GAMMA RAY BURSTS

Cosmic Mystery Objects Start to Yield Secrets

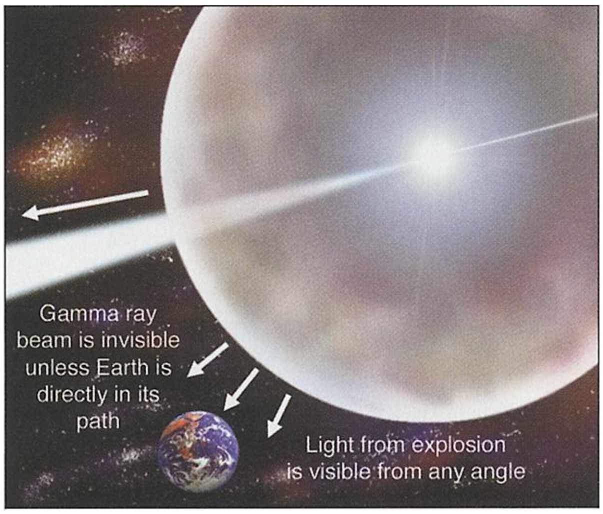
Powerful deep-space explosions remain a puzzle, but new data are giving important clues about their structure, origins, and numbers

Almost 5 years after astronomers first discovered their telltale afterglows, the brief, ultrabright flashes of high-energy radiation known as cosmic gamma ray bursts (GRBs) are still among the most mysterious phenomena in the universe. Most researchers agree that the most common GRBs—those that last between about a second and a minute—signal the catastrophic collapse of massive, rapidly rotating stars into black holes. The details of their origin, however, are unknown, and the nature of bursts that wink out in less than a second is anybody's guess (see bottom sidebar, p. 1817).

Nevertheless, astronomers have made enormous progress in understanding these events, the biggest explosions in the universe, and they hope that satellites such as NASA's High-Energy Transient Explorer 2 (HETE-2; see top sidebar, p. 1817) will help unravel the remaining mysteries. At a recent workshop,* researchers presented evidence that GRBs are surprisingly frequent—one pops off somewhere in the universe every single minute—and that the bursts may be closer kin to normal supernova explosions than scientists had assumed. Soon, experts hope, these bright beacons might be used to study the first generation of stars, the origin of the large-scale structure of the universe, the history of the cosmic star-formation rate, and the chemical evolution of the universe. "The promise of gamma ray bursts as cosmological probes is enormous," says Donald Lamb of the University of Chicago.

The first GRBs were serendipitously discovered by military satellites in the late 1960s. During the 1990s, NASA's Compton Gamma Ray Observatory detected some 400 bursts per year, but their precise sky positions, distances, and energy yields remained unknown until 1997. That year, the small Italian-Dutch satellite BeppoSAX discovered the first afterglows: the fading embers of the explosions, faintly glowing at x-ray and optical wavelengths, that last for weeks or months (*Science*, 23 May 1997, p. 1194).

Analysis of the radiation from the afterglows showed that GRBs occur in extremely remote galaxies. That presented a puzzle: If GRBs spew out high-energy gamma rays in all directions, the tiny fraction reaching Earth over such vast distances implied that they are producing more energy than any known natural mechanism could explain. Instead, astronomers had to assume that at least some GRBs concentrate their energy in two oppositely directed jets and become visible only when one jet happens to point toward Earth. Without knowing how tightly focused the jets are, however, they could not estimate the total energy output of a burst or what proportion of GRBs they could see.



Light touch. Astronomers hope to spot "orphan afterglows" of bursts whose gamma ray beams don't point toward Earth.

Now, a group of astronomers led by Dale Frail of the National Radio Astronomy Observatory in Socorro, New Mexico, has determined the strength of the so-called beaming effect. By carefully analyzing the fading of 17 afterglows at a variety of wavelengths, they deduced that most jets are just a few degrees wide. In that case, Frail and colleagues conclude in a paper accepted for publication in *Astrophysical Journal Letters*, a typical GRB gives off only slightly more energy than a regular supernova, the terminal explosion of a massive star. What's more, that total energy output appears to be remarkably similar for all GRBs—a result that raises the possibility that GRBs might serve as "standard candles" for astronomical measurements. According to team member Re'em Sari of the California Institute of Technology in Pasadena, the strong beaming effect also means that for every observed GRB, there must be some 500 unobserved bursts whose jets do not point in our direction. "If a gamma ray burst signals the birth of a black hole," Sari says, "this means a birthrate of one black hole per minute."

Most models imply that GRBs whose beams don't point at Earth still produce observable afterglows, because the afterglow radiation is emitted in all directions. Several searches for such "orphan afterglows" are under way. Already, astronomers at the Sloan Digital Sky Survey may have detected one on images obtained in March 1999 and May 2000. "I can't completely rule out that [this variable source] is a nearby dwarf nova," says Daniel Vanden Berk of the Fermi National Accelerator Laboratory in Batavia, Illinois, "but all non-afterglow explanations are really unlikely." Tomonori Totani of the National Astronomical Observatory of Japan is planning a search using a sensitive camera at Japan's 8.2-meter Subaru Telescope on Mauna Kea, Hawaii. With a field of view almost as large as the full moon—very wide for a big telescope like Subaru—Totani hopes the camera will catch an average of one orphan afterglow on six random exposures.

Other clues to the nature of GRBs may come from faint "fossil remnants" of the bursts that remain in the sky long after the afterglows have faded. Ralph Wijers of the State University of New York, Stony Brook, believes such fossil remnants may already have been found in the form of soft x-ray transients: binary systems in which gas from a low-mass star glows with x-rays as it falls into a companion black hole. Models show that in such a system, the black hole probably started out as a rapidly spinning massive star, just the sort of object needed to produce a GRB. If the soft x-ray transients that have been discovered in our Milky Way galaxy are indeed the descendants of GRBs, Wijers says, it may become possible to conduct detailed postmortems on GRBs. Such studies could reveal the mass of the black hole, the "kick velocity" the explosion imparted to it, and the changes in chemistry the exploding star wrought on its smaller companion.

Meanwhile, other astronomers are peering backward in time to study the oldest bursts of all. In the early universe, theorists believe, GRBs must have been much more common than they are today. Astrophysical models

* Gamma-Ray Burst and Afterglow Astronomy 2001, 5–9 November, Woods Hole, Massachusetts.

ILLUSTRATION: C. SLAYDEN

show that first-generation stars probably were very massive and contained almost no heavy elements—both properties that make them likely to collapse into black holes, triggering a GRB. Because the radiation takes time to reach Earth, the oldest GRBs are the most distant. By studying these luminous beacons, which can easily be observed over distances of billions of light-years, astronomers hope to learn how many stars were being born at different stages of the universe's history.

Some astronomers believe they have already spotted such ancient GRBs. John Heise of the Space Research Organization Netherlands in Utrecht thinks that the numerous x-ray flashes observed by BeppoSAX may be far-off bursts, their gamma ray emissions stretched into longer wavelength, lower energy x-rays by the expansion of the universe. The stretching would also make a burst appear to last longer. Indeed, the most recent x-ray flash, detected on 30 October, lasted over 8 minutes—the longest on record.

Unfortunately, the distance of the October x-ray flash is still unknown—a nagging information gap that also plagues the majority of GRBs. The reason, in the case of GRBs, is that gamma rays give no information about redshift, the change in an object's spectrum that astronomers use to measure distance. To find the redshift of a GRB, astronomers need to observe its afterglow in optical light. The first optical afterglow, however, was not discovered until 1997, and for many GRBs no afterglow has been found at all, possibly because cosmic dust blocks their light. Consequently, of the nearly 3000 GRBs detected in the past 30 years, fewer than 1% have known distances.

But help may be on the way. Some astronomers hope to calculate a burst's true luminosity from subtle properties of its gamma rays themselves: a slight difference in arrival time between high- and low-energy gamma photons of the burst, and the rate at which the burst flickers. Then, by comparing the true luminosity to the observed brightness of the gamma rays, they will be able to determine the distance to the source.

According to Bradley Schaefer of the University of Texas, Austin, the various provisional distance indicators agree fairly well. When they can be calibrated more precisely, he says, observations of luminosity and redshift may help astronomers deduce whether the expansion of the universe has sped up or slowed over time. "Astronomers who used distant supernovae [as cosmological probes] have made enormous progress in the past 10 years," Schaefer says. "We could do the same with gamma ray bursts. In the future, both techniques may be combined."

To make such visions a reality, astronomers will need a large sample of GRBs with known distances. Within a few years, a wealth of data should arrive from satellites such as NASA's Swift mission, an orbiting GRB observatory due to be launched in September 2003. By then, says HETE's principal investigator George Ricker of the Massachusetts Institute of Technology, HETE-2 is expected to have pinpointed the locations of some 35 GRBs, about a dozen of which are likely to show optical afterglows. Welcome information indeed—but probably not enough to solve the many mysteries that still surround these cosmic superbombs.

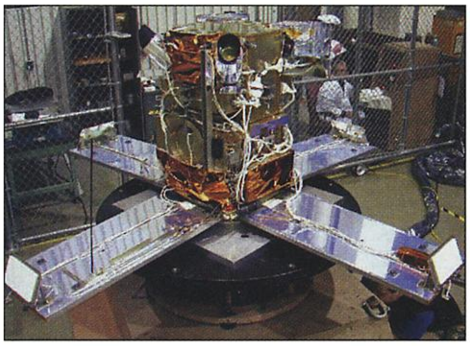
—GOVERT SCHILLING

Govert Schilling is an astronomy writer in Utrecht, the Netherlands. His book *Flash! The Hunt for the Biggest Explosions in the Universe* will be published by Cambridge University Press in March 2002.

HETE-2, in Business at Last

When NASA's High-Energy Transient Explorer 2 (HETE-2) went up on 9 October 2000, astronomers who hoped to search for optical afterglows eagerly awaited a stream of gamma ray burst localizations: precise sky positions, nailed down within seconds after a burst. But it took almost a year for the small satellite, an international project led by the Massachusetts Institute of Technology, to get down to business. The first "HETE afterglow" was found only last month.

"It took a long time, but we got there," says principal investigator George Ricker. According to Ricker, the main bottleneck was labor. "When NASA came up with additional money in May, most of our problems were solved," he says. But there were also technical hurdles to overcome. Optical filters on HETE-2's soft x-ray cameras—the instruments that provide the most precise sky positions—were destroyed by oxygen atoms in the uppermost layers of Earth's atmosphere, slashing the cameras' observational efficiency by 75%.



Survivor. After months of setbacks, the HETE-2 satellite is finally bagging GRBs.

"This has been our major technical problem," says HETE-2 team member Joel Villaseñor. In addition, new software had to be written and uploaded to solve a problem with the telemetry. Glitches arose in the tracking system. And there's still an occasional hiccup in the Burst Alert Network, 14 ground stations that disseminate burst localizations around the globe.

Colleagues are philosophical. "Low-cost missions are difficult," team member John Doty points out. But things are looking up, Ricker says: "Most of the problems are now fixed." —G.S.

Short-Lived Mysteries

Although most astrophysicists agree that "long" gamma ray bursts (GRBs), those lasting more than about a second, stem from the catastrophic collapse of rapidly rotating massive stars (see main text), the origin of short bursts remains in doubt. The bursts—which make up about one-third of all observed GRBs—differ markedly from long ones not only in duration but also in having a larger proportion of high-energy gamma rays in their energy distribution. Depending on which theorist you ask, they may result either from a special kind of stellar collapse, or from the merger of two compact neutron stars or of a neutron star and a black hole.

To test these theories, astronomers need to study x-ray or optical afterglows of short bursts. Unfortunately, the wide-field x-ray cameras (WFCs) on the Italian-Dutch BeppoSAX satellite have never detected x-rays from a short burst, although they should be able to do so in principle. Nor has NASA's High-Energy Transient Explorer 2 (HETE-2), advertised as the first spacecraft designed to locate short GRBs. WFC project scientist John Heise of the Space Research Organization Netherlands in Utrecht suspects that x-rays from short bursts are harder to detect than x-rays from longer bursts because their shorter duration makes them less likely to stand out from background noise. But George Ricker, HETE-2's principal investigator, thinks his satellite is up to the job. "We observe a larger part of the sky [than BeppoSAX], and our instruments have a better time resolution," he says. So far, though, no optical or x-ray afterglow has turned up for the one short GRB the satellite has spotted. —G.S.

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