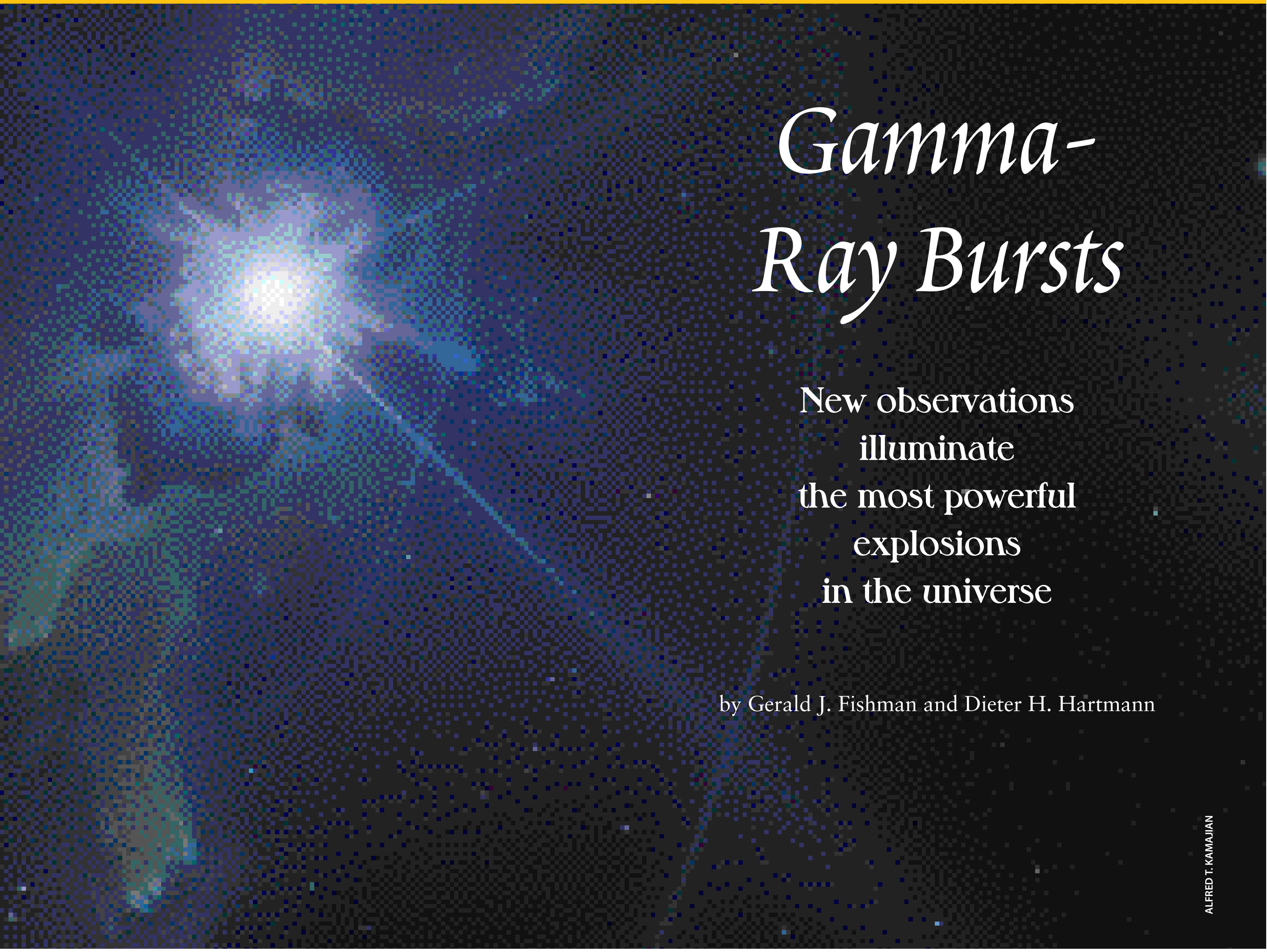


Gamma-Ray Bursts

New observations illuminate the most powerful explosions in the universe

by Gerald J. Fishman and Dieter H. Hartmann

ALFRED T. KAMAJIAN

About three times a day our sky flashes with a powerful pulse of gamma rays, invisible to human eyes but not to astronomers' instruments. The sources of this intense radiation are likely to be emitting, within the span of seconds or minutes, more energy than the sun will in its entire 10 billion years of life. Where these bursts originate, and how they come to have such incredible energies, is a mystery that scientists have been attacking for three decades. The phenomenon has resisted study—the flashes come from random directions in space and vanish without trace—until very recently.

On February 28, 1997, we were lucky. One such burst hit the Italian-Dutch Beppo-SAX satellite for about 80 seconds. Its gamma-ray monitor established the position of the burst—prosaically labeled GRB 970228—to within a few arc minutes in the Orion constellation, about halfway between the stars Alpha Tauri and Gamma Orionis. Within eight hours, operators in Rome had turned the spacecraft around to look in the same region with an x-ray telescope. They found a source of x-rays (radiation of somewhat lower frequency than gamma rays) that was fading fast, and they fixed its location to within an arc minute.

Never before has a burst been pinpointed so accurately and so quickly, allowing powerful optical telescopes, which have narrow fields of view of a few arc minutes, to look for it. Astronomers on the Canary Islands, part of an international team led by Jan van Paradijs of the University of Amsterdam and the University of Alabama in Huntsville, learned of the finding by electronic mail. They had some time available on the 4.2-meter William Herschel Telescope, which they had been using to study the locations of other bursts. They took a picture of the area 21 hours after GRB 970228. Eight days later they looked again and found that a spot of light seen in the earlier photograph had disappeared.

On March 13 the New Technology Telescope in La Silla, Chile, took a long, close look at those coordinates and discerned a diffuse, uneven glow. The Hubble Space Telescope later resolved it to be a bright point surrounded by a somewhat elongated background object. In a few days the Hubble reexamined the position and still found the point—now very faint—as well as the fuzzy glow, unaltered. Many of us believe the latter to be a galaxy, but its true identity remains unknown.

Even better, on the night of May 8, Beppo-SAX operators located a 15-second burst, designated GRB 970508. Soon after, Howard E. Bond of the Space Telescope Science Institute in Baltimore photographed the region with the 0.9-meter optical telescope on Kitt Peak in Arizona; the next night a point of light in the field had actually brightened. Other telescopes confirm that after becoming most brilliant on May 10, the source began to fade. This is the first time that a burst has been observed reaching its optical peak—which, astonishingly, lagged its gamma-ray peak by a few days.

Also for the first time, on May 13 Dale Frail, using the Very Large Array of radio telescopes in New Mexico, detected radio emissions from the burst remnant. Even more exciting, the primarily blue spectrum of this burst, taken on May 11 with the Keck II telescope on Hawaii, showed a few dark lines, apparently caused by iron and magnesium in an intervening cloud. Astronomers at the California Institute of Technology find that the displacement of these absorption lines indicates a distance of more than seven billion light-years. If this interpretation holds up, it will establish that bursts occur at cosmological distances. In that case, gamma-ray bursts must represent the most powerful explosions in the universe.

Confounding Expectations

For those of us studying gamma-ray bursts, this discovery salves two recent wounds. In November 1996 the Pegasus XL launch vehicle failed to release the High Energy Transient Explorer (HETE) spacecraft equipped with very accurate instruments for locating gamma-ray bursts. And in December the Russian Mars '96 spacecraft, with several gamma-ray detectors, fell into the Pacific Ocean after a rocket malfunction. These payloads were part of a set designed to launch an attack on the origins of gamma-ray bursts. Of the newer satellites equipped with gamma-ray instruments, only BeppoSAX—whose principal scientists include Luigi Piro, Enrico Costa and John Heise—made it into space, on April 20, 1996.

Gamma-ray bursts were first discovered by accident, in the late 1960s, by the Vela series of spacecraft of the U.S. Department of Defense. These satellites were designed to ferret out the U.S.S.R.'s clandestine nuclear detonations in outer space—perhaps hidden behind the moon. Instead they came across spasms of radiation that did not originate from near Earth. In 1973 scientists concluded that a new astronomical phenomenon had been discovered.

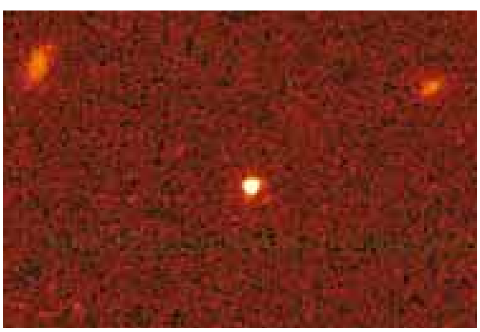
These initial observations resulted in a flurry of speculation about the origins of gamma-ray bursts—involving black holes, supernovae or the dense, dark star remnants called neutron stars. There were, and still are, some critical unknowns. No one knew whether the bursts were coming from a mere 100 light-years away or a few billion. As a result, the energy of the original events could only be guessed at.

By the mid-1980s the consensus was that the bursts originated on nearby neutron stars in our galaxy. In particular, theorists were intrigued by dark lines in the spectra (component wavelengths spread out, as light is by a prism) of some bursts, which suggested the presence of intense magnetic fields. The gamma rays, they postulated, are emitted by electrons accelerated to relativistic speeds when magnetic-field lines from a neutron star reconnect. A similar phenomenon on the sun—but at far lower energies—leads to flares.

In April 1991 the space shuttle *Atlantis* launched the Compton Gamma Ray Observatory, a satellite that carried the Burst And Transient Source Experiment (BATSE). Within a year BATSE had confounded all expectations. The distribution of gamma-ray bursts did not trace out the Milky Way, nor were the bursts associated with nearby galaxies or clusters of galaxies. Instead they were distributed isotropically, with any direction in the sky having roughly the same number. Theorists soon refined the galactic model: the bursts were now said to come from neutron stars in an extended spherical halo surrounding the galaxy.

One problem with this scenario is that Earth lies in the suburbs of the Milky Way, about 25,000 light-years from the core. For us to find ourselves near the center of a galactic halo, the latter must be truly enormous, almost 800,000 light-years in outer radius. If so, the halo of the neighboring Andromeda galaxy should be as extended and should start to appear in the distribution of gamma-ray bursts. But it does not.

This uniformity, combined with the data from GRB 970508, has convinced most astrophysicists that the bursts come from cosmological distances, on the order of three billion to 10 billion light-years away. At such a distance, though, the bursts



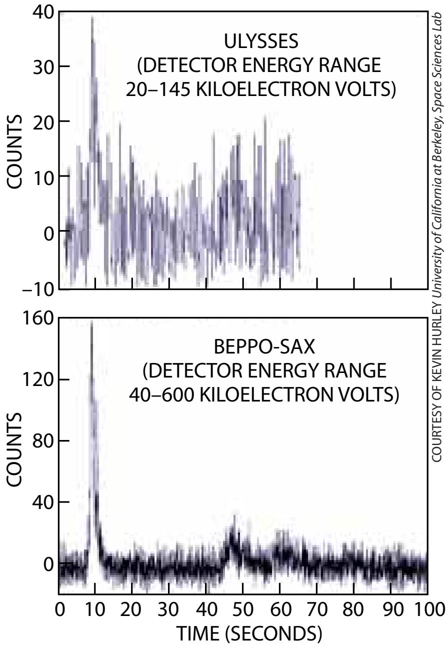
HUBBLE SPACE TELESCOPE

ROGER RESSMEYER *Corbis*

VERY LARGE ARRAY of radio telescopes (*right*) discovered radio waves from a burst (GRB 970508) for the first time in May 1997. The burst (*above, at center*) had a cosmological origin but showed no underlying galaxy, confounding theorists.

should show the effects of the expansion of the universe. Galaxies that are very distant are moving away from Earth at great speeds; we know this because the light they emit shifts to lower, or redder, frequencies. Likewise, gamma-ray bursts should also show a "redshift," as well as an increase in duration.

Unfortunately, BATSE does not see, in the spectrum of gamma rays, bright or dark lines characterizing specific elements whose displacements would betray a shift to the red. (Nor does it detect the dark lines found by earlier satellites.) In April astronomers using the Keck II telescope in Hawaii obtained an optical spectrum of the afterglow of GRB 970228—smooth and red, with no telltale lines. Still, Jay Norris of the National Aeronautics and Space Administration Goddard Space Flight Center and Robert Mallozzi of the University of Alabama in Huntsville have statistically analyzed the observed bursts and report that the weakest, and therefore the most distant, show both a time dilation and a redshift. And the dark lines in the spectrum of GRB 970508 are substantially shifted to the red.



TIME PROFILE of GRB 970228 taken by the Ulysses spacecraft (*top*) and by Beppo-SAX (*bottom*) shows a brief, brilliant flash of gamma rays.

A Cosmic Catastrophe

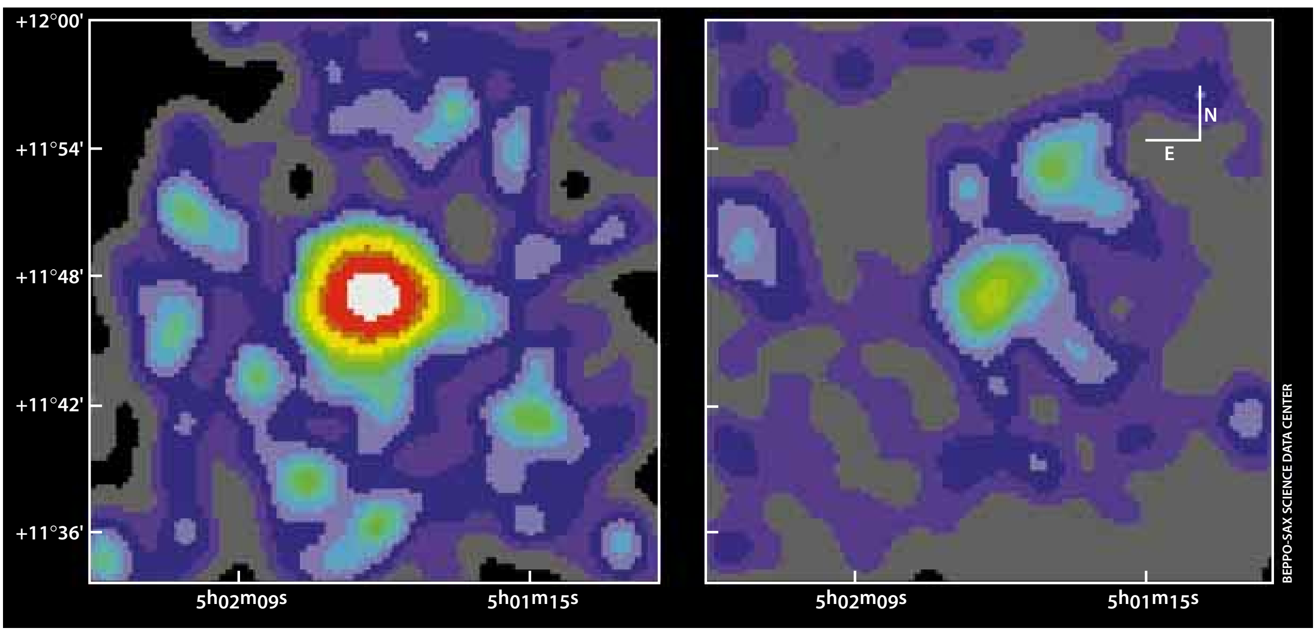
One feature that makes it difficult to explain the bursts is their great variety. A burst may last from about 30 milliseconds to almost 1,000 seconds—and in one case, 1.6 hours. Some bursts show spasms of intense radiation, with no detectable emission in between, whereas others are smooth. Also complicated are the spectra—essentially, the colors of the radiation, invisible though they are. The bulk of a burst's energy is in radiation of between 100,000 and one million electron volts, implying an exceedingly hot source. (The photons of optical light, the primary radiation from the sun, have energies of a few electron volts.) Some bursts evolve smoothly to lower frequencies such as x-rays as time passes. Although this x-ray tail has less energy, it contains many photons.

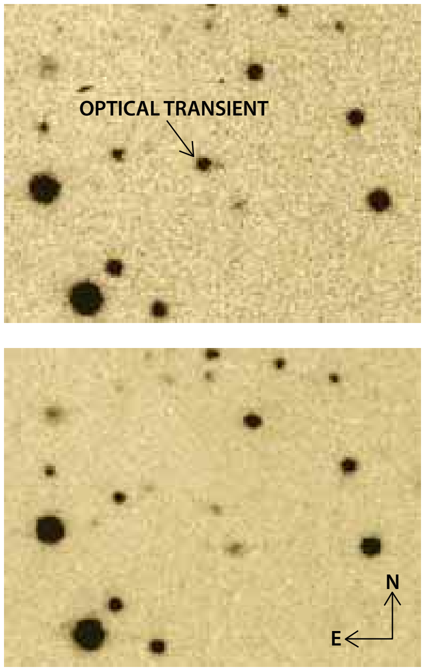
If originating at cosmological distances, the bursts must have energies of perhaps 10^{52} ergs. (About 1,000 ergs can lift a gram by one centimeter.) This energy must be emitted within seconds or less from a tiny region of space, a few tens of kilometers across. It would seem we are dealing with a fireball.

The first challenge is to conceive of circumstances that would create a sufficiently energetic fireball. Most theorists favor a scenario in which a binary neutron-star system collapses [see "Binary Neutron Stars," by Tsvi Piran; Scientific American, May 1995]. Such a pair gives off gravitational energy in the form of radiation. Consequently, the stars spiral in toward each other and may ultimately merge to form a black hole. Theoretical models estimate that one such event occurs every 10,000 to one million years in a galaxy. There are about 10 billion galaxies in the volume of space that BATSE observes; that yields up to 1,000 bursts a year in the sky, a number that fits the observations.

Variations on this scenario involve a neutron star, an ordinary star or a white dwarf colliding with a black hole. The details of such mergers are a focus of intense study. Nevertheless, theorists agree that before two neutron stars,

X-RAY IMAGE taken by Beppo-SAX on February 28, 1997 (*left image*), localized GRB 970228 to within a few arc minutes, allowing ground-based telescopes to search for it. On March 3 the source was much fainter (*right image*).





OPTICAL IMAGES of the region of GRB 970228 were taken by the William Herschel Telescope on the Canary Islands, on February 28 (*top*) and March 8 (*bottom*). A point of light in the first image has faded away in the second one, indicating a transient afterglow.

PAUL GROOT, TITUS GALAMA AND JAN VAN PARADIS *University of Amsterdam*

say, collapse into a black hole, their death throes release as much as 10^{53} ergs. This energy emerges in the form of neutrinos and antineutrinos, which must somehow be converted into gamma rays. That requires a chain of events: neutrinos collide with antineutrinos to yield electrons and positrons, which then annihilate one another to yield photons. Unfortunately, this process is very inefficient, and recent simulations by Max Ruffert and Hans-Thomas Janka of the Max Planck Institute in Munich, as well as by other groups, suggest it may not yield enough photons.

Worse, if too many heavy particles such as protons are in the fireball, they reduce the energy of the gamma rays. Such proton pollution is to be expected, because the collision of two neutron stars must yield a potpourri of particles. But then all the energy ends up in the kinetic energy of the protons, leaving none for radiation. As a way out of this dilemma, Peter Mészáros of Pennsylvania State University and Martin J. Rees of the University of Cambridge have suggested that when the expanding fireball—essentially hot protons—hits surrounding gases, it produces a shock wave. Electrons accelerated by the intense electromagnetic fields in this wave then emit gamma rays.

A variation of this scenario involves internal shocks, which occur when different parts of the fireball hit one another at relativistic speeds, also generating gamma rays. Both the shock models imply that gamma-ray bursts should be followed by long afterglows of x-rays and visible light. In particular, Mario Vietri of the Astronomical Observatory of Rome has predicted detectable x-ray afterglows lasting for a month—and also noted that such afterglows do not occur in halo models. GRB 970228 provides the strongest evidence yet for such a tail.

There are other ways of generating the required gamma rays. Nir Shaviv and Arnon Dar of the Israel Institute of Technology in Haifa start with a fireball of unknown origin that is rich in heavy metals. Hot ions of iron or nickel could then interact with radiation from nearby stars to give off gamma rays. Simulations show that the time profiles of the resulting bursts are quite close to observations, but a fireball consisting entirely of heavy metals seems unrealistic.

Another popular mechanism invokes immensely powerful magnetic engines, similar to the dynamos that churn in the cores of galaxies. Theorists envision that instead of a fireball, a merger of two stars—of whatever kind—could yield a black hole surrounded by a thick, rotating disk of debris. Such a disk would be very short-lived, but the magnetic fields inside it would be astounding, some 10^{15} times those on Earth. Much as an ordinary dynamo does, the fields would extract rotational energy from the system, channeling it into two jets bursting out along the rotation axis.

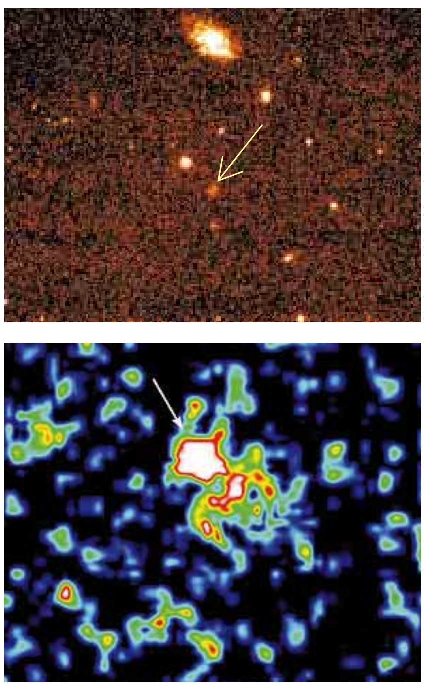
The cores of these jets—the regions closest to the axis—would be free of proton pollution. Relativistic electrons inside them can then generate an intense, focused pulse of gamma rays. Although quite a few of the details remain to be worked out, many such scenarios ensure that mergers are the leading contenders for explaining bursts.

Still, gamma-ray bursts have been the subject of more than 3,000 papers—about one publication per recorded burst. Their transience has made them difficult to observe with a variety of instruments, and the resulting paucity of data has allowed for a proliferation of theories.

If one of the satellites detects a lensed burst, astronomers would have further confirmation that bursts occur at cosmological distances. Such an event might occur if an intervening galaxy or other massive object serves as a gravitational lens to bend the rays from a burst toward Earth. When optical light from a distant star is focused in this manner, it appears as multiple images of the original star, arranged in arcs around the lens. Gamma rays cannot be pinpointed with such accuracy; instead they are currently detected by instruments that have poor directional resolution.

Moreover, bursts are not steady sources like stars. A lensed gamma-ray burst would therefore show up as two bursts coming from roughly the same direction, having identical spectra and time profiles but different intensities and arrival times. The time difference would come from the rays' traversing curved paths of different lengths through the lens.

To further nail down the origins of the underlying explosion, we need data on other kinds of radiation that might



SPACE TELESCOPE SCIENCE INSTITUTE

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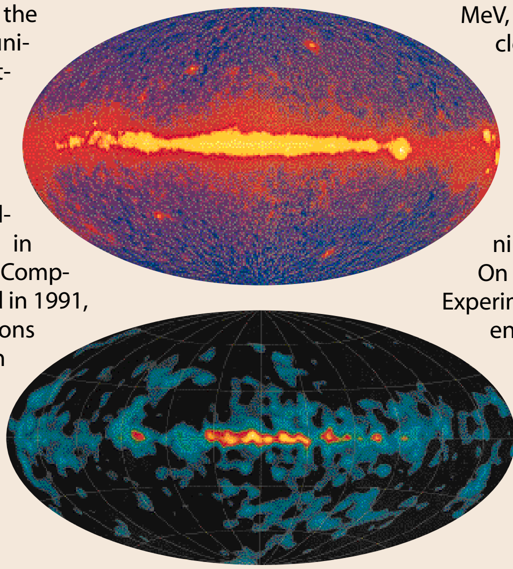
OPTICAL REMNANT of GRB 970228 was pictured by the Hubble Space Telescope. The afterglow (*near center of top image*), when seen in close-up (*bottom*), has a faint, elongated background glow that may correspond to a galaxy in which the burst occurred.

The Gamma-Ray Sky

Gamma-ray astronomy elucidates the structure and evolution of the universe by means of the photons of greatest energy. Because gamma rays are absorbed by the atmosphere of Earth and, moreover, are hard to detect, their study poses a challenge to technology.

Early detectors were flown on balloons. Nowadays instruments based in space survey the sky for these rays. The Compton Gamma Ray Observatory, launched in 1991, uses complex detectors to catch photons in the energy range of 10 kilo electron volts to 30 giga electron volts (GeV). Future instruments, such as the Gamma-ray Large Area Space Telescope (GLAST) planned for 2004, will survey the sky even more sensitively at higher energies of up to 300 GeV.



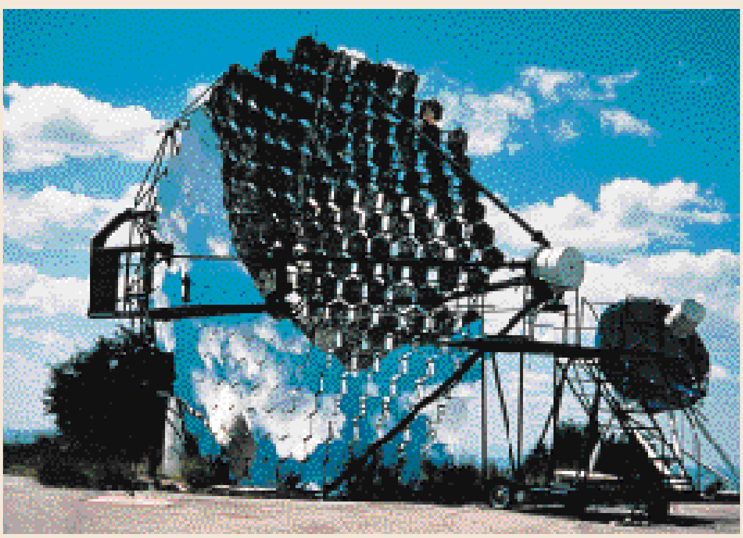
SKY MAP (*top*) in photons of more than 100 million electron volts (MeV) traces the fastest particles in the universe, glowing when they interact with interstellar matter and light.The isolated spots far from the Milky Way (*lateral line*) are blazars. The map in photons of a precise energy, 1.8 MeV (*bottom*), reveals the presence of aluminum 26 and therefore the distribution of past supernovae. It demonstrates that the synthesis of elements and their dispersion from supernovae is an ongoing process throughout the galaxy.

EGRET, COMPTON OBSERVATORY (*top*); R. DIEHL AND U. OBERLACK *Max Planck Institute for Extraterrestrial Physics* AND COMPTEL, COMPTON OBSERVATORY (*bottom*)

When a photon's energy becomes large enough, it creates an avalanche of particles on penetrating the atmosphere. These particles then emit optical light that can be detected on the ground by large mirrored collectors such as Whipple in Arizona. Whipple currently detects particles of energy 300 GeV or higher. If it is upgraded, as planned, to VERITAS (Very Energetic Radiation Imaging Telescope Array System), the array will detect particles of energy as low as 100 GeV, closing the gap with the satellite data.

Gamma rays are emitted by the most violent explosions in the universe. As a result, they allow astronomers to study essential processes such as the production of elements in the universe. Heavy elements created within stars are dispersed by supernovae explosions; new stars and planets are then born from the chemically enriched gas, ultimately incorporating the new substances into emerging life.

One of the nuclei thus produced and ejected is aluminum 26, which decays in about a million years by emitting a photon of 1.8 million eV (MeV). Two instruments on the Compton observatory map the sky in this line, thereby providing an image of the past supernovae activity in the Milky Way. Tens of thousands of supernovae (occurring at a rate of one per century) contribute to a diffuse glow at 1.8 MeV, providing testimony to the amazing cycle of stellar birth and death as an ongoing process. The INTEGRAL (International Gamma Ray Astrophysics Laboratory) satellite, to be launched early in the next century, will continue the quest for gamma-ray maps of special spectral lines, such as aluminum 26 and titanium 44.



WHIPPLE OBSERVATORY

WHIPPLE OBSERVATORY on Mount Hopkins in Arizona surveys the sky in gamma rays. An energetic gamma-ray photon penetrating the atmosphere releases a shower of optical photons that the 10-meter reflector detects.

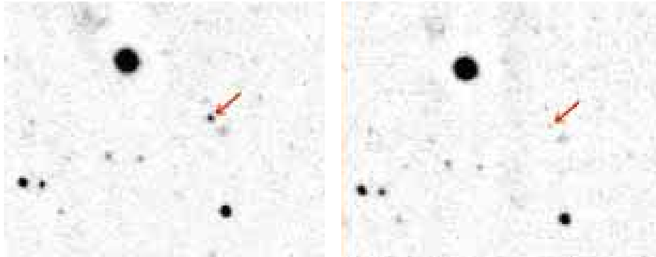
On Compton, EGRET (Energetic Gamma Ray Experiment Telescope) has mapped the sky at energies above 100 MeV, finding a bright and diffuse glow concentrated along the galactic midplane. The radiation is emitted by fast particles—from supernovae explosions—as they slam into the molecular gas between the stars. Apart from tracing such remnants of violent processes, the EGRET image also shows pointlike sources. Some of these, close to the plane of the galaxy, are pulsars, stable cores left in the wake of supernovae.

These dense, compact objects often have extremely strong magnetic fields—a trillion times that of Earth—and rotate very rapidly, with periods of milliseconds. The magnetized atmospheres of some such "dead stars" emit strongly beamed gamma rays. But if the rays miss the detectors, astronomers may never notice the star even if it is nearby. Although radio astronomers have found about 1,000 pulsars, gamma-ray astronomers have detected only half a dozen. Even so, these gamma-ray pulsars have taught us a great deal about the behavior of matter under extreme conditions. One example is the process by which electrons emit radiation when in magnetic fields too high to be created on Earth.

Yet another kind of point source of gamma rays is a blazar. Blazars are active galaxies in whose centers lie black holes as massive as a billion suns. The gas and stars the black hole draws in emit a beam of gamma rays. These rays allow us to probe the conditions of matter near a black hole and the ways in which it spirals inward.

And then, of course, there are the gamma-ray bursters, perhaps the most mysterious of all.

—G.J.F. and D.H.H.



ASTROPHYSICAL RESEARCH CONSORTIUM

OPTICAL TRANSIENT for a third burst, GRB 971214, provided a New Year's gift to astronomers. The images were taken at the Apache Point Observatory in Sunspot, N.M., on December 15 (*left*) and 16 (*right*).

accompany a burst. Even better would be to identify the source. Until the observation of GRB 970228 such "counterparts" had proved exceedingly elusive. To find others, we must locate the bursts very precisely.

Since the early 1970s, Kevin Hurley of the University of California at Berkeley and Thomas Cline of the NASA Goddard Space Flight Center have worked to establish "interplanetary networks" of burst instruments. They try to put a gamma-ray detector on any spacecraft available or to send aloft dedicated devices. The motive is to derive a location to within arc minutes, by comparing the times at which a burst arrives at spacecraft separated by large distances.

From year to year, the network varies greatly in efficacy, depending on the number of participating instruments and their separation. At present, there are five components: BATSE, Beppo-SAX and the military satellite DMSP, all near Earth; Ulysses, far above the plane of the solar system; and the spacecraft Wind, orbiting the sun. The data from Beppo-SAX, Ulysses and Wind were used to triangulate GRB 970228. (BATSE was in Earth's shadow at the time.) The process, unfortunately, is slow—eight hours at best.

Watching and Waiting

Time is of the essence if we are to direct diverse detectors at a burst while it is glowing. Scott Barthelmy of the Universities Space Research Association at the NASA Goddard Space Flight Center has developed a system called GCN (Gamma-ray burst Coordinate Network) to transmit within seconds BATSE data on burst locations to ground-based telescopes.

BATSE consists of eight gamma-ray detectors pointing in different directions from eight corners of the Compton satellite; comparing the intensity of a burst at these detectors provides its location to roughly a few degrees but within several seconds. Often GCN can locate the burst even while it is in progress. The location is transmitted over the Internet to several dozen sites worldwide. In five more seconds, robotically controlled telescopes at Lawrence Livermore National Laboratory, among others, slew to the location for a look.

Unfortunately, only the fast-moving, smaller telescopes, which would miss a faint image, can contribute to the effort. The Livermore devices, for instance, could not have seen the afterglow of GRB 970228. Telescopes that are 100 times more sensitive are required. These mid-size telescopes would also need to be robotically controlled so they can slew very fast, and they must be capable of searching reasonably large regions. If they do find a transient afterglow, they will determine its location rather well, allowing much larger telescopes such as Hubble and Keck to look for a counterpart.

The long-lasting, afterglow following GRB 970228 gives new hope for this strategy. The HETE mission, directed by George Ricker of the Massachusetts Institute of Technology, is to be rebuilt and launched in about two years. It will survey the sky with x-ray detectors that can localize bursts to within several arc minutes. Ground-based optical telescopes will receive these locations instantly and start searching for transients.

Of course, we do not know what fraction of bursts exhibit a detectable afterglow. Moreover, even a field as small as arc minutes contains too many faint objects to make a search for counterparts easy.

To further constrain the models, we will need to look at radiation of both higher and lower frequency than that currently observed. The Compton satellite has seen a handful of bursts that emit radiation of up to 10 billion electron volts. Better data in this regime, from the Gamma-ray Large Area Space Telescope (GLAST), a satellite being developed by an international team of scientists, will greatly aid theorists. Photons of even higher energy—of about a trillion electron volts—might be captured by special ground-based gamma-ray telescopes. At the other end of the spectrum, soft x-rays, which have energies of up to roughly one kilo electron volt (keV), can help test models of bursts and obtain better fixes on position. In the range of 0.1 to 10 keV, there is a good chance of discovering absorption or emission lines that would tell volumes about the underlying fireball.

When the Hubble telescope was pointed to the location of GRB 970508, it picked up the fading light from the optical transient. Much to our surprise, however, it saw no galaxy in the immediate vicinity—not even a hint of one [*see left illustration on page 69*]. This absence emphasizes a potential problem noted by Bradley E. Schaefer of Yale University: bursts do not occur in the kind of bright galaxies within which one would expect an abundance of stars. So whereas astrophysicists now have strong evidence of the cosmological distances of bursts, we are still confounded as to their host environments and physical origins.

Just in time for New Year's 1998, nature provided a third afterglow from a gamma-ray burst. Again, Beppo-SAX discovered the initial event, following which Jules P. Halpern of Columbia University and John R. Thorstensen of Dartmouth College used the 2.4-meter telescope on Kitt Peak to find an optical transient. The glow dimmed in a manner similar to that of the previous two transients. As this article goes to press, we wait for Hubble to discern if this burst, GRB 971214, has a bright underlying galaxy or not. SA

The Authors

GERALD J. FISHMAN and DIETER H. HARTMANN bring complementary skills to the study of gamma-ray bursts. Fishman is an experimenter—the principal investigator for BATSE and a senior astrophysicist at the National Aeronautics and Space Administration Marshall Space Flight Center in Huntsville, Ala. He has received the NASA Medal for Exceptional Scientific Achievement three times and in 1994 was awarded the Bruno Rossi Prize of the American Astronomical Society. Hartmann is a theoretical astrophysicist at Clemson University in South Carolina; he obtained his Ph.D. in 1989 from the University of California, Santa Cruz. Apart from gamma-ray astronomy, his primary interests are the chemical dynamics and evolution of galaxies and stars. This article updates a version that appeared in *Scientific American* in July 1997.