be observable from the stronger bursts. Palmer (1993) models the expected radio dispersion of such emission. He notes that the radio dispersion, if observed from bursts at cosmological distance could sample the density of the large-scale intergalactic plasma density, which is now poorly known. Based on his emission model, Katz (1994) is not so optimistic. He argues that synchrotron emission from a shocked, relativistic plasma would produce a low-energy spectrum with a spectral index of ~1/3. For a moderately strong γ-ray burst, this would produce an optical counterpart with m_v ~ 18 and a radio counterpart with a flux of ~100 micro-Jansky.

7.4   Very High Energy Photon Searches and Other Counterpart Searches

The EGRET observations of delayed GeV emission from γ-ray bursts (Sections 2.2, 3.2) have led to renewed interest in the search for even higher energy γ-ray emission from γ-ray bursts using ground-based high-energy air shower arrays and atmospheric Cerenkov detectors. The atmospheric Cerenkov telescope of the Whipple Observatory has been used in a search for clusters of TeV γ rays (Chantell et al 1993, Connaughton et al 1994). The sensitivity of that telescope has been improved greatly in recent years, through the use of a Cerenkov ring imaging technique that greatly reduces the background rate due to cosmic rays. At even higher energies, the Cygnus-I extensive air shower array was used to search for ultra-high-energy photons (>100 TeV) in coincidence with BATSE γ-ray burst times, so far without positive results (Alexandreas et al 1994, Schnee et al 1994).

In addition to the more conventional counterpart searches in the electromagnetic spectrum, there have been a number of ground-based searches for coincident events occurring in high-energy particle detectors, neutrino detectors, and gravitational wave detectors. Paczyński & Xu (1994) and Plaga (1994) consider the production of neutrinos from γ-ray burst sources. The BATSE experiment has provided lists of γ-ray burst times for these purposes, but there have been no positive detections. Two examples of such searches include those made by the Soudan-2 muon-neutron detector in underground Minnesota (DeMuth et al 1994) and the IMB underground muon-neutrino detector in Ohio (Becker-Szendy et al 1993, LoSecco 1994).

8.   MODELS OF GAMMA-RAY BURSTS

A theoretical understanding of γ-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. The primary problem with the distance scale is that the angular and intensity distributions argue for sites at cosmological distances, while the spectral and temporal characteristics of bursts may be more easily explained by much closer, and thus less energetic, events.

While there have been over a 100 theoretical papers proposing a wide range of scenarios for γ-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 (Imamura & Epstein 1987). 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.

A important consequence of the BATSE observations is that the burst luminosity appears to be about $10^{42} \times f$ erg/s for Galactic halo sources, or $10^{51} \times f$ erg/s for cosmological sources, where f is the beaming solid angle fraction. In either case, the challenge to theorists is to put this much energy into a burst with a nonthermal spectrum of almost exclusively gamma rays, lasting of order 10 seconds.

8.1 *Fireballs*

The rapid temporal variability of γ-ray bursts implies emission regions smaller than ~ 100 km. The high luminosity then implies high photon densities. The optical depth for photon-photon pair production is at least 10^{12} in typical cosmological scenarios, and at least 10^{6} in extended Galactic halo scenarios. In either case, the expected result is a relativistically expanding pair plasma, referred to as a fireball (Cavallo & Rees 1978, Goodman 1986, Piran 1994). The photons can escape when the fireball has expanded and cooled to $kT \sim 20$ keV. The emitted radiation could be blueshifted by the expansion to typical γ-ray burst energies, but the spectrum is approximately black-body and does not resemble a γ-ray burst. Another difficulty is that the radiant energy of the fireball is readily transferred into kinetic energy of baryons. In cosmological fireballs, the presence of even 10^{-9} solar masses of baryons is sufficient to significantly reduce the radiation to the point that the fireball becomes optically thin. With baryon loadings above $\sim 10^{-5}$ solar masses or more, the expansion never becomes relativistic. The apparent inevitability of fireballs has always been the main stumbling block for cosmological models. The extended halo models also must face this difficulty. In fact, Piran & Shemi (1993) have argued that the characteristics of bursts are even more problematic for fireballs in an extended Galactic halo than at cosmological distances, because the Lorentz factors are lower.

8.2 *Cosmological Models*

The isotropy and inhomogeneity of the bursts are nicely accommodated by placing the sources of the bursts at cosmological distances (cf Piran 1992). As described in Section 5.5, the burst intensity distribution is consistent with a standard candle peak luminosity of about 10^{51} erg/s and a distance to the weakest events of about $z = 1$. Such models require event rates of about 10^{-6} per galaxy per year. A number of possibilities for the energy source have been suggested. Mergers of binaries consisting of either two neutron stars or a neutron star and a black hole (Paczyński 1986, Eichler et al 1989, Narayan 1992, Mochkovitch et al 1993) can release $\sim 10^{53}$ erg in ~ 1 ms. A significant

fraction of this energy is radiated as neutrinos and antineutrinos, a fraction of which can annihilate to produce electrons and positrons, resulting in a fireball with $\sim 10^{51}$ erg. Baryon loading might be prevented if the fireball forms on the rotational axis of a neutron star merger, where the matter density is low. In a neutron star–black hole merger, the neutrinos emitted by the disrupted neutron star might be focused by the black hole to annihilate in a matter-free region (Meszaros & Rees 1992).

Other recent cosmological models have been similarly innovative. Woosley (1993) considered the gravitational collapse of rapidly rotating Wolf-Rayet stars, a "failed type Ib supernova." In this model, a black hole with a massive accretion disk is formed, and neutrino annihilation along the rotation axis produces a fireball. Carter (1992) suggested the tidal distribution of an ordinary star by a 10^4–10^6 solar mass black hole. The tidal compression produces temperatures of order 100 keV on satisfactory time scales, but the spectrum is thermal. Usov (1992) proposed a model in which rapidly rotating neutron stars with strong magnetic fields ($\sim 10^{15}$ gauss) lose rotational energy catastrophically, resulting in a mildly relativistic pair plasma. Melia & Fatuzzo (1992) suggested that γ-ray bursts are caused by extragalactic radio pulsar glitches.

The main impediment in all of these scenarios is getting the energy out as γ rays with the observed spectral and temporal characteristics of bursts. Fireballs yield thermal spectra with time scales in the millisecond range, unlike the observations. A possible solution was proposed by Meszaros & Rees (1993; also Rees & Meszaros 1994), who considered the interaction of the expanding fireball with interstellar matter. If the baryon loading is in the range 10^{-9} to 10^{-6} solar masses, then the kinetic energy in the baryons can be converted to radiation with the required temporal and spectral properties via deceleration shocks. Katz (1994) has developed these ideas further and argues that the shocks generated when the fireball interacts with the interstellar medium yield temporal structure typical of individual pulses in observed bursts. Another advantage of this scenario is that the complex temporal structure seen in many bursts is plausibly explained as resulting from inhomogeneities in the interstellar environment. An alternative possibility for extracting a nonthermal spectrum from a fireball (Shemi 1994a,b) is upscattering of UV or optical radiation in dense globular clusters or galactic nuclei. Brainerd (1994a) suggests that a very large Compton opacity due to dense molecular clouds in the source region (at cosmological distances) can reproduce the observed spectral characteristics and the diverse time profiles.

8.3   *Extended Galactic Halo Models*

There remains interest in Galactic halo models. The advantages of such models are the much lower energy requirements and the ability to generate cyclotron absorption lines. The overriding difficulty, however, is to postulate a reasonable distribution of Galactic sources that reproduce the isotropy and inhomogeneity

observations. The usual approach uses neutron stars ejected from the Galaxy to populate an extended Galactic halo. Li & Dermer (1992) proposed a model in which neutron stars are ejected with velocities of around 1000 km s^{-1} and have a delayed turn-on time of typically 30 Myr. The model requires careful adjustment of the parameters to match the BATSE results and also requires that low-velocity pulsars, which would show a disk distribution, are somehow prevented from generating bursts. Duncan et al (1993) have conjectured that bursts may be beamed in a cone parallel and antiparallel to the velocity vector of a highly magnetized neutron star. This yields a low anisotropy even with a constant burst rate. Podsiadlowski et al (1994) used a nonspherical Galactic potential and found that low anisotropy can be achieved in a Galactic halo model if neutron stars are ejected from the disk with velocities of about 600 to 700 km s^{-1}. If magnetic fields provide the energy for bursts, then field strengths of $\sim 10^{15}$ gauss are required. These scenarios find some support from the recent finding of Lyne & Lorimer (1994) that the average velocity of neutron stars is 450 km s^{-1}, higher than previously thought.

Alternatives to ejection of neutron stars from the Galaxy have been proposed. Eichler & Silk (1992) suggested that the neutron stars could be born in the halo as a result of white dwarf mergers. Hartmann (1992) also mentions the possibility of burst sources born in the halo. Fabian & Podsiadlowski (1993) suggested that burst sources are ejected from the Large Magellanic Cloud to form an extended Galactic halo.

9.   FUTURE OBSERVATIONS

9.1   *New Experiments for Gamma-Ray Burst Studies*

There are two new US spacecraft containing γ-ray burst instruments. *WIND* was launched in 1994 and *HETE* is scheduled for launch in 1995. The TRGS (Transient Gamma-Ray Spectrometer) is an experiment on the US *WIND* space-craft (Owens et al 1991). The detector is a high-resolution, passively cooled germanium detector that operates between 20 keV and 8 MeV. It has a nearly hemispherical field of view and a typical energy resolution of about 2 keV. The *WIND* spacecraft also contains two *KONUS* scintillation detectors. The *HETE* (*High Energy Transient Explorer*) satellite is a small satellite mission dedicated to the study of γ-ray bursts (Ricker et al 1992). The prime objective is the precise localization and rapid follow-up observation of γ-ray burst locations by onboard UV detectors and by observatories on the ground. *HETE* consists of an array of wide-field scintillation detectors that can operate from 6 keV to greater than 1 MeV with good energy resolution, a set of two coded-mask x-ray propor-tional counters, and an array of sensitive UV CCD detectors. Burst localization to $\sim 0.1°$ can be achieved by the x-ray detectors and to 3 arc-sec 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 and observing sites for rapid follow-up observations.

There has not been a successful interplanetary probe launched with a γ-ray burst detector since *Ulysses* in 1990 (Hurley et al 1992). The Russian *Mars '96* spacecraft will carry a set of scintillation detectors, similar to previous Soviet missions and a germanium detector. It will become an important component of the Interplanetary Network of γ-ray burst detectors.

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-real-time, 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).

9.2   *Other Observational Possibilities*

The hypothesis of an extended halo of γ-ray burst sources surrounding the Galaxy can be tested by the observation of a similar population around other nearby galaxies, notably M31. The current required radius of such a halo is at least 100 kpc (Hakkila et al 1994a). Since this is a significant fraction of the distance to M31, an extremely sensitive future detector system pointed toward M31 may be able to detect the faint γ-ray bursts presumably emanating from its halo. The high sensitivity may be attainable by proper detector background reduction and collimation of the field. Such a high sensitivity detector system is currently under study (T Prince & W Lewin, private communications).

Several researchers have suggested the possibility of measuring the absorption of soft x rays from bursts in the Galactic plane as a means of determining their distance (cf Paczyński 1991, Schaefer 1994b, Owens 1994, Liang & Kargatis 1994). X-ray observations of γ-ray bursts would permit numerous other diagnostics, including searches for associated periodicities, polarization, and cooling blackbody radiation (Liang 1994).

Another potential γ-ray burst diagnostic with x rays is the observation of x-ray halos around γ-ray burst positions (Klose 1994). The theory of such halos, produced by scattering from interstellar dust grains, had been predicted for x-ray sources many years ago (Overbeck 1965). Several observations of halos around x-ray sources have been made by the *Einstein* satellite (Catura 1983). The arrival time of the halo emission around γ-ray bursts would be delayed from that of the original burst. This would aid in their observation by narrow-field, focused x-ray telescopes, which could be re-pointed toward the burst direction. The form and magnitude of the delay (several days for bursts at cosmological distances) could provide a more direct measure of their distance (Paczyński 1991, Klose 1994). A positive detection could also reduce

the burst location uncertainty to the arc-second range through the localization of the centroid of the halo.

Following the *Mars Observer* failure, there will now be a trend toward smaller and more simple interplanetary spacecraft. Fortunately, γ-ray burst detectors for interplanetary network timing are relatively simple and small. Hurley & Cline (1994) discuss the anticipated performance of a future interplanetary network of detectors at >100 AU separation that would provide arc-second locations. Multiple, long interplanetary baseline distances would prove invaluable for precise locations and unambiguous counterpart identifications.

The Laser Interferometer Gravity-wave Observatory (LIGO) will attempt the detection of gravitational wave radiation from coalescing neutron stars (or other massive compact objects) at great distances (Kochanek & Piran 1993, Markovic 1993, Cheroff & Finn 1993, Cutler & Flanagan 1994). Such observations, in coincidence with γ-ray bursts, would be a resounding confirmation of this model as the source of γ-ray bursts. Construction has already begun on the LIGO project; it is expected to begin operation by 1999.

10.   CONCLUSIONS

In the past few years, γ-ray burst research has switched from a field with sparse data and detailed theoretical models to one of abundant data and models with little or no detail. The consensus opinion of the locale of the sources of γ-ray bursts has changed from a fraction of a Galactic scale height to either an extended Galactic halo or to cosmological distances. This has resulted in a large number of exotic new models for γ-ray bursts. However, some theorists have deferred work on γ-ray bursts until the new data and their interpretation (some of which is still controversial) become more stable or definitive. Other theorists are aggressively developing new models (primarily cosmological) in more detail, but these are only now beginning to appear in the scientific literature, and only in a preliminary form.

For those theorists who maintain a Galactic neutron star model for γ-ray bursts, similar to those developed in the 1980s, the BATSE isotropy and inhomogeneity observations force them to put the neutron stars at very large Galactic distances. This in turn requires high-velocity neutron stars that are only weakly bound (or perhaps unbound) to the Galaxy, with a very small radial gradient (large core radius) in order to be compatible with the observed upper limits to the dipole and quadrupole moments. If the neutron star velocities are so high that the majority are unbound, then a mechanism must be found so that they only burst for a small fraction of the Hubble time, so that they would not fill intergalactic space uniformly and defeat the observed inhomogeneity. Also, it may be required that they do not produce γ-ray bursts within the first 10^6 years or so of their birth, presumably near the Galactic plane, or else a Galactic quadrupole moment would be readily observable. These ad hoc restrictions of γ-ray burst

production during limited epochs of high-velocity neutron stars are attainable only with increased complexity of the models and ad hoc assumptions. Similarly, a mechanism must be invoked to prevent γ-ray bursts from occurring in low-velocity neutron stars that are tightly bound to the Galactic plane. The recent observations of high-velocity pulsars, and the association of soft γ-ray repeaters with plerionic supernovae remnants, are providing encouragement for these models (Li & Dermer 1992, Podsiadlowski et al 1994).

Several new observational ideas are being actively pursued that would provide a more direct observational test of the burst source distance using either more sensitive detectors or detectors that extend into the x-ray region. At the same time, cosmological effects predicting burst redshift and time dilation continue to be sought and tested with new analyses of existing data. Present results of these studies are suggestive, but they are not conclusive and are somewhat controversial.

The γ-ray burst enigma appears to be as great now as it was 20 years ago (Ruderman 1975). A wealth of new data on time profiles, spectral characteristics, and burst distributions has thus far failed to provide conclusive evidence on the distance scale, central object(s), or emission mechanism(s) for the classical γ-ray bursts. The isotropy and inhomogeneity of the bursts show only that we are at the center of the apparent burst distribution. Many feel that the identification of a burst with an object in another wavelength region may be the key to understanding these objects. The recent EGRET-*CGRO* discovery of delayed GeV emission from a burst is yet another severe constraint for many of the burst models. The field continues to provide us with elements of excitement and frustration.

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We use the following abbreviated notation for some frequently cited conference proceedings:

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