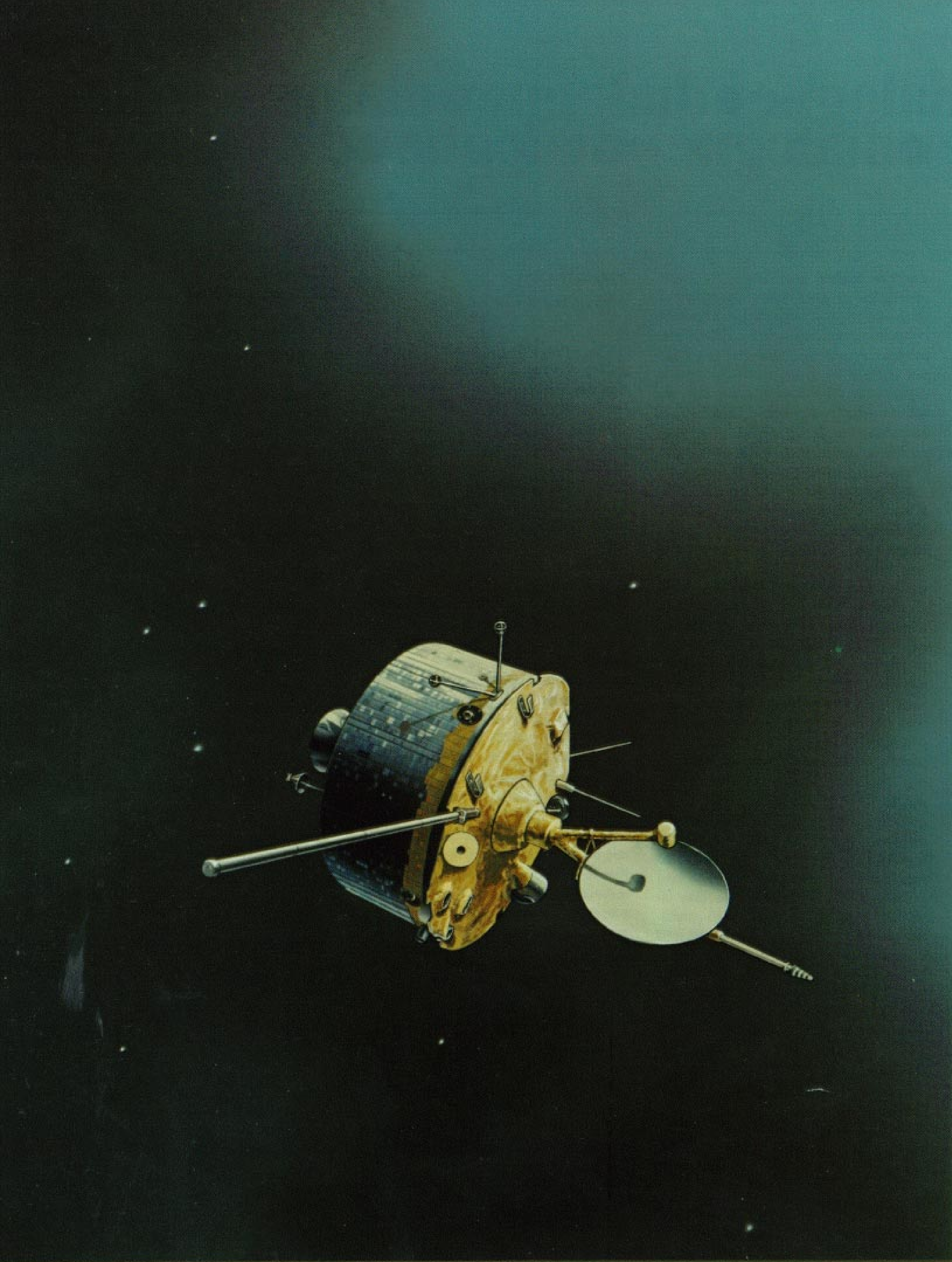


Cosmic Gamma-Ray Bursts

—a continuing mystery

by Ray W. Klebesadel, W. Doyle Evans, Edward E. Fenimore, John G. Laros, and James Terrell

Orbiting detectors have revealed the variable nature of gamma-ray bursts. While the bursts probably originate from neutron stars, the generating mechanism remains enigmatic.

The discovery, in 1973, of cosmic gamma-ray bursts created tremendous excitement in the astrophysics community. These bursts had been recorded by gamma-ray detectors aboard the Vela nuclear-test surveillance satellites. Despite the detection of about a hundred such events in the ensuing years, enthusiasm toward gamma-ray bursts gradually waned because detailed information was lacking. However, on March 5, 1979 an event was recorded that was unprecedented in the annals of gamma-ray burst astronomy. Six of the ten spacecraft recording this event carried the first generation of instruments specifically designed to characterize gamma-ray bursts. The detectors were built to record events ten times more intense than any previously observed burst, yet even these were driven to the brink of saturation. Although distinctly different in important details from typical gamma-ray bursts, this event was closely related phenomenologically, and it inspired vigorous new efforts to model gamma-ray bursts.

The Pioneer Venus Orbiter, a distant member in an international network of satellites that detects and locates cosmic gamma-ray bursts.

The burst originated from the precise direction of an extragalactic supernova remnant in the Large Magellanic Cloud, 180,000 light years from the earth. If the source was, indeed, within the Large Magellanic Cloud, the peak intensity of gamma rays briefly exceeded the luminosity, at all wavelengths, of the entire Milky Way Galaxy. A consensus had been developing that the sources of the bursts must be located within our own galaxy, yet this event—clearly the brightest ever seen and the first for which a source identification could be suggested—seemed to lie within a neighboring galaxy. Theoreticians struggled in attempts to propose mechanisms to explain the event, but many concluded that the suggested association could only be accidental.

To date there is no completely satisfactory explanation of the March 5, 1979 event—or, for that matter, of any other cosmic gamma-ray burst. The data have considerably improved, both quantitatively and qualitatively, since the early 1970s, but the increased knowledge has not yet led to any single model that satisfactorily describes the data. Rather, the data have only eliminated from contention a number of proposed models. In addition to the seriously proposed models, the *National Enquirer* in 1979 fantasized that the explanation was real-life star wars between alien civilizations somewhere in outer space. There is one point, however, on which everyone agrees: Satellite detection of gamma-ray bursts has opened a new window on the universe. These sudden, intense bursts of energy show an aspect of the universe that is much more chaotic and transient than had previously been imagined by either casual star-gazers or professional astronomers.

Our Changing View of the Universe

Ancient astronomers believed that the universe was largely ruled by static regularity, although meteors, comets, and such rare visible supernovae as the one observed in the constellation Taurus by Chinese and American Indian astronomers in 1054 contradicted this picture. With the development of the telescope, more distant, fainter supernovae, as well as other classes of stellar variability, were seen with increased frequency. Nevertheless, the mistaken impression of regularity and slow evolution in the universe persisted into the 1960s.

The feeling that transient cosmic events were rare was certainly prevalent in 1959 when summit meetings were being held between England, the United States, and Russia to discuss a nuclear test-ban treaty. One key issue was the ability to detect treaty violations unambiguously. A leading proposal for the detection of exo-atmospheric nuclear explosions was the use of satellites with instruments that included detectors sensitive to the gamma rays emitted by the explosion as well as those emitted later during the radioactive decay of the fission products. During the discussion of the capabilities of these satellites, Stirling Colgate (currently a Laboratory scientist, but at that time attached to the U.S. State Department) suggested that gamma rays from a supernova might resemble the radiation of a nuclear test explosion closely enough to trigger an alarm by the satellite detection system. Could this rare event lead to dangerous accusations of a treaty violation? Were there characteristics of a supernova outburst that would distinguish between a weapon test and a cosmic burst?

In the early 1960s, Los Alamos scientists Jack Asbridge, Sam Bame, Jerry Conner, Ray Klebesadel, and Sid Singer, directed by Jim Coon, designed and built detectors for exe-atmospheric nuclear-test surveillance, In the period from 1963 to 1970 six pairs of the Air Force Vela satellites carrying these detectors were placed in orbit far beyond the atmosphere (which absorbs gamma rays and other nuclear radiations). While these detectors served a number of valuable scientific functions, the initial examination of the gamma-ray data emphasized the spacecraft's primary mission to gather information critical to U.S. security.

Stirling Colgate and Edward Teller had followed up Colgate's summit meeting comment by making specific predictions in 1965 of gamma-ray emission during the initial stages of the development of supernovae, They suggested that examination of the Vela data might disclose evidence of bursts of gamma rays at times close to the appearance of supernovae. Such searches were conducted; however, no distinctive signals were found.

On the other hand, there was evidence of variability that had been ignored. For example, the earliest x-ray data from small rocket probes and from satellites were often found to disagree significantly. The quality of the data, rather than actual variations in the sources, was suspected as the reason for these discrepancies. Also, a background of transient detector responses in much of the x- and gamma-ray data masked the similar responses to true cosmic bursts. These background responses were generated by a variety of mechanisms, many due to local effects of charged particles trapped in the earth's magnetosphere and others due to instrumental "glitches" (such as high-voltage arcing, electronic crosstalk, or telemetry errors). The Vela instruments responded to these spurious signals frequently enough to discourage careful inspection of every record. However, if the signals were spurious, it would be improbable for more than one Vela satellite to have responded at the same time. Thus, to identify nonspurious events, the data were searched for those occurring nearly simultaneously between spacecraft. However, data records were referenced only to the independent clocks in the spacecraft. These had to be referred to a common time in order to determine simultaneity. Moreover, the detection systems produced copious numbers of spurious records. Only the application of computerized data processing allowed the search for simultaneity to be performed on this volume of data.

Since the concept of a nearly static universe prevailed at this time, it was not expected that the search would reveal anything extraordinary. The intention was to verify that there were no natural background events that would mimic the signature of an exe-atmospheric nuclear detonation. Surprisingly, however, the survey soon revealed that the gamma-ray instruments on widely separated satellites had sometimes responded almost identically. Some of these events were attributable to solar flare activity. However, one particularly distinctive event was discovered for which a solar origin seemed inconsistent. Fortunately, the characteristics of this event did not at all resemble those of a nuclear detonation, and thus the event did not create concern of a possible test-ban treaty violation.

This first tantalizing indication of a cosmic gamma-ray burst had been found in 1969. By 1972, an extension of the search had revealed a surprising number of events—sixteen bursts over a three-year period. Each of these bursts, for intervals of up to several seconds, dominated the gamma radiation of the entire sky. It was only then that the violent behavior of the cosmos became clear: chaos and rapid change prevail in the x-ray and gamma-ray regime.

Evolution of Detector Systems

Despite the remarkable nature of these events, full awareness of the implications of the phenomenon developed only gradually. In fact, other evidence of variability, such as was observed in the quasar 3C273 in 1963, was only then causing astronomers to reconsider seriously their view of the universe. As the picture of the universe changed, new instruments were designed and placed aboard satellites to answer a growing list of questions. However, the long lead times and the space and weight limitations of satellite experiments did not allow rapid action toward answering these questions. Fortunately, scientists associated with other space projects graciously allowed the piggybacking of unscheduled gamma-ray burst experiments, thus circumventing the usual delay of several years until the next generation of satellites could be put into orbit.

One of the first questions to be addressed

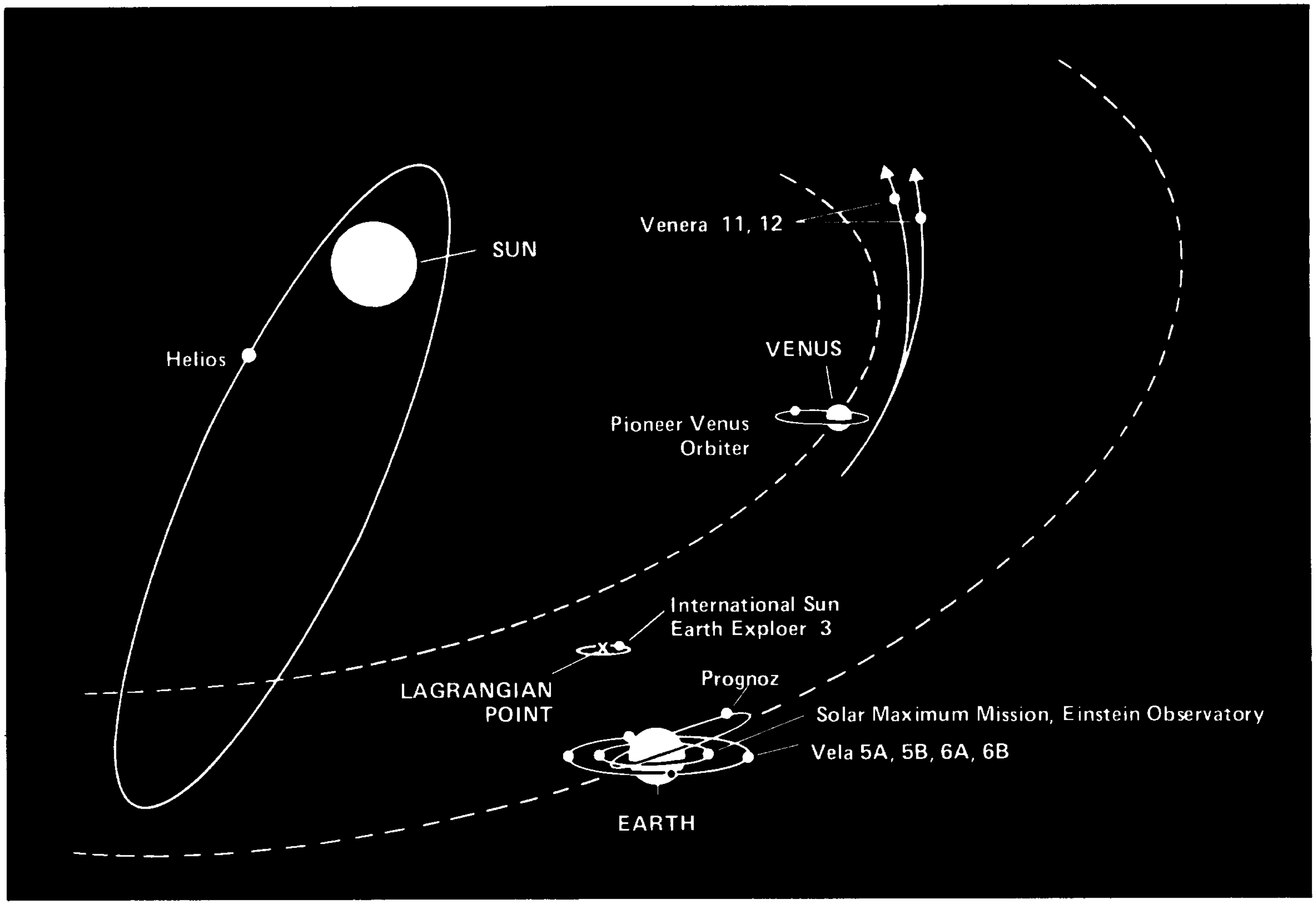


Fig. 1. Satellite network. The four main groups of satellites used from 1978 to 1980 to detect and locate precisely the direction of gamma-ray bursts are here represented schematically. The near-Earth group consisted of eight satellites including four Vela satellites and three others in geocentric orbits. Also considered a member of this group was the International Sun Earth Explorer 3 satellite (ISEE-3) located at one of the gravitationally metastable Lagrangian points. Two "groups" consisted only of single satellites: the Helios 2 satellite in orbit about the sun and the Pioneer Venus Orbiter at Venus. The fourth group comprised the two Soviet Venera satellites in solar orbits past Venus.

was how rapidly the intensity of a burst varied. The original Vela satellites carried Los Alamos instruments designed to respond to, among other things, the gamma rays from the fission debris of nuclear tests. Because such radiation would last for a relatively long time, the earliest Vela detectors provided only 32-second resolution. The third pair of Vela satellites (Vela 3) were sent aloft with detectors that included triggering systems designed to respond automatically to sudden increases in the signal, recording fractional-second time variations. It was an improved version of those detectors, carried by Vela 4, that first revealed the rapid variability found in the gamma-ray energy regime.

It was obvious that an understanding of gamma-ray bursts would be greatly assisted if it were possible to identify the source objects. The Vela observations provided a capability to locate sources of some events to within a few degrees. Although this was sufficient to exclude the sun and the planets, it was totally inadequate to identify uniquely the actual source objects from among the many stars included within this region. Thus, a considerable improvement in the resolution of the source locations was needed. The technique first employed in locating the sources depended on differences in the signal's times of arrival at members of the distributed array of Vela satellites (see sidebar "Time-of-Arrival Location Technique"). This technique could be made more accurate in two ways: by measuring the arrival times more accurately and by increasing the differences between the arrival times (by increasing the distances between satellites). Sufficient improvement in measuring the times of arrival was impractical. The most reasonable approach toward providing improved precision in locations was to increase the distances between satellites. Thus, a number of spacecraft were equipped with modest instruments designed to record these events and were distributed over interplanetary distances.

By 1979 the far-flung network of satellites was in place (Fig. 1 and Table I). The international consortium cooperating to establish this network included scientists from the United States, France, the USSR, and Germany. Tom Cline, at the NASA Goddard Space Flight Center, provided a gamma-burst instrument for the German/American Helios-2 satellite. Another American scientist, Kevin Hurley, at the Centre d'Etude Spatialle des Rayonnements in Toulouse, France, designed detectors that were mailed

TABLE I

INTERNATIONAL ARRAY OF SATELLITES FOR DETECTION OF BURSTS

Satellite	Launch Date	Orbit Description	Institution Responsible for Gamma-Ray Instrumentation	Present Status
Vela 5A, 5B, 6A, and 6B	1969, 1970	Geocentric at 1.2×10^5 km from Earth	Los Alamos	Active
International Sun Earth Explorer 3 (ISEE-3)	1978	At a Lagrangian point 1.5×10^6 km from Earth	One instrument by University of California, Berkeley/ Los Alamos and two other instruments by NASA Goddard Space Flight Center	Healthy
Prognoz 7	1978	Geocentric, highly elliptical	Centre d'Etude Spatiale des Rayonnements (Toulouse)	Telemetry lost in 1980
Einstein Observatory (HEAO-2)[a]	1978	Geocentric, very near Earth	---	Pointing ability lost in 1981
Solar-Maximum Mission[a]	1979	Geocentric, very near Earth		Partially active
Helios 2	1976	Heliocentric, highly elliptical	NASA Goddard Space Flight Center	Telemetry lost in 1980
Pioneer Venus Orbiter	1978	Highly elliptical about Venus	Los Alamos	Healthy
Venera 11 and 12	1978	Heliocentric with the two satellites diverging from each other	On each satellite one instrument by Centre d'Etude Spatiale des Rayonnements (Toulouse) and a second by A. F. Ioffe Physico-Technical Institute (Leningrad)	Telemetry lost in 1980

[a]A NASA-lauched satellite carrying instruments not specifically designed to observe gamma-ray bursts. The data collected were, however, helpful in analyzing gamma-ray bursts. Several institutions were responsible for the instruments aboard.

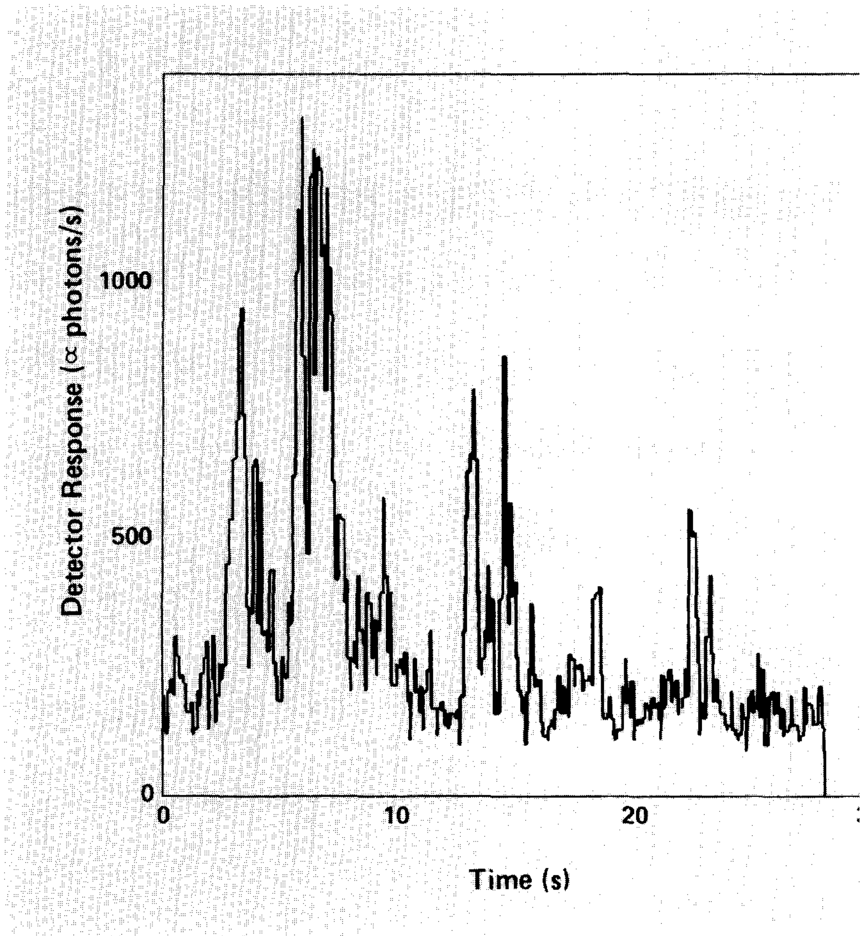


Fig. 2. Time dependence of burst intensity. These data, taken on November 4, 1978 with the Los Alamos gamma-ray detection system aboard the Pioneer Venus Orbiter, illustrates the dramatic, highly variable nature of a typical gamma-ray burst.

to Siberia and placed on Soviet spacecraft. In addition to the instruments aboard the Vela satellites, Los Alamos contributed toward this network with a modification to the University of California, Berkeley Solar X-Ray Spectrometer (aboard International Sun Earth Explorer 3, or ISEE-3) that allowed the instrument to record temporally resolved spectral data for both gamma-ray bursts and solar flares. Also, in a joint development with Sandia National Laboratories, Los Alamos supplied the gamma-ray burst monitor that has been operating aboard the Pioneer Venus Orbiter since May 1978 (see sidebar "Eyes for Gamma Rays" for a description of this system). This network of satellites has been used to determine precise locations for several intense bursts to within one arc-minute of uncertainty.

Typical Gamma-Ray Bursts

Many of the second generation of gamma-burst monitoring instruments were in operation during a burst recorded November 4, 1978. This event is the third most intense burst yet observed, and its features are typical of most gamma-ray bursts. Figure 2 shows a record (from Pioneer Venus Orbiter) of the burst's behavior in time. Its intensity rises and falls dramatically in fractions of a second. A number of distinct outbursts, each lasting on the order of a second, are clearly isolated by periods in which the signal has returned nearly to the background level. Even within the individual outbursts there are statistically significant variations. Although the major peaks suggest a periodicity, detailed analysis does not indicate that the behavior is strongly periodic.

RAPID VARIABILITY. Rise and fall times of about 0.01 to 1 second are characteristic of gamma-ray bursts. These times can be used to obtain a qualitative insight into certain physical attributes of the burst emission region. For example, there is a simple constraint on the source size because the fluctuation time scale cannot be much faster than the travel time of light across a typical source dimension. For a O. 1 -second rise time, a source size less than about 30,000 kilometers is inferred. This is extremely small on an astronomical scale and indicates that compact objects such as white dwarfs, neutron stars, or black holes are logical candidates for the burst sources. of course, if the emission region is very small (a neutron star is only about 10 kilometers across), the characteristic burst time scales probably reflect other dynamical time scales of the system such as a heating or cooling time.

MULTIPLE OUTBURSTS. Another important time-dependent feature of typical bursts is the complexity of burst waveforms, with multiple outbursts occurring over intervals of tens of seconds (Fig. 2). This implies a mechanism that is not catastrophic. For example, a supernova explosion would be expected to produce a single outburst. Further, the multiple bursts do not show strong evidence for periodicities. However, the burst waveforms often contain similar, repeating patterns that suggest systematic and reproducible mechanisms at work. Additionally. Vela x-ray observations have recently disclosed repeated outbursts of x rays associated with gamma-ray bursts. The initial gamma-ray bursts extended to x-ray energies and were followed by additional, weaker x-ray outbursts occurring over intervals of hundreds of seconds. No gamma radiation was observed coincident with these latter x-ray bursts, so the question remains whether these are truly gamma-ray bursts detected only by the x-ray instruments or are softer x-ray outbursts.

THE ENERGY SPECTRUM. The energy to which the Vela 4 instruments responded gave the first indication that gamma-ray photons characterized these bursts, and the difference in energy response of detectors in the Vela 5 and Vela 6 spacecraft further confirmed the

time-of-arrival location technique

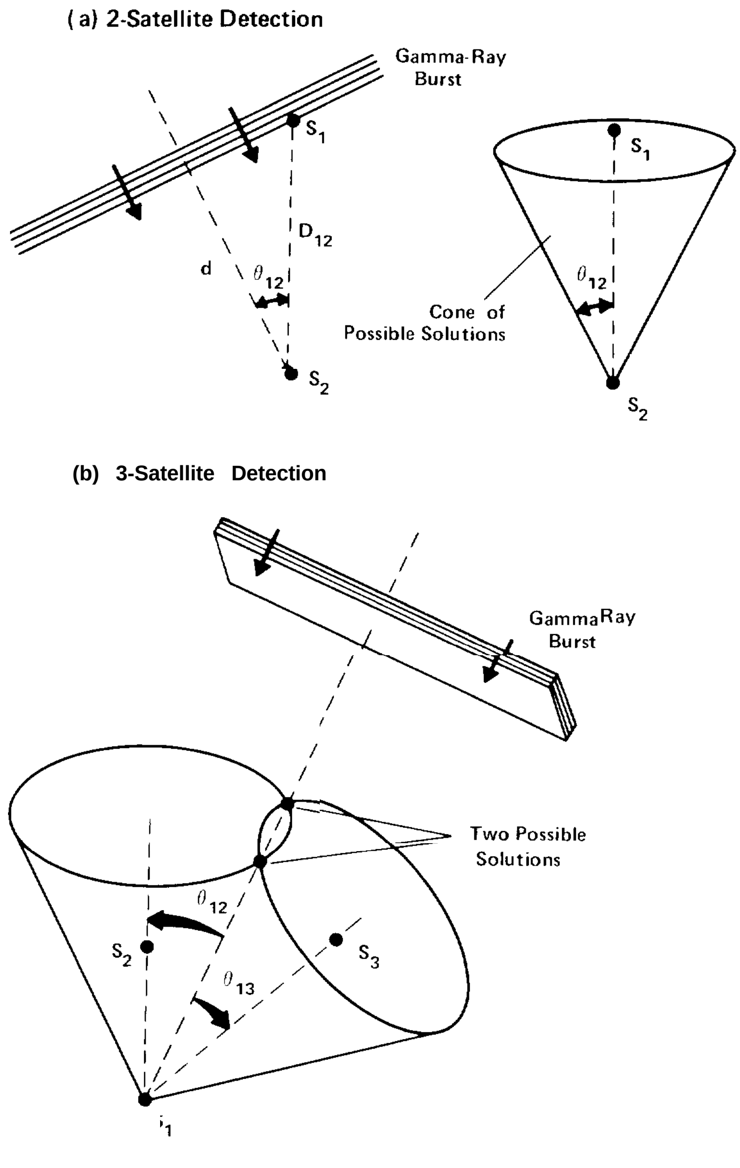


Fig. 1. Time-of-arrival location technique. (a) When a cosmic gamma-ray burst is letected by two satellites (S_1 and S_2), the angle θ_{12} between the line connecting the satellites and the direction of motion of the burst wavefront can be calculated using the known separation D_{12} between the satellites and the distance d determined from the difference in arrival times of the burst at the satellites. This angle gives a cone of possible directions to the gamma-ray burst source. (b) With three satellites, two solution cones are generated, and the intersections of these cones give two possible directions.

Garoma-ray bursts occur unpredictably in time and in location, Instruments with an inherent capability to locate these bursts precisely are extremely complex and, indeed, not yet fully developed. However, the locations of burst sources can be determined with relatively simple instrumentation from the arrival times of the burst wavefront at each of several widely separated satellites, The absolute difference At in the arrival time of the signal at any two satellites is directly related to the absolute difference in the path length *d* over which the signal travels ($d = c\Delta t$). With only two satellites the many locations that satisfy this relationship define a hyperboloid of revolution about the line between the two satellites. As shown in Fig. la, this hyperboloid of resolution may be approximated by a cone if the distance to the source is large compared to the distance between the satellites. If observations from a third satellite are available, the allowed locations are reduced to two directions in space defined by the intersections of two such cones (Fig, lb). One of these is the true location of the source and the other is its mirror image in the plane defined by the three satellites. Addition of a fourth satellite, not located in the same plane, allows discrimination against this mirror image.

In practice the cones are presented as their circular projections on the celestial sphere. Also, in accounting for the uncertainties in defining these circles, they must be presented

Sidebar 1

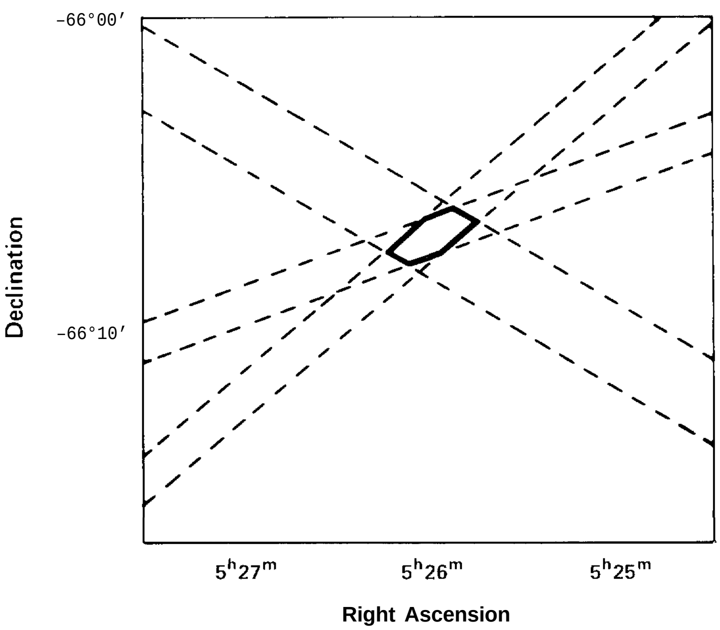


Fig. 2. The location box. The dashed bands here are the projections of the cones and their associated uncertainties onto the celestial sphere for the initial determination of the March 5, 1979 burst. The polygon resulting from the intersections of the bands contains the location of the source.

as annular bands, the widths of which are proportional to the estimated uncertainty. The intersections of these bands define an "error box" that contains the location of the source (Fig. 2).

In the present detection network, satellites that are close to each other (for example, the group in orbit about the earth) do not generally improve the accuracy of the location. However, if a variety of detection systems are present in such a cluster, the data can be crosschecked, systematic errors can often be identified, and the arrival time at this cluster determined with a high degree of confidence. For an observation performed by a single satellite, or two identical satellites, it is difficult to verify that there are no systematic errors remaining in the data.

Thus, various factors, including the intensity of the event, the presence of bold temporal features that can serve as identifiable time markers from detector to detector, the spatial distribution of the members of the array at the time of the event, and the availability of shared data, affect the accuracy with which the location of the source can be resolved. The intensity, rapid rise time, and redundancy of observation of the March 5, 1979 burst gave the members of the international consortium an opportunity to verify the accuracy of the location technique. While a number of systematic errors were disclosed and corrected in the analysis of this event, a discrepancy that exceeds the anticipated errors still remains in the analysis of some other events. ■

nature of the spectrum. The Vela 5 detectors responded to photons with energies between 150 and 750 kiloelectron-volts (keV), whereas the Vela 6 detectors responded to somewhat higher energies between 300 and 1500 keV. A comparison of the response of both systems to the same events provided the first crude indication of the energy spectrum. Soon, however, measurements by true spectrometers became available. For example. instruments aboard two International Monitoring Platform satellites (IMP 6 and 7) measured the spectral distribution of many events more definitively. Over the energy range of the measurements, the observations could be fit by a simple exponential function with a characteristic index of 150 keV; that is, the number of photons at energy E is proportional to exp(-E/150).

A few bursts, however, have been observed by x-ray detectors with responses down to lower photon energies. One of these measurements (performed from Apollo 16) demonstrated that the spectral distribution for that event was consistent with the shape expected for thermal bremsstrahlung from an optically thin plasma at temperatures of several billion kelvins (thermal bremsstrahlung is discussed below in the section "Radiation Mechanism."). This result is not at odds with the exponential shape defined by the IMP observations, but represents further definition of the spectral shape by extension of the measurement to lower photon energies. Two other gamma-ray bursts were observed by the x-ray detectors aboard the Vela spacecraft, and one of these was also observed by an x-ray detector aboard the Orbiting Solar Observatory satellite, 0S0-7. These measurements were also consistent with a thermal bremsstrahlung distribution.

By 1978 the Soviet KONUS experiment began routinely to observe gamma-ray bursts over a wide energy range: 30 to 1000 keV. These observations also indicated a spectral shape consistent with optically thin thermal bremsstrahlung. In addition KONUS had sufficient energy resolution to resolve spectra] features. Many KONUS events appeared to have an emission feature around 400 to 450 keV (also observed by the ISEE-3 high-resolution spectrometer), which was explained as radiation from electron-positron annihilation, gravitationally redshifted 10 to 20 percent. Since the gravitational field required to redshift a line by 10 percent is the field expected at the surface of a neutron star, these lines were the first strong evidence that gamma-ray bursts occur on neutron stars.

Low-energy absorption features have also apparently been revealed in the KONUS data. These absorption features have been attributed to cyclotron radiation, implying an exceptionally strong magnetic field (about 10^{12} gauss). Since such magnetic fields can only occur near the surface of neutron stars, this result was taken as further evidence that neutron stars were involved. However, the cyclotron lines are subject to question because the features may be artificially generated in the process of data analysis.

What do these spectral measurements reveal? First, gamma-ray bursts are considerably harder than x-ray bursts; that is, high-energy photons dominate the spectra (Fig. 3). Second, the overall shape of these spectra appears to be approximately consistent with thermal bremsstrahlung from an optically thin plasma. Third, the line features suggest that the bursts occur on neutron stars. probably highly magnetized neutron stars.

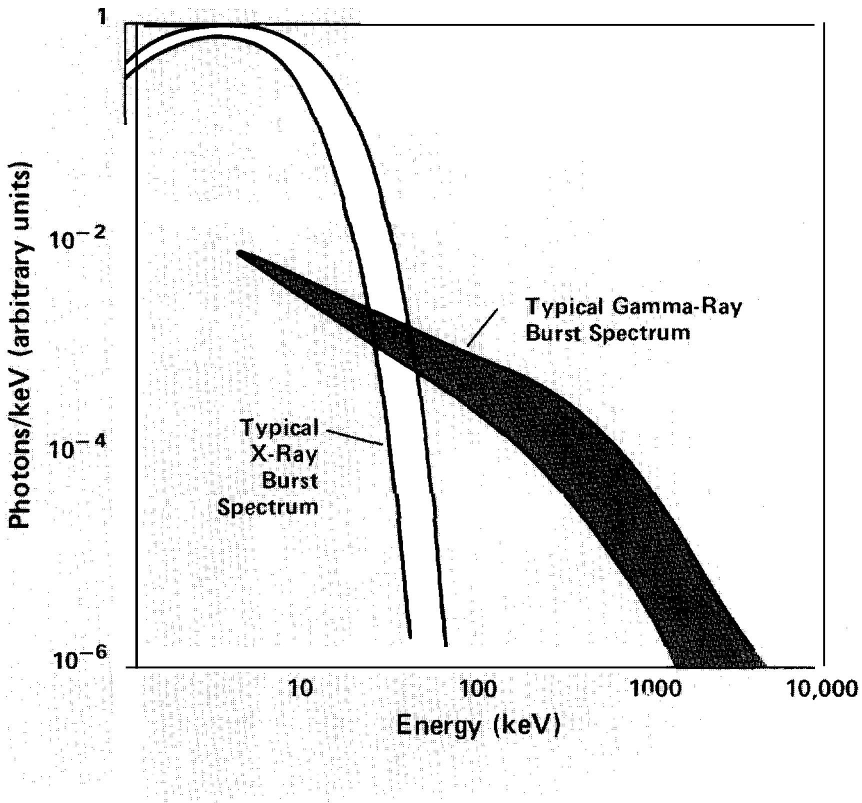


Fig. 3. Gamma-ray and x-ray burst spectra. Each band represents the range of spectral shapes typically observed for both gamma-ray and x-ray bursts. The spectra have been arbitrarily normalized, but indicate the general relationship between the two phenomena. X-ray bursts are typically observed to be much more intense at lower energies, but gamma-ray bursts are much stronger at energies above 100 keV.

SPATIAL DISTRIBUTION. The number of bursts observed as a function of their intensity provides insight into the overall distribution of the sources in the space around us. The apparent intensity of a burst at the detector decreases as the square of the distance to the burster. The volume containing average sources grows with the distance, the exact relationship depending on the type of spatial distribution. If the sources are distributed homogeneously, the volume (and hence the number of burst sources) increases as the third power of the distance. The number N of events observed to be greater than an apparent intensity S should then follow a –3/2 power-law dependence (that is, $N \propto S^{-1.5}$). On the other hand, if the sources are distributed in a thin plane, the number increases only as the square of the distance. The dependence of N on S is then that of a -1 power function ($N \propto S^{-1}$).

Early observations indicated that the intensity distribution was consistent with a –3/2 power law, which implies a homogeneous distribution, but these data were limited by instrument sensitivity. More recently. M. C. Jennings and R. S. White, using data obtained by sensitive balloon-borne instruments, concluded that the event frequency at low intensities was inconsistent with an extrapolation of the –3/2 power law from data at high intensity. This suggests that there is some boundary to the spatial distribution of the sources. This boundary would probably be either the extent of our own galaxy or the limit to which the universe can be observed. Since the intensity distribution does not show evidence of what should

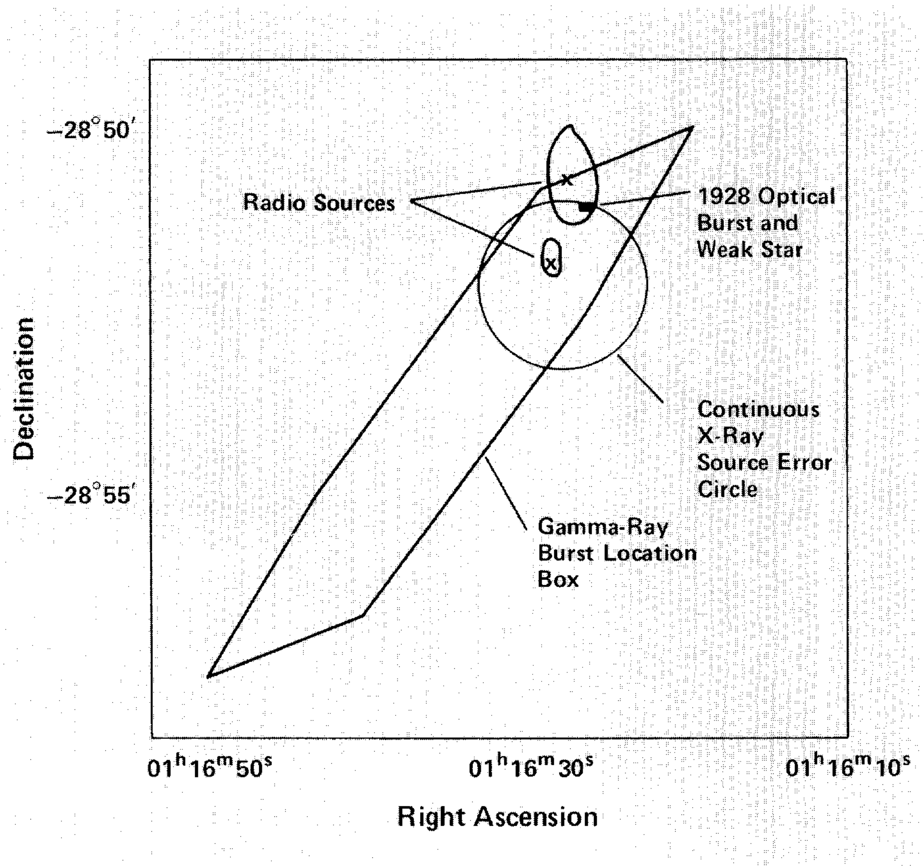


Fig. 4. The locations of the November 19,1978 burst and associated radio, x-ray, and optical sources. The two radio sources were resolved by the Very Large Array radio telescope; the circle locating a weak x-ray source was determined by an x-ray detector aboard the Einstein Observatory. Falling within the regions mapped for the gamma-ray burst and for the x-ray source is the location of the 1928 optical transient (small rectangle) with a weak (23rd magnitude) star at the same position. [T. L. Cline et. al., The Astrophysical Journal 246, L133-L136 (1981) and B. E. Schaefer, Nature 294, 722-724 (1981).]

be significant contributions from nearby groups of galaxies, and since levels of energy at the sources would be beyond comprehension if they were as far away as the limit to which the universe can be observed, it can be concluded that the sources lie within our own galaxy.

SPECIFIC LOCATIONS, This indication that the sources lie within our galaxy suggests that the sources might be located near the galactic plane. To the contrary, even the crudely located bursts do not distinctly show such a preference, and none of the directions for the few precisely determined bursts lie close to the galactic plane. Why not? Only the more intense events can be located precisely, and these are also likely to be from the closest sources. Since the galaxy is actually a thick disk rather than a thin plane, objects near to us would appear to be distributed uniformly if their distances were less than the approximately 1000-light-year thickness of the disk.

Because there was no strong preference for the galactic plane where stars are most dense, it was expected that there should be relatively few stars randomly contained within the precisely located regions. Indeed, only a few, very faint stars were typically found—none with any exciting characteristics.

In general there was no association between gamma-ray bursts and objects that had seemed to be remarkable when observed at other wavelengths. Gradually, however, searches for x-ray, radio, and optical sources revealed interesting correlations. An example is the November 19, 1978 gamma-ray burst. This was the second most intense event recorded to date and could be precisely located (Fig. 4). When the x-ray detector aboard the Einstein Observatory (HEAO-2) was directed to scan this field, a marginally detectable, continuous x-ray source was observed. Additionally, the Very Large Array radio telescope in Socorro, New Mexico resolved at least two weak radio sources within the locational uncertainty. Neither the radio nor the x-ray sources, though, were consistent with any optically resolved stellar images down to the 22nd magnitude. Recently, however, Bradley Schaefer of the Massachusetts Institute of Technology discovered a heretofore unknown type of optical transient event in this field. He searched archival photographic plates at the Harvard College Observatory for unusual optical objects at the three published precise gamma-ray burst locations. In the case of the November 19, 1978 event, his search apparently proved successful. On one plate in a series of six made at a station in South Africa on November 17, 1928—almost fifty years to the day previous to the burst!—he discovered a 10th magnitude star that did not appear on any other plate. The image had the characteristics of one formed through the telescope optics, but the negligible trail (compared to the other stellar images) left by the star during the 45-minute exposure suggested that its brightness lasted for only seconds or minutes.

Plates of this region made by Martha Liner of the Harvard College Observatory subsequent to this discovery seem to include a barely observable 23rd-magnitude star at the position of the optical transient. Certainly this must be an unusual subject. It flared up in a brief flash in 1928 to a hundred-million times its present brightness, and then in 1978 it again flared up, being observed as an intense burst of gamma rays. Whether visible radiation and gamma rays were simultaneously present in either case is not, of course, determined. But if this unremarkable—and even almost undetectable—star is typical of the quiet state of gamma-ray burst sources, it will be very difficult to study them at optical wavelengths.

The March 5, 1979 Burst —An Atypical But Important Event

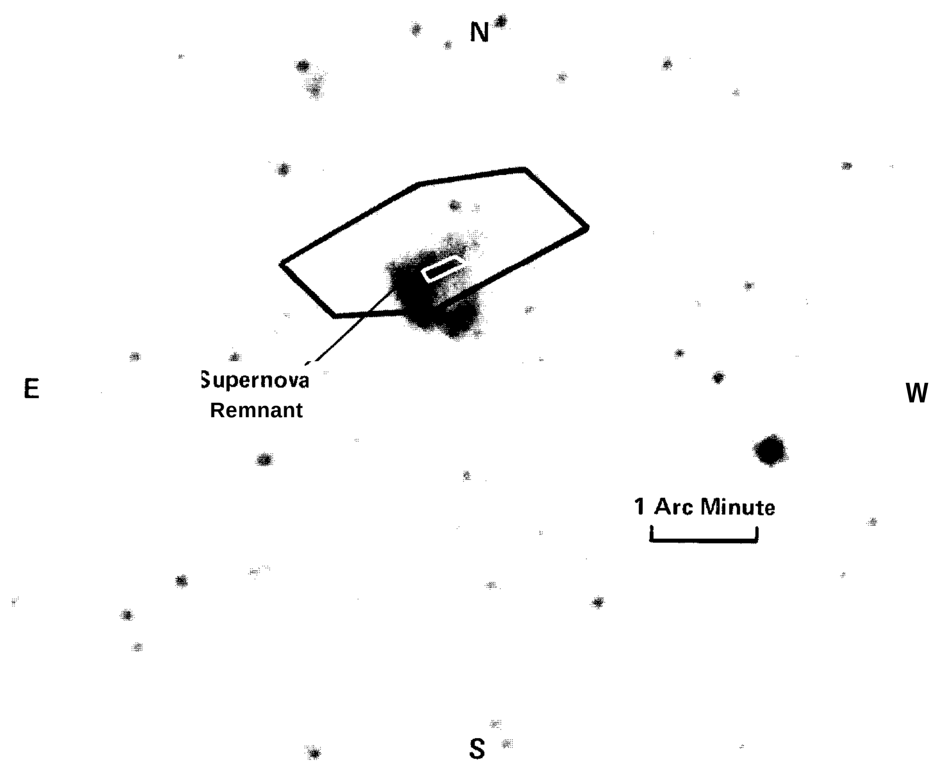


Fig. 5. The location of the March 5, 1979 burst. The initially determined location of the March 5, 1979 gamma-ray burst based on time-of-arrival data from three spacecraft is shown as the outer box on this negative-image field of stars. The hot, expanding cloud of gases of N49, a relatively young supernova remnant located in the Large Magellanic Cloud, lies within this box, After the small systematic errors in the satellite network were identified, the error box outlined in white was determined using data from all ten spacecraft. The new location falls within the supernova remnant and represents an area that is only a fraction of a square arc-minute.

The unusual gamma-ray burst observed on March 5, 1979 was remarkable in many respects, including an intensity ten times greater than previously observed. This event may, in fact, represent a different class of gamma-ray bursts. Features that distinguish it from typical bursts are

- a spectrum that lies between those for typical x- and gamma-ray bursts,
- its possible association with a specific and remarkable object at an implied distance 100 times farther than was thought likely,
- a long, regularly pulsing “afterglow,”
- a rise time more than 10 times faster than previously observed, and
- a recurrence of outbursts observed on a time scale of days.

The spectral characteristics of the March 5, 1979 burst clearly set it apart from typical gamma-ray bursts. The photons had characteristic energies of about 50 keV rather than the more typical 300 keV. The spectral shape was not consistent with optically thin thermal bremsstrahlung. Additionally, this event was the first for which the spectrum was shown to include what was apparently a redshifted annihilation line, indicating that the burst occurred on a neutron star.

This gamma-ray burst was the first for which a precise location was determined. Of the several events now precisely located, only this one suggested an association with a specific source object previously known. Figure 5 shows the location of this burst and its relation to the supernova remnant N49 within the Large Magellanic Cloud, a neighboring galaxy. This association has been thought to be accidental by many astrophysicists because of the great energy implied by the observed flux if the source is assumed to be at the distance of the Large Magellanic Cloud.

An unusual and interesting feature ob-

Sidebar 2

eyes for gamma rays

Scintillation detectors mounted in satellites are the eyes that "see" bursts of gamma rays. Currently, our most distant eye, the Pioneer Orbiter circling Venus, contains a detector designed jointly by Los Alamos National Laboratory and Sandia National Laboratories. This detector consists of two scintillation spectrometers, mounted opposite each other at the periphery of the spacecraft, and a logic and data-storage module (see figure).

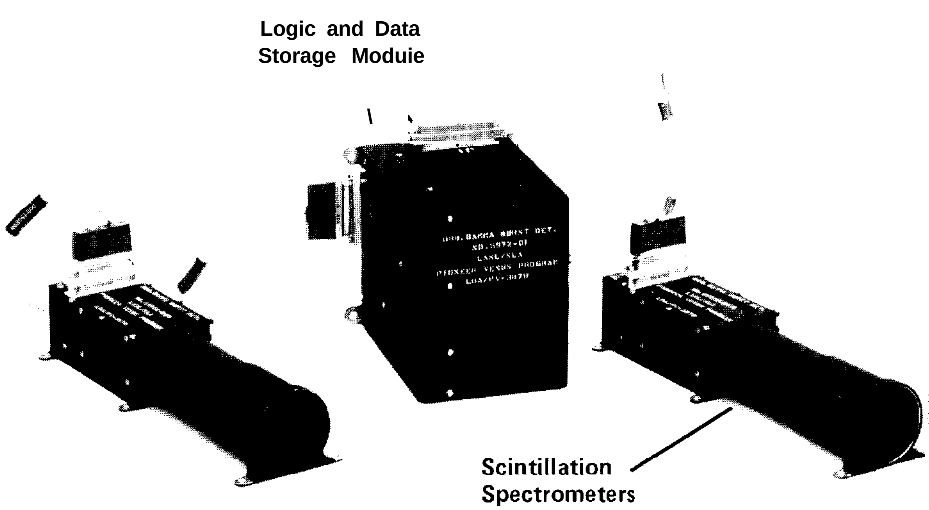
The "retina" in this system is a cylindrical cesium iodide crystal doped with a small amount of thallium. Gamma rays deposit energy in the crystal by kicking electrons from the crystal lattice. As the electrons recombine with positive charges at the thallium impurity sites, photons of visible light are produced; that is, the crystal "scintillates." The number of photons is proportional to the gamma-ray energy. A photomultiplier tube bonded optically to the crystal detects the light and sends a signal to the logic and data-storage module.

Because the penetrating charged particles of cosmic rays also produce scintillation in the cesium iodide, the crystal is surrounded with a shell of plastic scintillator that is sensitive primarily to these particies. Scintillation in the plastic occurs quickly, and the logic circuits use this signal to reject the accompanying but later signal caused by charged-particle interactions in the crystal.

Energy-level discriminators split the signal into four ranges of gamma-ray energy: 100 to 200, 200 to 500, 500 to 1000, and 1000 to 2000 kiloelectron-volts (keV). A trace of radioactive californium-249 deposited on the scintillator is used for in-flight calibration of the system.

When a significant increase in the signal above the average background signal occurs, the system automatically stores the data and the time of the burst in a dedicated solid-state memory. The detector count-rate history is recorded at a basic interval of 12 milliseconds, but the interval can be shortened when the intensity of the signal warrants more rapid sampling. Because the background signal is being continuously stored in memory, the important initial rise of the burst wavefront is captured (for exampie, see Fig. 2 of the main article). Also, a set of spectral data is recorded with every set of sixteen 12-millisecond samples. These data are retrieved later upon command from Earth.

At present, this detector, and similar detectors on about seven other satellites, are watching the heavens for bursts of gamma rays. Twenty-nine burst events were recorded by the Venus Orbiter during 1979, including the energetic event of March 5, 1979. ■



The gamma-ray detection system aboard the Pioneer Venus Orbiter spacecraft.

served for this burst is the pulsing afterglow, the pattern of peaks in Fig. 6 that was recorded for about 200 seconds after the initial spike. (Although this event is the only observed burst with any regular periodicity, the fact that the afterglow is about 500 times less intense than the initial spike means that it would not be possible to detect such an afterglow in data from weaker bursts.) Fourier analysis of this pattern gives clear evidence of a well-defined periodicity of 8 seconds. There is also present an obvious, but weaker, interpulse. The pulse and interpulse are probably due to the "lighthouse" effect (modulation induced by viewing two oppositely placed source regions on a rotating star, probably at the magnetic poles) rather than to a resonance effect.

This burst also had an exceptionally rapid rise time (≤ 1 millisecond), which suggests that the size of the source must be less than 1000 kilometers. A rotation period of 8 seconds and a radius less than 1000 kilometers can only be consistent with a neutron star, which might well have been produced by the supernova that formed the visible remnant N49. However, an 8-second periodicity might imply a neutron star whose rotation has slowed considerably and is thus very old ($> 10^6$ years), whereas the supernova remnant is believed to be only 10^4 years old.

Three additional, weaker outbursts were seen from this source on March 6, April 4, and April 24, 1979. These recurrences were similar to the March 5, 1979 event, but were much weaker and thus could not be as effectively studied.

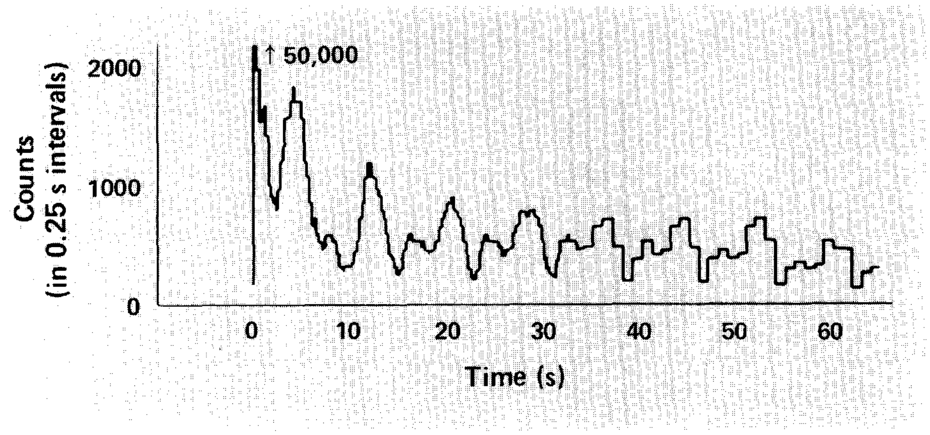


Fig. 6. Periodic "afterglow" of the March 5, 1979 burst, as detected by Venera 11. The 8-second period of the afterglow observed following this intense burst is clearly shown, together with an interpulse. The interpulse is in phase with the intense burst, and is observed to be growing in amplitude through the first four cycles. [E. P. Mazets, S. V. Golenetskii, V. N. Il'inskii, R. L. Aptekar', and Yu. A. Gur'yan Nature 282,587 (1979).]

Models of Burst Sources

Early in the history of gamma-ray burst observations there were many more source models proposed than there were bursts recorded. In fact, at one of the early scientific meetings, fifteen models were summarized—twelve of which have now been discarded. It has been obvious from the start that most of the proposed models were not capable of reproducing all the observations of this complex phenomenon. However, a general consensus has developed that, in fact, only neutron stars can provide the environment needed to account for the various characteristics observed, although a number of questions remain.

A neutron star is the end product of the evolution of a star several times more massive than our sun. The star has burned all of its nuclear fuel and has then lost about half its mass during a gravitational collapse and ensuing supernova explosion. The collapse crushes the remaining stellar material to a core that is somewhat like a giant nucleus composed of neutrons, with an iron skin. The star is so very small (only 10 kilometers in diameter, about the size of a small town) yet so incredibly massive (nearly a million times the mass of the earth) that a tremendous gravitational field is produced at the surface. It is also generally believed that a strong magnetic field may be condensed along with the stellar mass. Most of the models proposed to explain gamma-ray bursts invoke one or both of these fields.

SUDDEN ACCRETION. For example, some models assume the sudden accretion of a large amount of material onto the surface of a neutron star. The material might spill over in a diffuse form from a companion star or plummet to the surface in the concentrated form of a comet or asteroid. The large gravitational field accelerates the material to speeds near the velocity of light before it strikes the surface of the star. There the material, with the energy it has gained in falling, produces a hot plasma that emits gamma rays. The chaotic behavior in time is frequently attributed to "lumpiness" in the accreted material.

Stirling Colgate and Albert Petschek, and also Arthur Cox and Michael Newman, have developed models of gamma-ray bursts based upon collisions of asteroids with neutron stars. Although this model was directed specifically at the March 5, 1979 burst, variations on it might be relevant to typical gamma-ray bursts. Colgate and Petschek

Thermal Bremsstrahlung

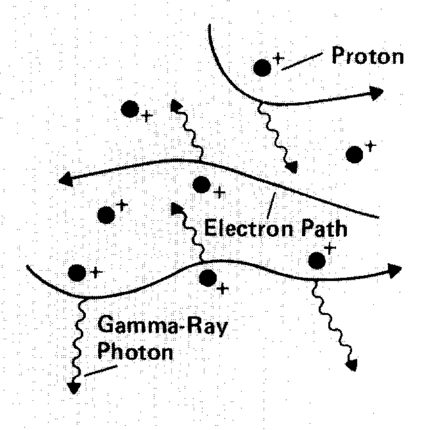


Fig. 7. Thermal bremsstrahlung emission. Very fast, high-temperature electrons are deflected by the Coulomb field of the heavier, slower protons. This acceleration of charge results in the emission of gamma-ray photons when the plasma temperature is greater than a billion kelvins (kT > 100 keV).

found that an iron-nickel asteroid about 6 kilometers in diameter falling toward the surface of a cold magnetized neutron star would be compressed and elongated by the gravitational field. Furthermore, the magnetic field lines flatten the material into a thin knife edge several millimeters thick and several kilometers wide. The material impacts the surface, causing a local explosion, and the hot, radiant material then expands along magnetic field lines into a fan of flux tubes. In fact, the strong magnetic field is essential for restraining the material long enough during this explosion to allow for release of significant amounts of energy. The plasma is supported by radiation pressure at the polar cusps in the tubes. This material continues to emit x and gamma rays while the neutron star rotates, producing the pulsing afterglow. The major uncertainty of this model is the poorly known probability for the occurrence of such a collision between an asteroid and a neutron star.

THERMONUCLEAR FLASH. The thermonuclear flash model also depends upon the accretion of material onto the surface of the neutron star. In this case the accretion, consisting mainly of hydrogen, occurs slowly and rather uneventfully. The hydrogen is heated as it impacts the surface, and, when a sufficient quantity has accumulated, nuclear burning is initiated. This burning proceeds quietly, combining four hydrogen nuclei into one helium nucleus and generating additional heat. The density of helium increases and the temperature rises until a violent, explosive reaction occurs in which helium burns to produce iron-group elements. In the thermonuclear flash model the complex time behavior is explained as a result of the uneven propagation of the thermonuclear reaction through the surface layer of helium. This model predicts that the heated region would produce a long-duration glow of x rays following the gamma-ray burst. However, the limited number of x-ray measurements of gamma-ray bursts do not show evidence of such a glow and thus seem to be inconsistent with the present concept of this model.

Both the sudden accretion model and the thermonuclear flash model have been used successfully to explain x-ray bursters. For a gamma-ray burst, a stronger magnetic field is usually required by the model, modifying the generating mechanism enough to produce gamma-rays rather than x-rays. In fact, in the thermonuclear flash model the accreting material may funnel down the field lines to a magnetic pole, and then again may be constrained by the magnetic field during the violent burning phase so that it spurts vertically off the surface in a fountain-like plume.

STARQUAKE. A third possible mechanism is a “starquake.” Many models of neutron stars predict a solid crust at the surface of the neutron star. Stresses can be set up in this crust by changes in the rotation of the star or changes in the magnetic field. Eventually, the strength of the crust is exceeded, and the stresses are relieved by restructuring of the star. This is accompanied by the release of a large amount of energy, probably through injection of a heated plasma into the stellar atmosphere. In fact, this may be the only mechanism able to release enough energy to account for extra-galactic source distances. However, no detailed modeling has been attempted for starquakes because of fundamental uncertainties about the actual dynamics.

Radiation Mechanism

Not only is there no consensus about the energy-releasing mechanism responsible for gamma-ray bursts, but neither is there agreement about how the gamma rays are produced. Three possible emission mechanisms have been considered.

THERMAL BREMSSTRAHLUNG. Early analyses of the spectra found that a reasonable tit to the data could be made by assuming optically thin thermal bremsstrahlung, which is expected from a very dilute and very hot plasma. Bremsstrahlung is the radiation emitted when charged particles are accelerated: in this case, the paths of high-temperature, very fast electrons are bent by the Coulomb field of more slowly moving ions, usually assumed to be protons (Fig. 7). The resulting thermal bremsstrahlung can escape the plasma without further interaction only if the plasma is very dilute, that is, optically thin. On the other hand. if the plasma was optically thick, the spectrum would be modified toward a black-body distribution. Optically thin thermal bremsstrahlung is particularly simple to model and produces the spectral distribution

$$N(E)dE = \frac{bg(T,E)\exp(-E/kT)}{E}N^2VdE \ ,$$

where b is a constant, $g(T,E)$ is the Gaunt factor (a correction for quantum mechanical effects), T is the temperature, k is the Boltzmann constant, N is the number density of the electrons, and V is the volume of the emitting plasma. The temperature T *is* the only free parameter that affects the shape of the spectral distribution. Typically, a fit of this expression to the data yields a temperature of 3 billion kelvins, which corresponds to an energy (equal to kT) of 300 keV.

The luminosity, that is, the total energy emitted per second, can be found by integrating over the spectral distribution. In principle, the distance to the source can be determined by relating this luminosity to the flux observed near the earth. Unfortunately, neither the electron density N nor the plasma volume V are known. However, it is fairly certain that the burst occurs near the surface of the neutron star and therefore must have a size less than about 10 kilometers. (In fact, most detailed theories predict sizes smaller by a factor of 10.) In addition, because the spectra do not appear to have been modified by Compton scattering, one can put an upper limit on the electron density. These limits on N and V result in an upper limit on the distance to the burst sources of about 3 light years. But the closest star is about 4.3 light years away. Thus, if optically thin thermal bremsstrahlung is the emission mechanism, most of the sources would have to be closer than the nearest visible star. Thermal bremsstrahlung simply does not create enough photons to be consistent with the fluxes we observe at the earth unless the objects are unreasonably close. Also, some detailed spectral observations disclosed that thermal bremsstrahlung did not provide the optimum fit.

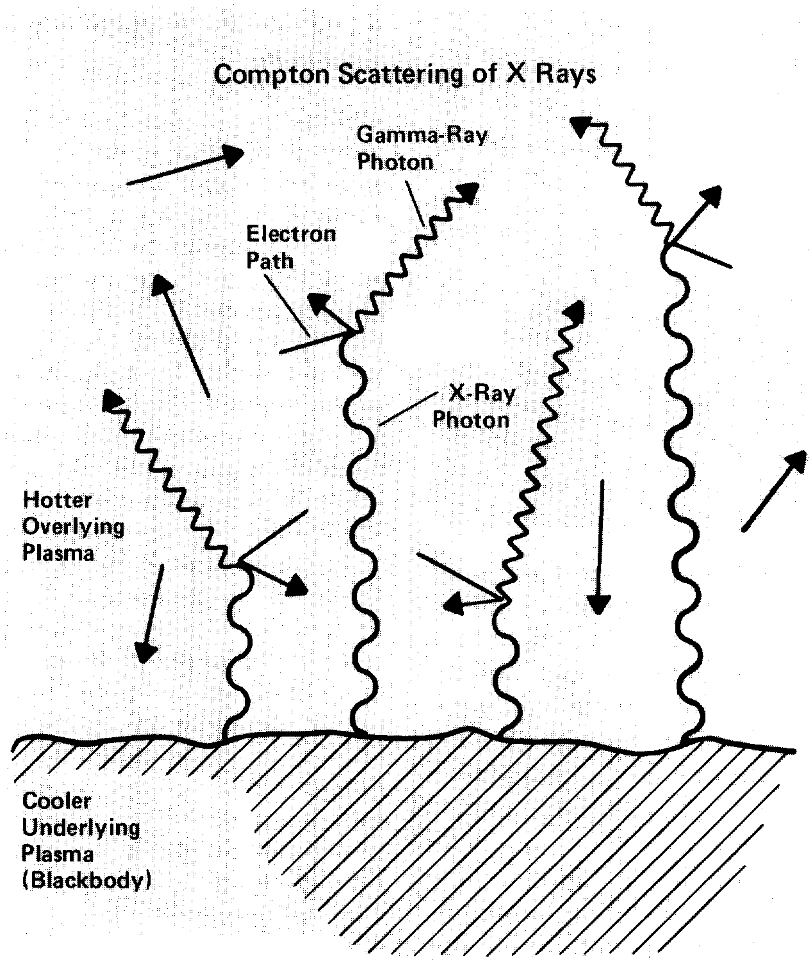


Fig. 8. Comptonized blackbody process. Lower energy x-ray photons with a blackbody spectral distribution are emitted by the cooler, underlying plasma. These photons interact with high-energy electrons in the hotter, overlying plasma and are "kicked" up to gamma-ray energies by inverse Compton scattering.

COMPTONIZED BLACKBODY. A major problem with the optically thin thermal bremsstrahlung model is the inefficient production of photons. Perhaps if another source were provided for the initial production of the photons, a thermal model might be consistent with the observed flux. In one such model the same hot dilute plasma lies over a cooler, more dense plasma that is able to produce the necessary copious supply of photons (Fig. 8). The initial blackbody distribution of photons undergoes inverse Compton scattering as it travels outward through the hotter plasma; that is, the photons scatter from highly energetic electrons and thereby gain energy. But does a Comptonized blackbody spectral distribution adequately tit the observations?

The burst recorded on November 4, 1978 provided excellent data for testing this model. Fortuitously, the source of this event lay within about 1 degree of the ecliptic plane, and, consequently, the emission over a

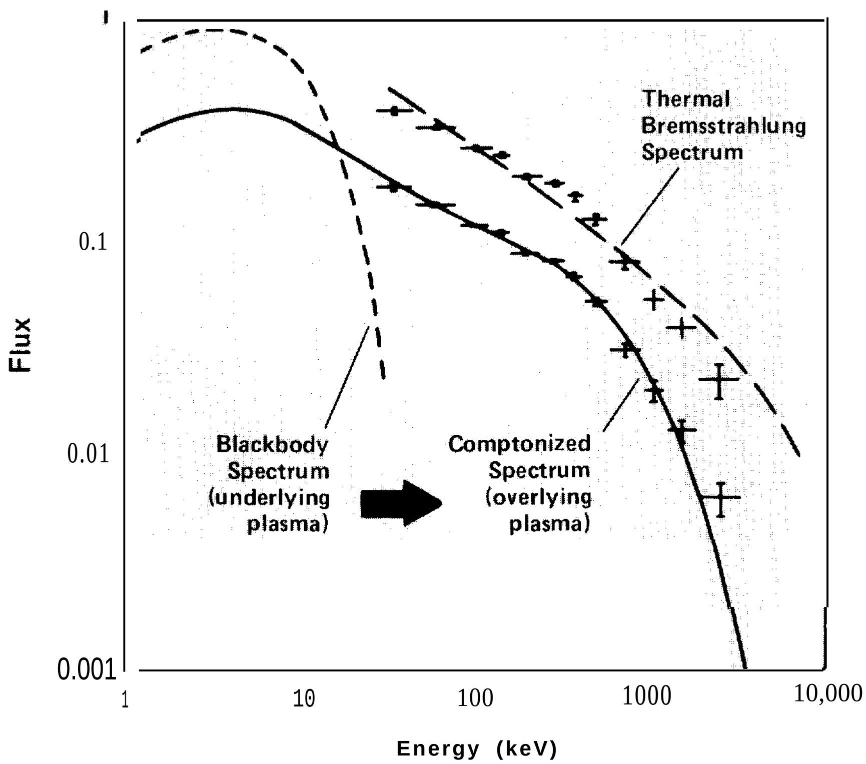


Fig. 9. Modeling of the November 4, 1978 burst spectrum. The data recorded for this gamma-ray burst by the ISEE-3 x-ray spectrometer (crosses) are fit with a Comptonized blackbody and a thermal bremsstrahlung spectrum (data and curves for the two cases are displaced vertically for clarity). The blackbody spectrum calculated for the cooler, underlying plasma in the Comptonized blackbody mechanism is also shown. The Comptonized blackbody spectrum provides a closer fit, yielding values for* kT *of about 2.4 keV and 1.55 keV, respectively, for the cooler and hotter plasmas.

wide range of energy was measured by the ISEE-3 solar x-ray spectrometer. Designed to observe the sun, the spectrometer viewed the entire ecliptic plane. Furthermore, because the spectrometer was sensitive to photons with energies from 20 to 2000 keV, it provided one of the most definitive measurements by a single instrument of the spectral characteristics of a gamma-ray burst.

To compare the November 4, 1978 burst with a Comptonized blackbody, the Compton cross section of a photon traveling into a very hot plasma was first calculated (including relativistic effects in the angular dependency of the cross section). A three-dimensional Monte Carlo computer program was then developed to track the photons from initial creation until they escaped from the hot plasma. Three free parameters (the temperature and density of the Comptonizing region and the source blackbody temperature) were varied within the program until the resulting spectrum best fit the observed data for the November 4, 1978 burst. Figure 9 shows the results. The short dashed curve is the spectral shape of the underlying, cooler plasma. The solid line is the spectral shape of the photons emerging from the overlying hotter plasma. The data points on the solid curve are for the burst as obtained from ISEE-3. For comparison the best-tit thermal bremsstrahlung spectrum (long dashed curve) is also shown, but it is clear that the Comptonized blackbody model provides a much better tit.

Other observations provide additional evidence that this may be the mechanism responsible for the spectra. One burst, seen on March 29, 1979, appeared spectrally as if the overlying plasma had apparently become temporarily transparent, revealing the underlying blackbody. In the November 19, 1978 burst, the overlying plasma apparently was initially so dense that the photons equilibrated to the temperature of the hotter plasma, producing a distinctive spectral shape known as a Wien peak.

Although the ability of the Comptonized blackbody mechanism to explain both unusual (the March 29, 1979 and November 19. 1978 events) and normal spectra is strong evidence in its favor, the model also has some problems. It predicts that all of the energy can be removed from the hotter plasma in a microsecond, thus necessitating a complex replenishment process. In addition. the model is only compatible with a magnetic field less than 10^9 gauss whereas there was a growing consensus that the bursts occurred on *highly* magnetized neutron stars.

CYCLOTRON RADIATION. There are two reasons why gamma-ray bursts are thought to be associated with very large magnetic fields. First. the plasma is certainly very hot, so hot that it is difficult to see how it could be held even briefly at the neutron star unless it was confined by a strong magnetic field.

Cyclotron Absorption

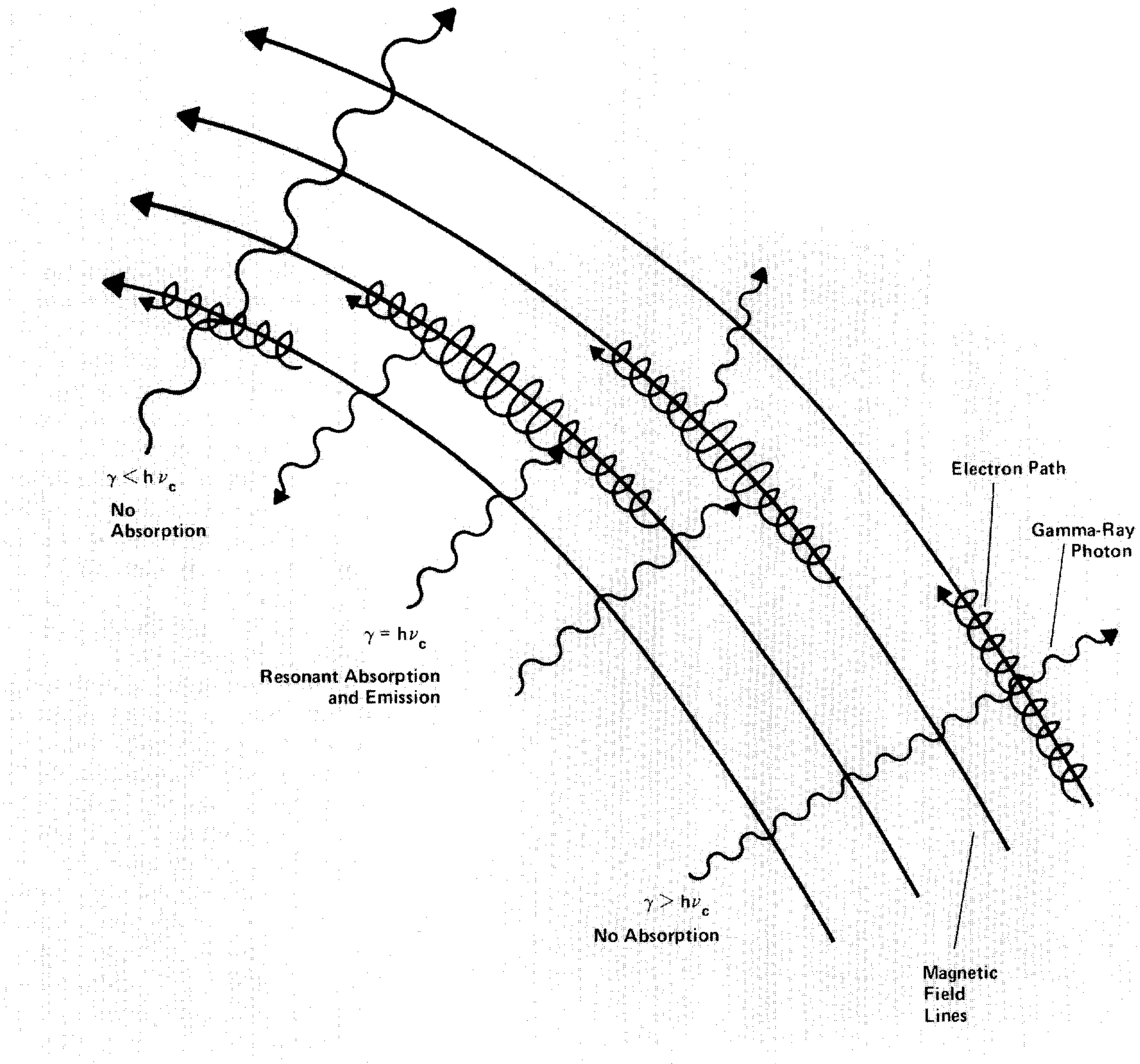


Fig. 10. Cyclotron process. Electrons moving in a strong magnetic field will spiral around the field lines. Here, the interactions of the gamma -ray photons with these electrons are represented schematically. Photons with energies greater or less than $h\nu_c$ ***the quantized transition energy of cyclotron absorption, will not be absorbed. Photons with energy equal to*** $h\nu_c$ ***can be absorbed by increasing the energy of the electron (depicted as a larger helical path). Eventually the electron will return to the unexcited state, emitting a photon with an energy of*** $h\nu_c$***. If the electrons are excited to many different orbits by collisional processes, the result of many subsequent deexcitations can, perhaps, produce the observed continuum.***

Second, the absorption features seen by KONUS near SO keV in some gamma-ray bursts are thought to be the result of an interaction between photons and electrons moving in a strong magnetic field. The magnetic force on a moving electron causes it to describe a helical path about the field lines (Fig. 10). The electron energy is quantized and must satisfy the relation

$$E_n = nh\nu_c = nh(eB/2\pi mc) \ ,$$

where n is an integer, h is Planck's constant. ν_c is the cyclotron frequency, e and m are, respectively, the charge and relativistic mass of the electron, B *is* the magnetic field, arid c is the speed of light. To change from one energy to another, the electron must either emit or absorb a photon with an energy of $\Delta E = (n_2 - n_1)h\nu_c$. The fundamental cyclotron radiation absorption feature should occur at photon energies equal to $h\nu_c$ (that is, $n_2 - n_1 = 1$). Knowledge of such a feature can be used to calculate the magnetic field ($B = 2\pi mc\nu_c/e$). In this way the absorption line, measured by the KONUS experiment at $h\nu_c =$ 50 keV, gives a magnetic field of about 5 x 10^{12} gauss, a reasonable value for a neutron star.

Unfortunately, there are problems with the above explanation. The plasma is so hot that there is sufficient energy for the electrons to undergo larger energy changes ($n_2 - n_1 =$ 2, 3, 4, ...) and one would expect to see cyclotron absorption lines at multiples of 50 keV as well. Such lines are not observed. Also, using data from the ISEE-3 satellite to check the KONUS result, it was found possible to produce a spurious indication of lines if either the instrument calibration was improperly defined or if one was incorrect in assuming thermal bremsstrahlung for the continuum shape.

Even though the cyclotron absorption lines could be spurious, many models require a strong magnetic field to confine the plasma. In such models, a smooth continuum could feasibly be made up of many broadened cyclotron lines. It remains to be seen if the observed continuum can be generated by this mechanism if reasonable parameters are assumed.

Summary

Much has been learned since the initial search to assure that natural phenomena would not affect test-ban treaty verification, Contrary to expectations, gamma-ray bursts were discovered, giving the first illustration of a violent aspect of the universe. This revelation inspired efforts that led to better characterization of gamma-ray bursts as well as discoveries of similar transients at x-ray and optical wavelengths. A decade of study has provided strong evidence that the bursts occur on neutron stars. Although this much has been learned, there is yet no clear picture of the physical process that releases the tremendous energy and produces the remarkable spectra. Greater insight will surely be achieved through further study of the data from existing instrumentation. There is little doubt that a full understanding of this enigmatic phenomenon will hinge upon future developments in space technology. ■

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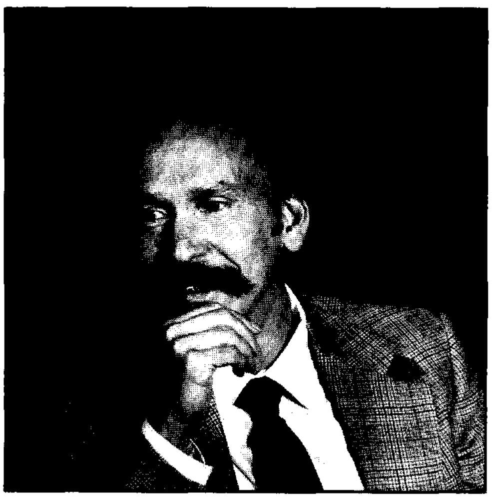
AUTHORS

Ray W. Klebesadel earned his Bachelor of Arts in electrical engineering from the University of Wisconsin in 1959. However, a part-time job sorting nuts and bolts in their Physics Department had led to a research assistantship coordinating the installation of the tandem Van de Graaff accelerator. In this latter capacity he was responsible to Professor H. H. Barschall, who is well known to the veterans of the Manhattan Project. Dr. Barschall recommended Los Alamos, feeling the environment to be in tune with Ray's expressed working and living preferences. In 1960, soon after receiving his Master of Science in physics from Wisconsin, Ray joined the Laboratory and the deep-space nuclear-test surveillance project and embarked on the astrophysical research for which this year he received the Laboratory's Distinguished Performance Award.

W. Doyle Evans joined the Laboratory's Space Sciences Group in 1961 with a Bachelor of Science in physics from Louisiana Tech University (1956) and a Master of Science in physics from the University of California, Los Angeles (1958). Previously he had taught at Louisiana Tech University for two years and had spent one year with NASA's Langley Research Center. At Los Alamos he developed rocket and satellite instrumentation for the 1962 high-altitude nuclear tests and x-ray instruments for the Vela satellite program. As a member of the Laboratory's Advanced Study Program he received his Ph.D. in physics from the University of New Mexico in 1966. His primary research interest is x- and gamma-ray astronomy, particularly high-energy transient sources, and he has helped design several satellite and rocket instruments for collecting data from such sources. He was principal investigator for the gamma-ray burst experiment on the NASA satellite that has been orbiting Venus since 1978. Currently. he is Deputy Division Leader of the Earth and Space Sciences Division.

Edward E. Fenimore received his B. S. in physics from Rensselaer Polytechnic Institute in 1970 and his M.S. from the University of Chicago in 1972. He came to Los Alamos in 1974 to work on a doctoral thesis concerning the ionization balance of the solar wind and its relationship to solar conditions. He became a Staff Member in 1978, and in 1980 he received his Ph.D. in astronomy and astrophysics from the University of Chicago. Besides solar-wind physics, his specialties include x-ray instrumentation and x- and gamma-ray astronomy. He has received five patents and a Distinguished Performance Award from the Laboratory for his development of "uniformly redundant array" x-ray cameras and advanced x-ray collimators. Recently he has been studying the mathematical properties of certain binary transformations and emission mechanisms of gamma-ray bursts. He is a member of the Optical Society of America. the American Geophysical Union, and the High Energy Astrophysical Division of the American Astronomical Society.

AUTHORS



John G. Laros became interested in astronomy as early as 1950 but fifteen years of doing mundane work elapsed before be found a way to “break into” the field, At that time he was able to join an astrophysics group at the University of California, San Diego that specialized in x- and gamma-ray astronomy. He remained there for eight years, receiving a Ph.D. in 1973 and holding a postdoctoral position until joining the Laboratory as a staff member in 1974. He has continued his work in x-ray and gamma-ray astronomy, with emphasis on the study of gamma-ray bursts, up to the present. When asked if he became discouraged at any time during his fifteen-year “wait” for his first astrophysics job, Laros replied, “Not really. You see in 1950 I was in the second grade!”

James Terrell, born in Houston, became an Assistant Professor of Physics at Western Reserve University after receiving a Ph.D. from Rice University in 1950, He has used his scientific skills in physics on a variety of problems since joining the Laboratory in 1951. His early work included studies of fission neutrons and relativity. In 1959 he discovered what was then a startling consequence of special relativity—the invisibility of the Lorentz contraction. The 1963 discovery of the obviously highly relativistic quasars caught his interest, and be has since published a series of papers on the time dependence of quasar brightness and on the possible ejection of quasars from the nucleus of our own galaxy. In the 1970s his work also included analyses of the rapid fluctuations of x rays from such objects as Cygnus X-1, the black-hole candidate, and solving optical and diffraction problems of high-power lasers. In 1977 he joined the effort to analyze and model the x- and gamma-ray data collected by various satellites.