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GAMMA RAY BURSTS: CURRENT STATUS OF OBSERVATIONS AND THEORY

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ABSTRACT

Gamma-ray bursts display a wide range of temporal and spectral characteristics, but typically last several seconds and emit most of their energy in the low-energy gamma-ray region. The burst sources appear to be isotropically distributed on the sky. Several lines of evidence suggest magnetic neutron stars as sources for bursts. A variety of energy sources and emission mechanisms have been proposed.

I. INTRODUCTION

Gamma-ray bursts (GRBs) may be summarized as brief, intense emissions of hard X-rays and gamma rays, lasting from milliseconds to tens of seconds, from sources isotropic in the sky, not generally repeating, and not detected at other wavelengths.

Since their discovery in 1973 (Klebesadel, Strong, and Olsen 1973) by the Vela satellites, hundreds of gamma-ray bursts have been observed. Magnetic neutron stars are usually invoked as the sites of gamma-ray bursts, but there is still no consensus in the nature of the sources or the emission mechanisms. The remarkable difficulty in understanding GRBs is primarily due to the dearth of observations of the burst sources at other wavelengths. Another problem is that GRBs encompass a wide range of temporal and spectral characteristics, so it is not yet clear how many separate phenomena we are dealing with. Recent reviews of GRBs include Liang and Petrosian (1986), Hurley (1988), and Higdon and Lingenfelter (1990).

This review follows the standard practice of identifying bursts by their date of occurrence. For example the burst of 1979 March 5 is GB 790305. Lower case letters are appended to distinguish bursts occurring on the same day.

II. TEMPORAL CHARACTERISTICS

Gamma-ray bursts exhibit a wide range of temporal characteristics, with durations that range from less than 0.1 s to over 100 s. Figure 1 (from Hurley 1988) shows the time histories of three very different events. The uppermost burst in Figure 1 consists of a single spike lasting less than 0.1 s; the middle burst consists of a single peak lasting a few seconds; the lowermost burst lasts at least 60 s and exhibits complex structure. Such complex temporal structure is quite common in GRBs and has been detected down to the limiting time resolution of instruments

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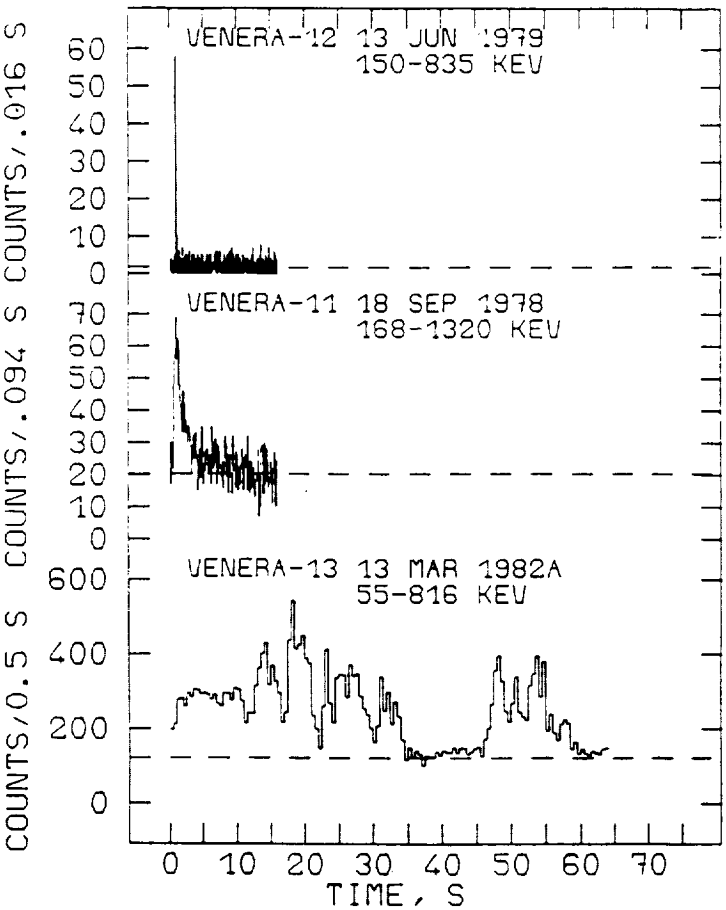

Figure 1. Three bursts (from Hurley 1988) showing a wide range of temporal structure. The dashed lines indicate background rates.

flown to date. In contrast, however, is the time history of GB 830801b, shown in Figure 2, which is smoothly varying (Kuznetsov et al. 1986). Classifications of bursts based on time histories have been proposed (Norris et al. 1984; Barat et al. 1984a), but none have found wide acceptance.

Periodicities are notably absent from GRBs. The only burst with an obvious periodicity is GB 790305, with an 8-s period (see Section IV). Kouveliotou et al. (1988) have presented evidence for a 2.2 periodicity in PVO and SMM data for GB 840805b. Schaefer and Desai (1988) have shown that no other claims of periodicities are statistically convincing. The paucity of measurements of periodicities has hampered understanding of the sources gamma-ray bursts. If

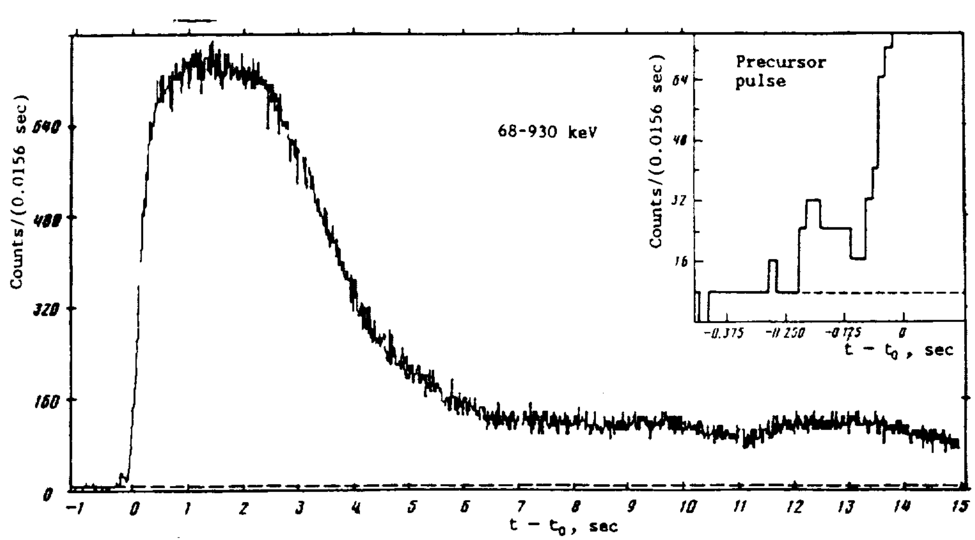

Figure 2. The time profile of GB 830801b shows no evidence of rapid variability.

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bursts are indeed produced by neutron stars, periodicities might be expected and would help to constrain the models. It may be that periodicities are often present but are obscured by the short duration and variability of the bursts.

III. SPECTRA AND SPECTRAL EVOLUTION

Some typical features of gamma-ray bursts are illustrated in Figure 3. These features may be summarized as follows: (1) Most of the energy is emitted in the hard X-ray and gamma-ray region. (2) Below a few hundred keV, the photon number spectra are reasonably well characterized by the function E^{-1} exp(-E/kT). (3) Absorption features have been seen in the spectra of many bursts in the 10 to 100 keV region (Mazets et al. 1981). These have been interpreted as cyclotron lines (see below). (4)

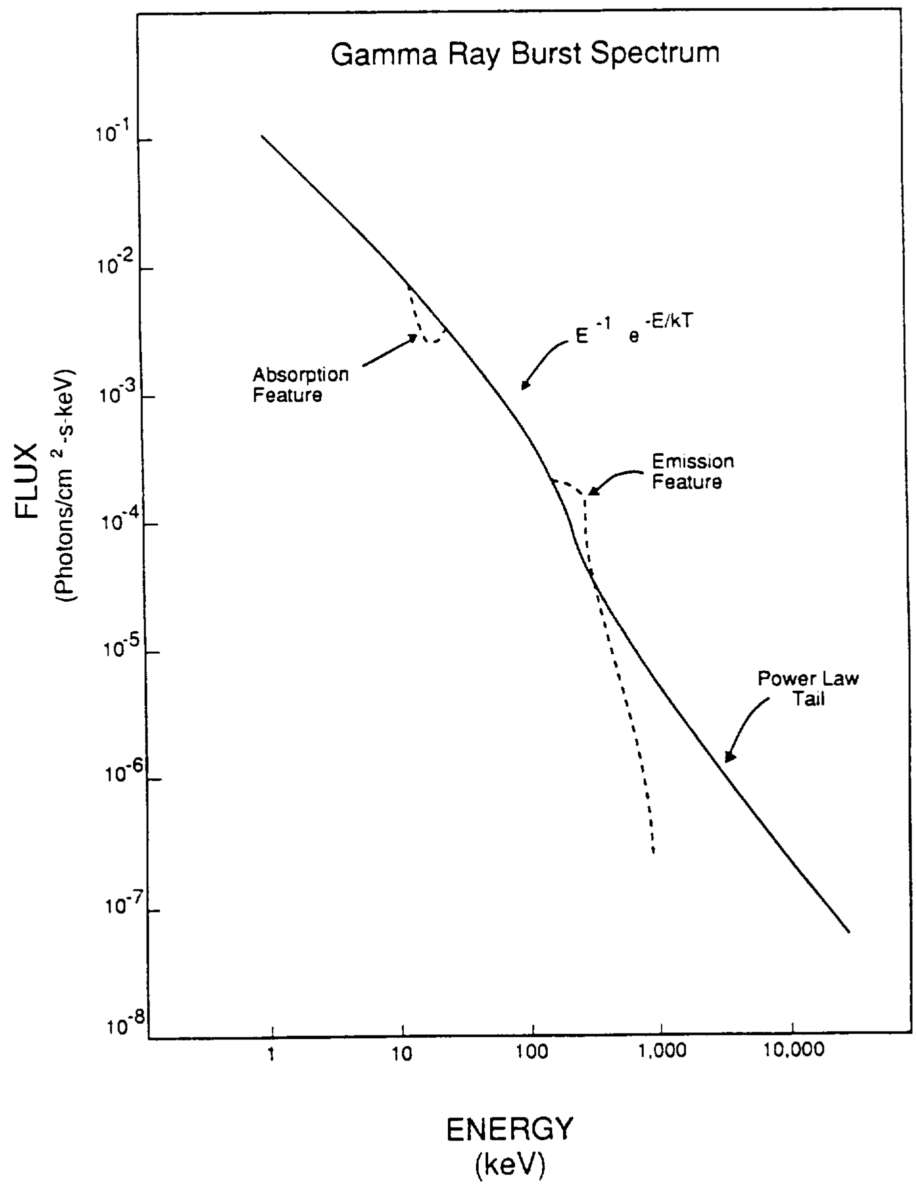

Figure 3. Typical features of gamma-ray burst spectra.

Emission features at around 400 keV have been reported. These have been interpreted as red-shifted annihilation lines. (5) Hard power law tails extending above 1 MeV have been observed in a majority of the bursts detected by SMM (Matz et al. 1985).

It should be kept in mind that most published spectra are integrations over times that may be long compared to time scales for spectral evolution. Rapid spectral variations are commonly observed by instruments capable of detecting them. Barat et al. (1984b) reported that the annihilation peaks in GB 781104 occurred in short time intervals. Norris et al. (1984) reported that the spectra of individual pulses in ten strong bursts showed a hard to soft evolution.

Soft X-rays have been detected from GRBs and they typically last longer than the gamma-ray emission. The intensity of the X-rays, however, is lower than would be expected if the gamma rays were emitted isotropically near the surface of a neutron star.

The best example of cyclotron absorption lines comes from GB 880205, observed by GINGA (Murakami et al. 1988). Figure 4 shows several different fits to the data, showing that the data require a spectral feature, and that a good fit is obtained using two approximately equal, narrow absorption lines at 19 and 39 keV. Fenimore et al. (1988) have explained these features as cyclotron absorption lines in a magnetic field of 1.7×10^{12} G. The narrowness

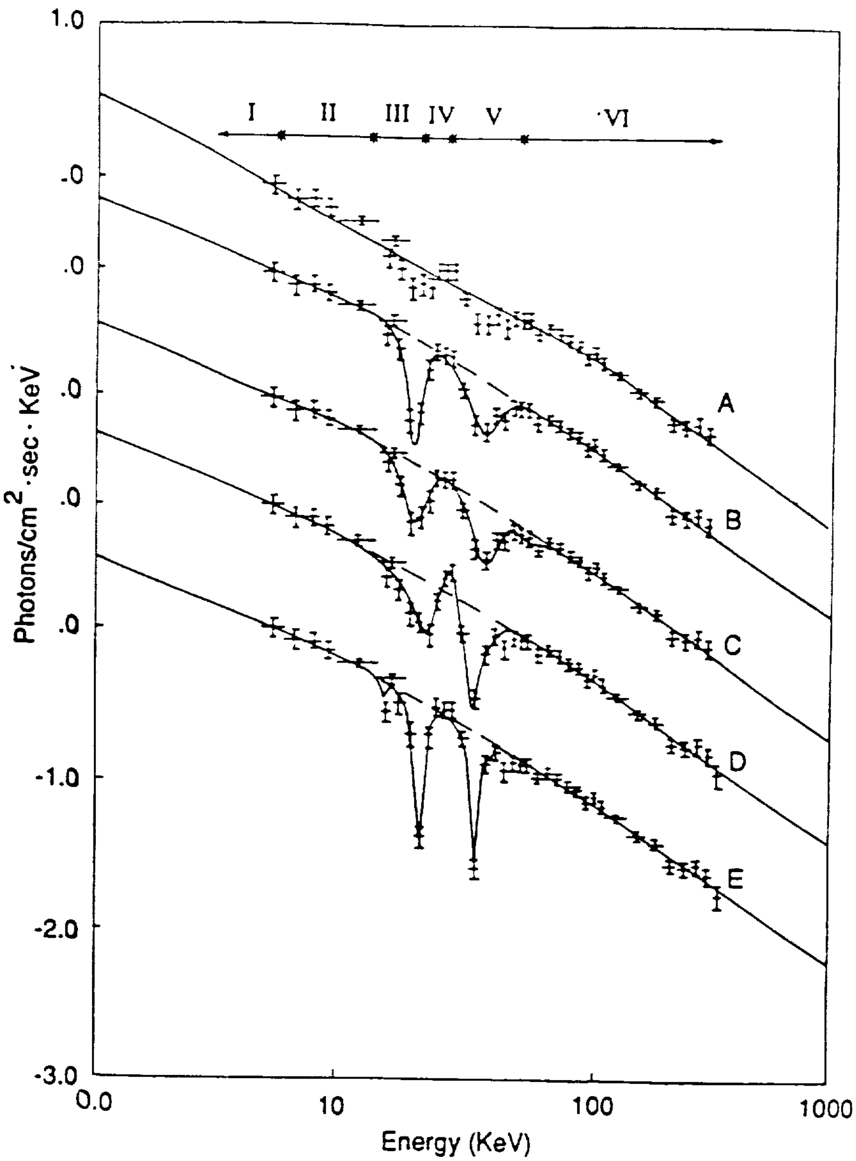

Figure 4. Spectral fits for GB 880205, showing evidence for cyclotron absorption lines (from Murakami et al. 1988).

of the lines implies a cool plasma in the region of line formation, while the continuum is produced in a much hotter region.

IV. SOFT GAMMA REPEATERS

Although no scheme for classifying bursts has met with universal approval, there is a consensus that certain burst sources, the Soft Gamma Repeaters (SGRs), form a distinct class. The characteristics of these bursts are short time scales, soft spectra, and repetitive behavior on a wide range of time scales. Three SGRs have been identified: SGR 0520-66, SGR 1900+14, and SGR 1806-20. The naming convention specifies the celestial coordinates.

The source SGR 0520-66 is the source of the most intense burst ever observed, the 1979 March 5 event. Figure 5 shows the time history of this unique event. This burst consisted of an intense initial spike, lasting only a fraction of a second, followed by a slowly decaying tail with a clear 8-s period. The initial risetime is unresolved and appears to be less than 0.2 ms. The location of the source is coincident with N49, a supernova remnant in the Large Magellanic Cloud (LMC). We are thus faced with the uncomfortable observation that the most intense GRB appears to be extragalactic. The most widely accepted model for this burst involves vibrations of a neutron star following a phase transition in the core (Ramaty et al. 1980). Cline (1980) has produced a review of the March 5 event. This source is included in the class of SGRs because recurrent, but much less

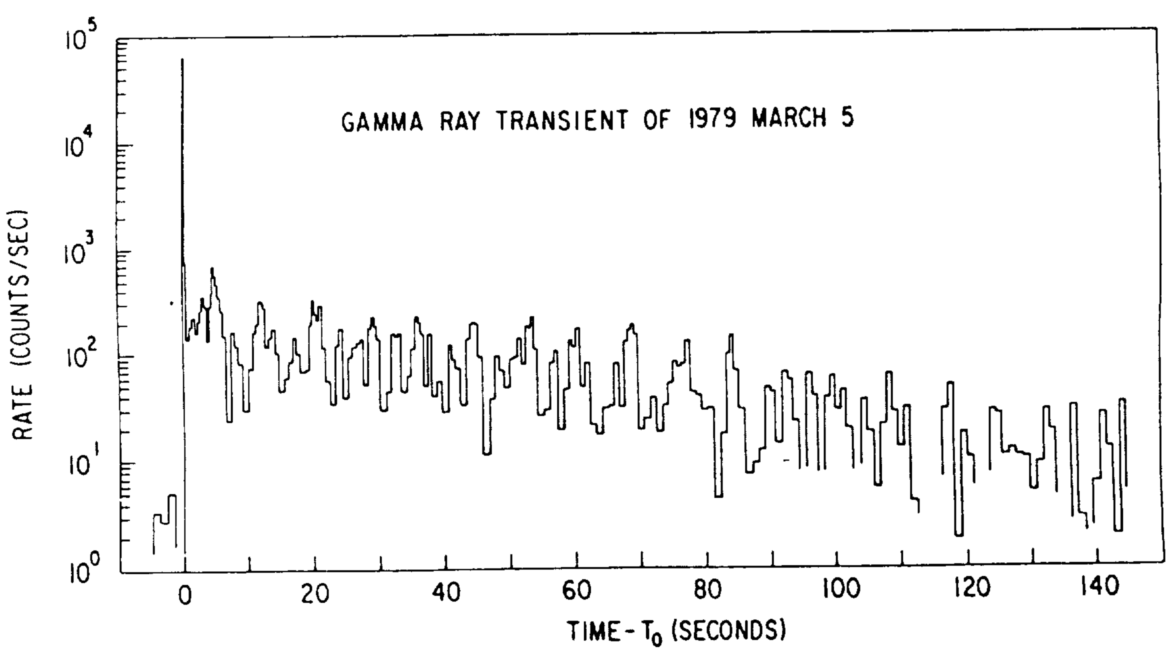

Figure 5. Time history of the unique event GB 790305 (from Cline et al. 1980).

intense, bursts were subsequently observed by the KONUS experiment (Golenetskii, Ilyinskii, and Mazets 1984).

The source SGR 1806-20 has produced at least 110 bursts (Laros et al. 1987; Atteia et al. 1987a; Kouveliotou et al. 1987). Figure 6 shows the rate of bursts from this source observed on the ICE spacecraft. The bursts appear to be clustered on a wide range of time scales. Models for this source include accretion of comets onto neutron stars (Livio and Taam 1987), accretion of comets onto magnetic white dwarfs (Boer, Hameury, and Lasota 1989), and starquakes (Norris et al. 1989).

V. SEARCHES AT OTHER WAVELENGTHS

Clearly, the detection of burst sources at other wavelengths would further theoretical understanding of gamma-ray bursts. A number of attempts have been made to observe both quiescent and burst emission in several wavebands. In general, these attempts have not been successful. For a summary of searches for burster counterparts see Pederson et al. (1986) and references therein.

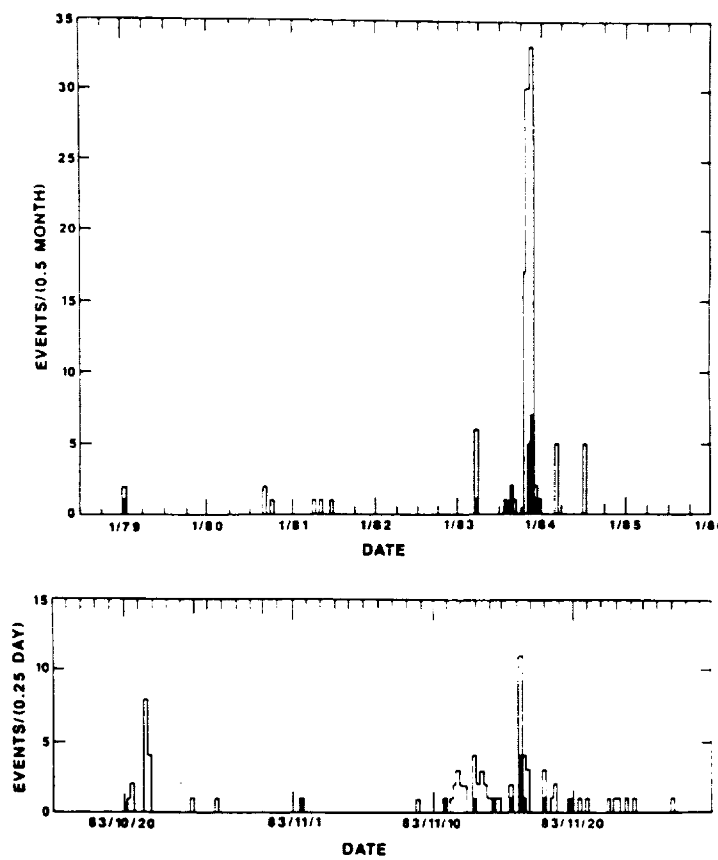

Figure 6. Rate of occurrence of 110 bursts from the Soft Gamma Repeater SGR 1806-20 observed by ICE (from Laros et al. 1987). The filled-in segments of the histograms indicate the number of bursts also observed by other spacecraft.

The only burst with good evidence for an optical counterpart is the 1979 March 5 event. This burst is probably associated with N49, a supernova remnant in the LMC. Only six other bursts have positions determined accurately enough to make optical searches worthwhile. While some candidates have been identified, no probable associations have emerged. As a result of these studies, it is concluded that most gamma-ray bursts are probably not associated with main sequence stars.

A number of studies of archival plates have been undertaken in an attempt to find optical transients at the locations of burst sources (Schaefer 1981; Schaefer et al. 1984; Atteia et al. 1985; Hudec et al. 1987). Claims of identification of three burst sources have been re-analyzed by Zytkow (1989), who finds that the evidence is not conclusive.

Searches for X-ray counterparts of well-localized bursters have been made using data from the Einstein Observatory (Pizzichini et al. 1986) and EXOSAT (Boer et al. 1988). A weak source was detected by Einstein at the location of GB 781119, but not seen by EXOSAT. The low intensity of quiescent X-ray emission from gamma-ray bursters places distance-dependent constraints on the temperatures and accretion rates in neutron star models. For example, the thermonuclear model predicts accretion rates close to the upper limits derived from X-ray observations.

Searches for radio counterparts (Schaefer et al. 1989) and infrared counterparts (Schaefer et al. 1987) have produced no probable associations, further constraining the models.

VI. SPATIAL DISTRIBUTION

Hartmann and Epstein (1989) have made the most detailed study of the spatial distribution of bursts using the Atteia catalog (Atteia et al. 1987b). They have computed the dipole and quadrupole moments of the distribution of 84 localized bursts. The distribution of these sources is shown in Figure 7. The burst distribution is consistent with isotropy. Hartmann, Epstein, and Woosley (1989) have examined the implications of the isotropic distribution for neutron star models of bursts. They attempted to calculate the distribution of old neutron stars and

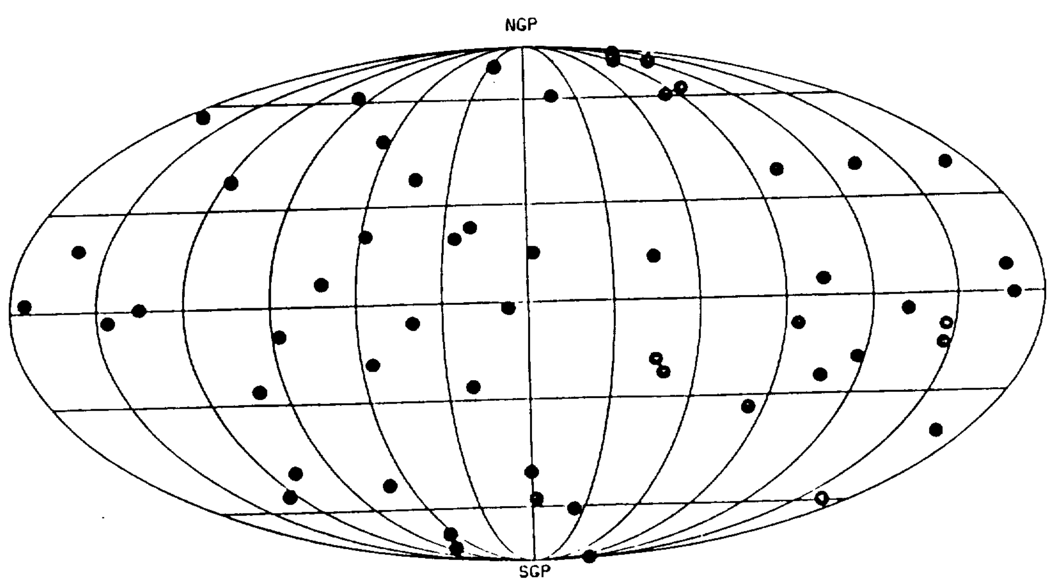

Figure 7. Distribution in galactic coordinates of 84 localized bursts from the Atteia catalog (Atteia et al. 1987b).

concluded that the burst sources must be within about 2 kpc for isotropy. Paczynski (1989) also attempted to calculate the neutron star distribution and got a very different answer. It must be concluded that we do not really know the distribution of old neutron stars. If gamma-ray bursts are finally determined to arise from old neutron stars, then the spatial distribution of bursts may provide new information on the distribution of neutron stars.

The size distribution of bursts also presents information on the distribution of the burst sources. However, this technique has been fraught with difficulties. The size distribution typically has been produced as a number of bursts above a fluence S (ergs/ cm^2) versus S (log N-log S). It has been repeatedly pointed out that instruments trigger on flux, not fluence, and the sensitivity as a function of fluence is typically not well determined. Figure 8 shows a log N-log S curve from the Los Alamos workshop (Epstein 1988). At high S, the -3/2 law seems to be obeyed, indicating a uniform distribution in three dimensions, consistent with the angular isotropy. At medium S, the curve seems to be flattening, possibly indicating the beginning of the

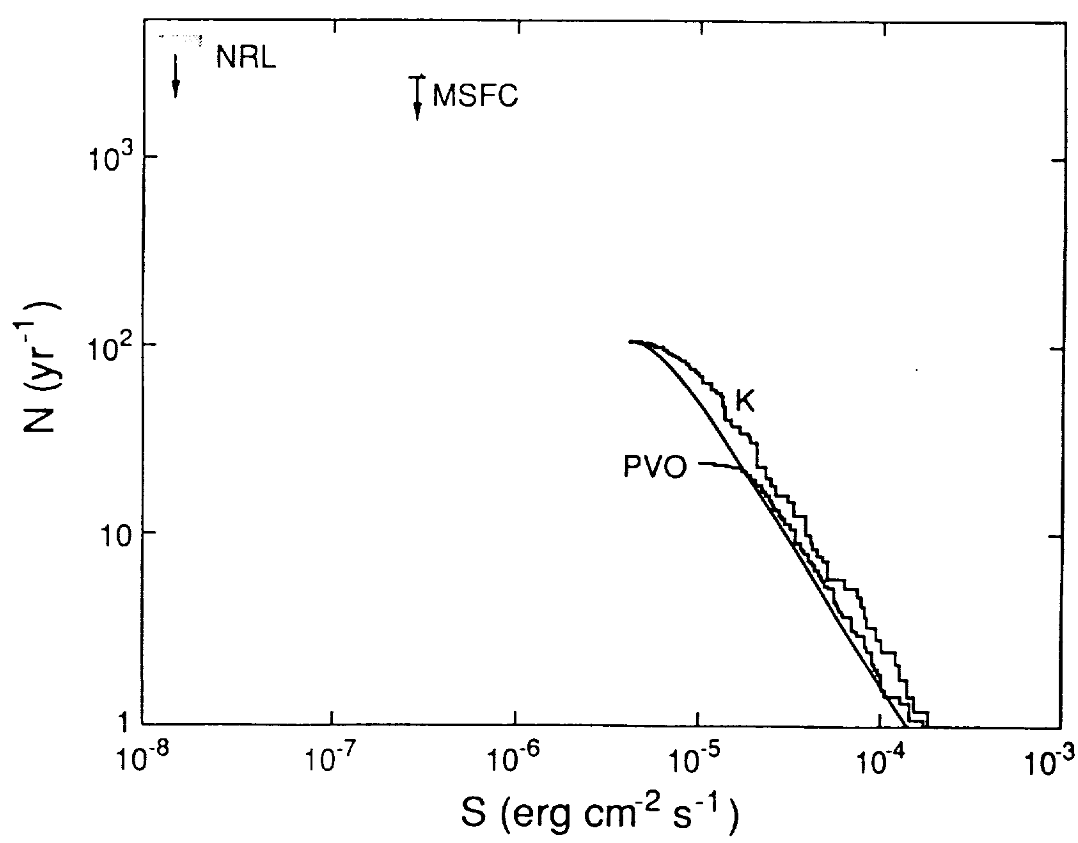

Figure 8. Size distribution of gamma-ray bursts. The distribution at high S is consistent with isotropy. Upper limits at low S indicate a flattening of the curve.

galactic plane distribution. However, this region contains great uncertainty in the sensitivity correction. The upper limits at the low end indicate that the curve is flattening.

An important statistical test, the V/V_{max} test, has been used by Higdon and Schmidt (1989) to examine the KONUS catalog for evidence of spatial non-uniformity. In this test, the intensity of each burst is compared to the minimum intensity required for detection of that burst. This test effectively removes the problems inherent in computing detector sensitivities. The V/V_{max} test cannot be considered a replacement for the size distribution because it does not relate the observations to physically important parameters, such as source distance and energy output, and it cannot be used by experiments that obtain only upper limits to burst rates. The V/V_{max} test is, however, an important internal test for data sets that can employ it. When applied to the KONUS observations, the V/V_{max} test indicates that the observed burst intensities are consistent with an isotropic distribution in space.

VII. THEORETICAL ISSUES

Theoretical papers on gamma-ray bursts are almost as difficult to categorize as the bursts themselves. Part of the problem is that most contributions are not complete models, but focus primarily on one aspect of the problem, such as the source of the energy or some detail of the emission mechanism. In the remainder of this paper, theoretical work is divided into three categories: the sites of the bursts, the energy sources, and the emission mechanisms. A complete "model" of gamma-ray bursts would require all three elements. For example, a thermonuclear model of the energy source and a synchrotron emission model are not really competing models, but separate, essential pieces of the puzzle.

It is important to note that the wide range of burst phenomena indicate that more than one model may be required. For this reason, it is useful to attempt to categorize bursts in a meaningful way. On the other hand, it must be kept in mind that very different observational characteristics may result from minor changes in the parameters of a model. For example, the angle between the viewing direction and the magnetic field can have a large effect on the energy spectrum. Also, the accretion rate and neutron star temperature greatly influence the nature of bursts in the thermonuclear model.

VIII. SITES

The sites of gamma-ray bursts must satisfy a variety of observational constraints, including the isotropy, lack of obvious recurrence, time profiles, energy spectra, and lack of counterparts. The site most often mentioned for GRBs is a nearby magnetic neutron star. Evidence for neutron stars as a site is summarized in Table 1. The cyclotron lines are perhaps the best

TABLE 1. Nearby Magnetic Neutron Stars as Sources of Gamma-Ray Bursts

EVIDENCE FOR:	
	RAPID VARIABILITY
	CYCLOTRON LINES
	ANNIHILATION LINES (?)
	LACK OF OPTICAL COUNTERPARTS
DIFFICULTIES:	
	DISTRIBUTION OF NEUTRON STARS UNKNOWN
	HIGH ENERGY EMISSION
	LACK OF X-RAY EMISSION
	LACK OF PERIODICITY
OTHER SITES PROPOSED:	
	MAGNETICALLY ACTIVE STELLAR SYSTEMS
	SUPERCONDUCTING STRINGS
	GRAVITATIONAL LENSING OF DISTANT SOURCES

evidence for neutron stars. However, the high energy tails indicate a low magnetic field (or beaming of the radiation along the field lines). The rapid variability indicates a small spatial region for the source, while photon-photon interactions at small volumes should cut off the spectrum at low MeV energies. The distribution of old neutron stars is not known, but there ought to be enough to satisfy the requirements of isotropy and repetition rate. The lack of optical counterparts is acceptable if the neutron star temperature is less than around a million degrees. Features at around 400 keV have been interpreted as red-shifted annihilation lines, but may be explained in other ways. Some of these difficulties are common to just about any model of GRBs. If neutron stars are the sites of most GRBs, then a comparison of the burst rate with estimates of the number of neutron stars in the galaxy indicates that the repetition time must be less than about 500,000 years. This time is shortened further if not all neutron stars make bursts. A lower limit to the repetition rate is determined from the statistics of the bursts and is usually quoted at around 10 years.

Other sites for gamma-ray bursts have been suggested. Vahia and Rao (1988) have revived the idea of large flares in magnetically active stellar systems, such as cataclysmic variables and RS Can Ven systems. This model requires the assumption that burst locations determined via interplanetary timing are inaccurate. Extragalactic models have not disappeared. Babul, Paczynski, and Spergel (1987) suggest superconducting cosmic strings, a disadvantage of which is that they are not known to exist. McBreen and Metcalf (1988) propose gravitational lensing of distant sources. This model implies that locations determined by interplanetary timing are not correct. Although these non-neutron star models are decidedly a minority opinion, the fact that they continue to be published is testimony to the difficulties in accounting for the observed properties of bursts.

IX. ENERGY SOURCES

Within the framework of the neutron star as the source of GRBs, a number of possibilities have been suggested for the source of the energy. Table 2 lists several of the most frequently discussed. In the thermonuclear model, explosion of accreted matter is posited. This model enjoys the most attention, and calculations are extensive, as will be discussed below. A difficulty is that the accretion must be low enough to avoid violating the constraints of the X-ray observations, which appears to be possible. Accretion of comets and asteroids and episodic accretion from a disc have also been suggested. These models run into difficulty maintaining the accretion in the face of super-eddington luminosities (in the latter case) and in retaining asteroids and comets in the evolution of a neutron star. Starquake models use the rotational energy of the neutron star. These models have been analyzed as a class by Blaes et al. (1989) who concluded that the energy and time scale requirements could be met but that recurrence of bursts presented a problem. They still concluded that starquakes represented the "most viable model." The phase transition model is a corequake model, in which a phase transition in nuclear matter occurs in the core of the neutron star. This model was used by Ramaty et al. (1980) to explain the March 5 event quite successfully. However, it is of limited applicability since this represents a single event in the life of a neutron star and cannot explain most bursts.

TABLE 2. Energy Sources for Neutron Star Models

THERMONUCLEAR EXPLOSION OF ACCRETED MATTER
ACCRETION OF COMETS, ASTEROIDS, OR FROM A DISK
STARQUAKE (CRUST)
PHASE TRANSITION (CORE)
REJUVENATED PULSAR

Ruderman and Cheng (1988) proposed the rejuvenated pulsar as a GRB source as part of study to put GRB sources in an evolutionary framework. They propose that the sources are aligned rotators with periods in the 0.1- to 0.2-s range. These neutron stars have evolved from gamma-ray pulsars and require a "match" to reignite the pulsar mechanism.

X. EMISSION MECHANISMS

A complete theoretical description of gamma-ray bursters must include a quantitative account of the production of the observed spectra. This requires understanding how the released energy is converted into high energy particles, and then how the particles generate the photon spectrum. A number of important considerations arise. The first problem encountered is the requirement for getting the energy out primarily in the gamma-ray region. The computed spectra must not exhibit higher X-ray flux than is observed. In the neutron star models, this means the gamma rays must be generated far enough from the surface to prevent reprocessing a significant fraction of the energy into X-rays. Another difficulty is the generation of narrow cyclotron absorption lines, which implies high magnetic fields and cool plasma, along with high energy power law tails, which implies hot plasma and low fields or beaming of the gamma rays along the field lines. An important consideration in models incorporating high fields is the very short time ($\sim 10^{-16}$ s) for particles to lose energy due to synchrotron radiation. Thus, particle acceleration must occur parallel to the magnetic field, and burst time scales must be governed by energy input, not cooling times. Another complication in comparing observed and computed spectra is that the observed spectra are usually integrations over times longer than typical temporal variations within the burst.

A summary of the status of burst emission mechanisms as of 1984 is provided in Chapter 2 of Liang and Petrosian (1986). A number of more recent publications have addressed the problem of computing spectra from assumed particle distributions in neutron star models of gamma-ray bursts. Brainard and Lamb (1987) have proposed a two-component (thermal plus non-thermal) electron distribution. Canfield, Howard, and Liang (1987) considered Compton upscattering of soft photons by a one-dimensional electron distribution. Baring (1988) included quantum effects in strong magnetic fields. Melia (1988) considered reprocessing of gamma radiation at the neutron star surface. Sturrock, Harding, and Daugherty (1989) proposed the "cascade" mechanism, whereby electron-photon cascades are produced via curvature radiation. Other work (Brainard 1989; Ho and Epstein 1989; Dermer 1989) specifically addressed the issue of suppressing the X-radiation.

The model of gamma-ray bursts that has received the most attention recently is the thermonuclear model, wherein matter is accreted onto a neutron star until it reaches temperatures and densities high enough for ignition. The implications of this model have been developed extensively (Hameury et al. 1982, 1983; Hameury, Bonazzola, and Heyvaerts 1983; Bonazzola et al. 1984; Hameury et al. 1985). A diagram of the main features of the thermonuclear model is presented in Figure 9. Here, matter is accreted at a rate of about E^{-15} solar masses per year on a strongly magnetized (10^{12} G) neutron star. A hydrogen flash ignites a fast helium flash when a critical temperature and density are reached. The energy is transported to the neutron star

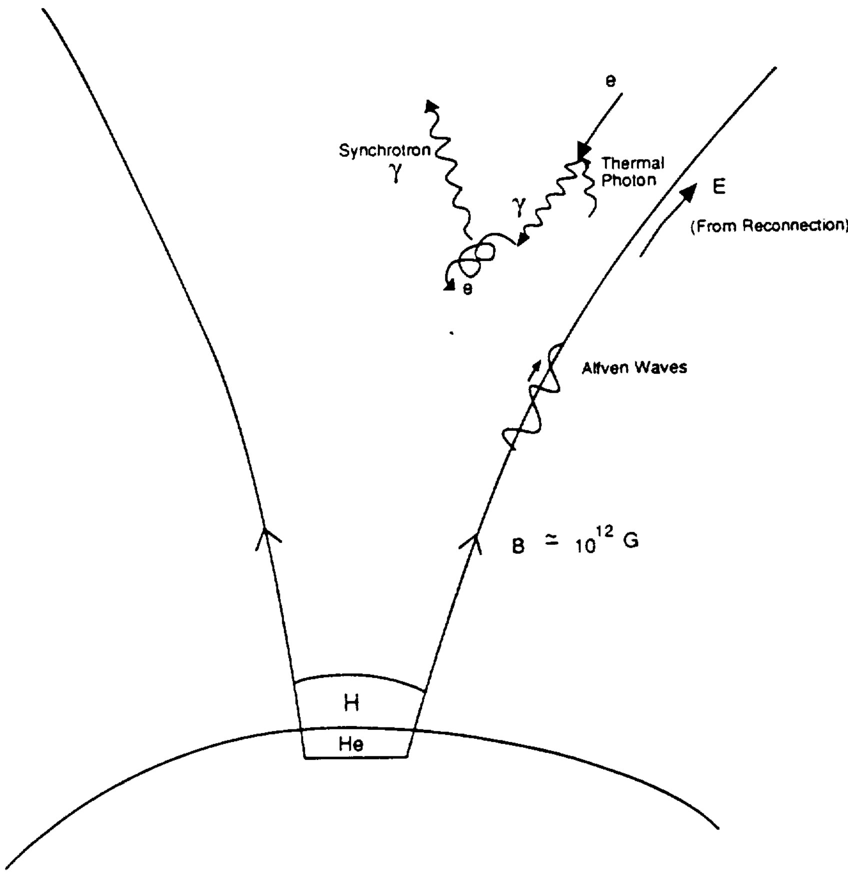

Figure 9. General features of the thermonuclear model. Accreted matter ignites, generating Alfven waves that propagate into the magnetosphere. Magnetic reconnection generates electric fields that accelerate electrons.

magnetosphere via Alfvén waves. Magnetic reconnection generates an electric field parallel to the magnetic field, which accelerates electrons and positrons to many MeV. The specific emission mechanism considered by Hameury et al. (1985) is one in which the particles scatter soft thermal and synchrotron photons to high energies, but beamed along the magnetic field. These gamma rays then excite electrons to high Landau levels, thus generating the observed gamma-ray spectrum via synchrotron radiation.

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DISCUSSION

Don Kniffen:

What is the lower limit to the period in the search for burst source periodicities? Specifically, does the search cover the periods expected if the burst sources are spent pulsars?

Thomas Cline:

Generally, periodicities or their limits, are set in the fractional - to several second region, and may be valid only in the case for the 79 March 5 event. Internal neutron star periods are acoustic, or several KHZ, and cannot be monitored; spin periods in the fractional second region may be undetectable in the event time variations.

Demos Kazanas:

We should really look for models that can reproduce a large number of bursts with variation of one (or maybe two) parameters. To my knowledge such an approach has not been taken yet.