Westford, Massachusetts. Like the Livermore group, his group hopes to perform closed-loop compensation using a sodium guide star. The goal is to investigate compensation for dimmer objects (most experiments so far have studied brighter stars in order to have better signal-to-noise ratios for testing the system), and in particular the ability to image dim objects close to bright objects. Then the group will move its 241-channel system to a 4-m-class astronomical telescope. A principal astronomical goal will be to investigate whether these systems can be used to identify planets and planetary systems forming around other stars.

In work outside the US, the European Southern Observatory, together with industrial and scientific partners in France, has had a steadily advancing natural-guide-star adaptive optics development program since 1986. In October 1989 diffraction-limit resolution images at 2200 nm were obtained with the COME-ON system at a 1.5-m telescope at the Observatoire de Haute Provence in France. Since April 1990 the system has been used regularly at the ESO's 3.6-m telescope at La Silla in Chile.

While a laser guide-star system is not yet included in the ESO budget and formal plans, a development program has begun. Prototype tests could begin in two to three years on a 3.6-m telescope at La Silla, followed by a one-beacon system and finally a four-beacon system on one of the 8-m telescopes of the Very Large Telescope facility—most probably using the sodium layer. "The whole activity has reached a higher level of priority now that the declassified results have demonstrated feasibility," says Fritz Merkle of the ESO.

In unclassified research in the US, Laird Thompson and Gardner[5] produced their own sodium beacon in January 1987 on Mauna Kea, but their laser was not sufficiently focused to allow wavefront measurements. After a two-year hiatus in funding Thompson began to produce Rayleigh beacons in 1990, and he was working toward wavefront measurements when the DOD research was declassified.

Edward Kibblewhite of the University of Chicago produced focused continuous-wave sodium-light beacons in June 1991. His group is building a system to be used with a sodium laser and a 3.5-m telescope run at Apache Point, New Mexico, by the Astrophysics Research Corporation—a consortium of universities. Kibblewhite's group anticipates having use for the next five years of a 69-actuator adaptive optics system that SDIO developed for an experiment involving the space shuttle but whose title is expected to be transferred to NSF.

Kibblewhite points out that compared with astronomical needs some of the military applications—for example, tracking a satellite—require much higher response speeds from components such as the deformable mirror. For astronomical observations, the coherence time of the atmosphere is essentially the coherence length divided by the wind speed—the speed at which a given patch of turbulence crosses the line of sight. For a target moving at orbital velocities in low Earth orbit the apparent velocity of the target is 10–100 times greater than the wind speed, and the adaptive optics system needs 10–100 times greater bandwidth. Kibblewhite believes great savings can be made by avoiding the technical problems of working at such speeds.

Primmerman comments that astronomers "really haven't faced up to the cost of these things. The astronomical community tends to view this still as instrumentation and they've pigeonholed it in that funding category. These systems will not be cheap, certainly not if we're talking about hundreds, perhaps thousands, of channels on an 8-m telescope. But given the cost of the telescope and the increase in resolution that's possible with these systems it seems to me they're cost effective."

For example, the 10-m Keck Telescope cost about $93 million, and the Hubble Space Telescope cost about $2 billion. Laird Thompson has estimated the cost of a multiple-Rayleigh-beacon system based on a 241-movable-actuator mirror manufactured by Itek to be $3.5 million. "If you put a mirror like that on a 2.5-m telescope you can correct optical wavelengths," he says. He calls the price extremely reasonable.

—GRAHAM P. COLLINS

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COMPTON OBSERVATORY DATA DEEPEN THE GAMMA RAY BURSTER MYSTERY

To monitor Soviet compliance with the nuclear test ban treaty of 1963, the US deployed the Vela series of military satellites, instrumented to detect sudden bursts of gammas. The surveillance satellites did indeed find dozens of gamma bursts, but by 1967 it was clear that these were not instances of Soviet cheating. They were coming from all directions of the sky above. The Vela satellites had inadvertently discovered a new class of celestial phenomena. Not until 1973 did the military allow this new discovery to be made public.

But now, after a quarter-century of ever more sophisticated observation, we still don't know what these "gamma-ray bursters" are. For all the astronomers know, the sources of these outbursts, which can last for milliseconds or minutes, may be as close as the outer reaches of our solar system or as distant as the quasars. Correspondingly, speculations about the energy released in a gamma burst range over 26 orders of magnitude. The very lively debate is reminiscent of the early 1920s, when astronomers argued hotly over whether the nebulae were local or extragalactic objects.

Over the years the directions of about 400 celestial gamma bursts have been recorded with some precision. There is almost never anything along the line of sight, at optical or any other wavelengths, that might be a steady-state counterpart; and there's no evidence of repeaters.

The Gamma Ray Observatory

The Compton Gamma Ray Observatory, deployed into Earth orbit from the shuttle Atlantis last April, began accumulating gamma-burst data with unprecedented sensitivity just two weeks after launch. Last month the group that operates the Burst and Transient Source Experiment aboard the GRO published its results on 153 gamma bursts recorded by BATSE through the end of October.[1] Most of these events were too faint to have been seen by any previous detector.

Ironically, these very impressive new data have, for the moment, contributed more to perplexity than to understanding. Before the first preliminary announcement of BATSE results last September, most of the experts were fairly confident that the gamma bursts were coming from neutron stars relatively nearby in the disk of our own Galaxy. The triggering event, they conjectured, might be a collision with an asteroid, a thermonuclear explosion of accreted material or a seismic adjstment of the neutron star's crust. The observed gamma fluxes were about right for such phenomena at such distances, and evidence of cyclotron-resonance structure in the energy spectra of some of the bursts suggested the enormous magnetic-field intensities characteristic of neutron stars. Furthermore, the millisecond rise times of gamma bursts tell us that their sources cannot be larger than a few hundred kilometers.

If the gamma bursters are indeed a local disk population of neutron stars, their angular distribution on the celestial sphere should have appeared quite isotropic, *so long as* our detectors were not sensitive enough to look much beyond a thousand light years—the local thickness of the Milky Way disk. And indeed that's what BATSE's predecessors had found: a fairly uniform angular distribution of bursters, with a burst-intensity distribution depleted at the low-intensty end in a way that suggested one was beginning to probe the outer limits of the population.

Thus all eyes were on NASA's powerful new GRO satellite last fall. The BATSE instrument, being more sensitive by an order of magnitude to weak bursts than any previous gamma-burst detector, would be able to look for neutron-star quakes and the like far beyond the upper and lower edges of the Galactic disk. Therefore the betting was that BATSE would see an angular distribution of bursters severely depleted in the directions perpendicular to the disk, especially for the weakest bursts.

BATSE's surprise

The figure on page 23 shows that anyone taking that bet would have made money. The angular distribution (in Galactic coordinates) of bursts seen by BATSE during 193 days last year shows no hint of the anticipated anistropy. Any source population concentrated in the disk or central bulge of the Milky Way would show a strong concentration on the Galactic equator or at the origin. There is none. Nor is there any enhancement in the direction of any other nearby galaxy or cluster of galaxies.

At the January meeting of the American Astronomical Society in Atlanta, Gerald Fishman (NASA Marshall Space Flight Center, Huntsville, Alabama), head of the BATSE group, updated the angular and intensity distributions to include all of the 210 gamma-ray bursters detected by 31 Decmber. "The angular distribution remains as isotropic as ever," he told his overflow audience.

If the placement of sources is not just isotropic with respect to the observer but also homogeneous and *unbounded* in three dimensions, Euclidean geometry tells us that dN/dL, the differential distribution of observed intensities L, should rise with decreasing intensity like $L^{-5/2}$. The old pre-BATSE data showed such a $^5/_2$-power distribution for the stronger bursts. But the intensity distribution at the weaker end rose more slowly, indicating a depleted population at large distances. The evidence for isotropy was statistically significant only for the $^5/_2$ population, which was presumed to be well inside the Galactic disk. It was expected that BATSE, by greatly enlarging the sample of weak bursters in the depleted region, would show them to have a pronounced concentration in the plane of the disk.

Because BATSE is so much more sensitive than the older burst detectors, most of the its events come from this low-intensity regime. The principal new piece of information that BATSE has delivered thus far is that the directional distribution of sources remains isotropic, even for the weak sources whose population is depleted relative to an $L^{-5/2}$ extrapolation from the distribution of stronger bursts. Presumably this means that the spherical symmetry of the source population, relative to us, is independent of distance. The range of intensities for all the gamma-ray bursts ever detected covers a factor of 10 000, from 10^{-3} erg/cm^2 down to 10^{-7} erg/cm^2. This suggests a range of distances covering a factor of about 100.

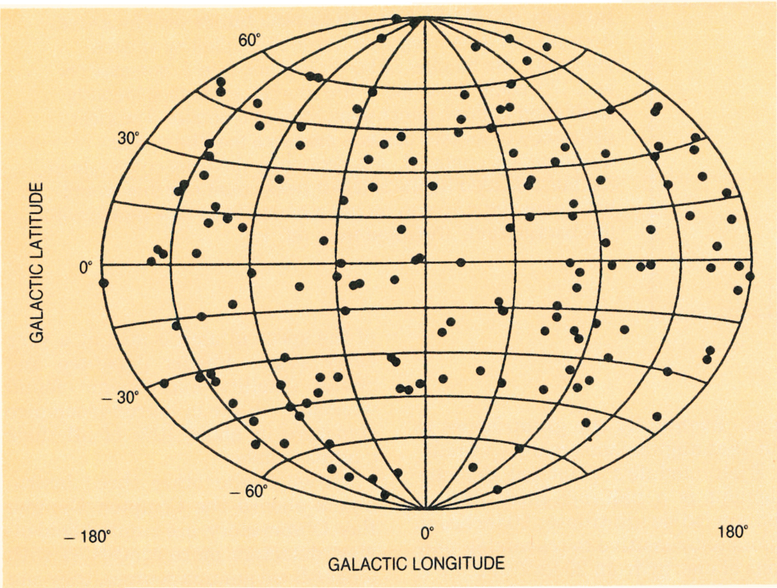
The intensity distribution found for the BATSE events, as shown in the figure on page 24, reveals that they continue to rise more slowly than $L^{-5/2}$. (Because this plot is an *integral* rather than a differential distribution, the blue line in fact shows $L^{-3/2}$.) This clearly indicates that whatever the sources are, they are not uniformly distributed in space without a distance limit. Or it might be that we are looking at a superposition of several different populations. But no one has as yet been able to find any telltale difference between strong and weak bursts.

If it's all a single population, that population is somehow confined in space. But what is it that circumscribes this population? Is it the Oort cloud of comets that surrounds our solar system or a distant halo of neutron stars around the Milky Way or, on a much grander scale of distance and time, cosmological redshifting or evolutionary effects?

What are they?

In the few months since the first BATSE results became known, the idea of a distant spherical halo population of neutron stars has become one of the two leading contenders to replace the suddenly moribund Galactic-disk hypothesis. Given the fact that we live some 25 000 light-years from the center of the Milky Way , an isotropic halo surrounding the Galaxy would look lopsided to us eccentric observers *unless* it was very far away. From the anisotropy limits on the present data one can conclude that most of the neutron stars in this putative halo would have to be at least 150 000 light-years away. That's much farther out than the edge of the luminous-star population, but not farther out than the Large Magellanic Cloud or the halo of dark matter that is presumed to govern the gravitational dynamics of the Galaxy. (See the article by Scott Tremaine on page 28.) This imagined halo of neutron stars is not to be confused with the well-established halo of globular star clusters, most of which are less than 40 000 light years from the center of the Galaxy.

How would all those neutron stars get so far out when the luminous stars of the Galaxy are nowadays confined by gravity to the disk, the central bulge and the halo of globular clusters? We know that pulsars, a particularly ostentatious subclass of young neutron stars, typically have velocities of several hundred kilometes per second relative to the Galaxy. Perhaps neutron stars in general are "hotter" than ordinary stars, in the sense of random stellar motion, because they are born in supernovae. The escape velocity from the Galactic disk is less than 300 km/sec, so that neutron stars in the tail of this hot velocity distribution would have the



Angular distribution of 153 gamma bursts seen last year by the Burst and Transient Source Experiment aboard the GRO. The equatorial axis is the Galactic plane, with the Galactic center at the origin. The distribution shows no statistically significant deviation from isotropy. (Adapted from ref. 1.)

freedom to stray far from the disk. Or perhaps we are seeing a spherical halo population that was actually born out there.

In any case, if the bursters are indeed in a great spherical halo a hundred times farther away than the local precincts of the disk, they would have to be ten thousand times more energetic than we had thought them to be. A burst event would have emit something like 10^{41} ergs worth of gammas. Conveniently it turns out that the stark-quake model and most of the other scenarios invoked for a disk population of neutron stars are flexible enough to accommodate a factor of ten thousand in energy.

The Galactic-halo picture, however, is not without its problems. For one thing, why aren't we seeing gamma bursts from halos around nearby galaxies like Andromeda or the Large Magellanic Cloud? As statistics accumulate, the BATSE group will have to see such a localized enhancement or some dipole anisotropy due to our eccentric location in the Milky Way before too long, or else abandon the halo picture. Furthermore, this picture implies the existence of a lot more neutron stars in our Galaxy than is usually assumed. That means a lot more supernovae and consequently a lot more iron and other heavy elements spewed into interstellar space. We don't see nearly enough iron in the Galaxy for that. Perhaps we have here a hint of a new astrophysical phenomenon: neutron stars produced by something other than supernova explosions.

Cosmological distances

If the directional distribution of gamma bursters remains stubbornly isotropic with increasing statistics, we will have to think about what we're *really* in the center of. The universe, for one thing. The "cosmological principle" asserts that any observer of the largest scales is as central as any other. Theorists are speculating that the gamma bursters are neutron stars in distant galaxies. These galaxies would have to be very far indeed if we cannot see them with telescopes. The fact that we see neither optical counterparts nor any evidence of concentration in the directions of the known superclusters of galaxies leads people to argue that a typical distance to such a cosmological gamma burster would have to be several *billion* light-years.

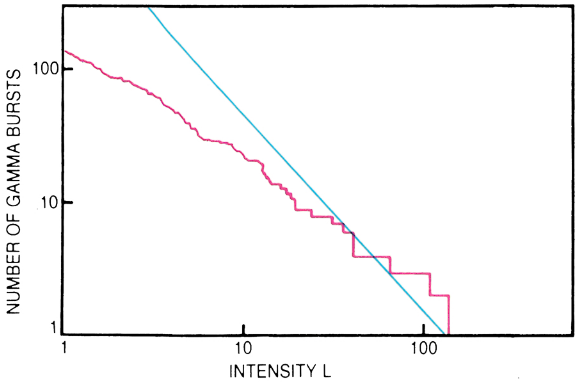
But such enormous distances would imply that a burst event releases something like 10^{51} ergs worth of gammas. What sort of stellar process could possibly radiate so much gamma energy in a sudden burst? The gravitational binding energy of a neutron star is about 10^{53} ergs. The sudden coalescence of two neutron stars in a collision or a dying binary pair should indeed release the full binding energy of one of them. But it's hard to make the case that anything like 1% of the energy released would come out in gammas.

Princeton theorist Bohdan Paczynski, a pioneer of the cosmological camp, points out another problem. The gamma bursts, he argues, are also too broad in energy and time for a straightforward, unadorned merger of two neutron stars, which would be over and done with in about a millisecond. A typical burst lasts about half a minute, with lots of millisecond substructure. The energy spectrum, typically peaking near 1 MeV, is much broader than the approximately blackbody distribution one would expect from a simple merger. Paczynski offers a more elaborate scenario.[2] He argues that a decaying binary pair of compact objects (either two neutron stars or a neutron star paired with a black hole) will often merge into a black hole by way of a brief intermediate phase. Most of the mass will already be in the preexisting or newly formed black hole. But a surrounding accretion disk of neutron-star material, he calculates, will survive in orbit around the black hole for tens of seconds to generate the extended gamma burst. The millisecond substructure of the burst would be indicative of the orbital period of the disk.

Such a black-hole merger, Paczynski told us, could release as much as 10^{54} ergs, a fair fraction of a neutron-star rest mass. "But I have no idea how much of that would come out in gammas." In this accretion-disk scenario, the gamma burst from an individual merger is likely to be strongly beamed rather than isotropic. That means it wouldn't have to be quite so energetic for us to see it, *if* it's beaming at us. But then we'd see fewer of them.

The cosmological theories raise some spectroscopic questions: If all gamma bursts are really so cataclysmic, it is difficult to understand how some burst spectra can exhibit anything as fragile as cyclotron-resonance structure. An earlier Soviet orbiting detector also produced some evidence of the positron–electron annihilation line at 0.5 MeV in gamma-burst spectra. If the burst events are really distributed over a factor of 100 in cosmological distance, corresponding to fractional redshifts ($z = \Delta\lambda/\lambda$) ranging from about 0.05 to 1.5, why have the spectral data, meager as they may be, given no hint thus far of any redshift variation?

The nearest of these events would be "only" 500 million light-years away, a distance at which an ordinary galaxy should be optically discernible.



Intensity distribution of 140 gamma bursts seen by BATSE. Because this is an integrated distribution, plotting at each intensity L the number of bursts *brighter* than L, one expects an $L^{-3/2}$ falloff (blue line) if the sources are homogeneously distributed in three dimensions without a bound. The clear deficiency of weaker bursts is evidence that the source distribution is confined. L is defined as the peak count rate in the burst divided by the smallest peak count rate that would have triggered BATSE to record a burst of this time profile with this background. (Adapted from ref. 1.)

Why haven't we seen them? Some have suggested that bursters are mostly neutron stars in pathologically subluminous galaxies. Or perhaps they occur only on cosmic strings, not in galaxies at all.

To round out this survey of proposed solutions with the most speculative of them all, we must come back much closer to home. Some speculators have taken note of the Oort cloud of cometary nuclei as a suggestively symmetrical shell around those of us living in the inner reaches of the solar system. If the gamma bursts originated somewhere out there, perhaps a hundred light-*hours* from us, each burst event would have to radiate only about 10^{26} ergs in gammas. But it's difficult to conjure up any process that would generate even so modest a gamma burst out among the comets. About the only thing people have come up with is the annihilation of infalling chunks of antimatter. That would pose more questions than it answered. In any case, whatever the distance scale of the gamma-ray bursters may turn out to be, the BATSE data have already made it very likely that we will be confronted with something quite new.

The instruments

The 16-ton Compton Gamma Ray Observatory is the heaviest scientific payload ever placed in orbit by a shuttle. BATSE is one of four gamma-detector systems aboard the GRO, but it is the only one that can monitor the whole sky (except what's blocked by the Earth), all the time, for burst events. BATSE comprises eight identical modules, one at each corner of the GRO. Each module looks out in one of the eight directions normal to the planes of a regular octahedron, so that a burst from any direction will be seen by four of them. BATSE is not an imaging detector; it determines the angular location of a burst to within about 5° by comparing the signal intensities seen by the different modules. Eventually the group hopes to cut that angular uncertainty in half.

Each module's principal detector element is a half-inch-thick disk of sodium iodide scintillator 20 inches in diameter, sensitive to traversing photons of energy from 20 keV to 2 MeV. Each of these large-area scintillators is supplemented by a thicker NaI crystal of much smaller area that absorbs gammas and measures their energies with good resolution. These small spectroscopy elements are sensitive to gammas all the way up to 100 MeV.

The number of gammas counted by the large-area detectors in various time bins (64 msec to 1 sec) is monitored continually. Whenever two or more detectors simultanously see the gamma count rate rise 5.5 standard deviations above background, the system is triggered to record a burst candidate. BATSE's threshold flux for detecting a burst is about 10^{-7} erg cm^{-2} sec^{-1}.

The efficiency of the on-board trigger depends on the intensity of the burst, its time structure and the gamma-ray background in that particular direction at that moment. It is essential to take account of such biases if one is to make sense of the observed distribution of intensities. Therefore the conventional parameter used to characterize the intensity of a burst event is its peak count rate *divided by* the least peak count rate that would have activated the on-board trigger under those particular circumstances of background and time profile.

The gamma bursts exhibit a great variety of time profiles. "I'm sure they're trying to tell us something," Fishman told his audience at the Atlanta meeting. The spectroscopic results could prove crucial to a decision between the halo and cosmological conjectures. Thus far the group has not yet reported any evidence of cyclotron-resonance or positron-annihilation structure. But the analysis of the spectral data is still at a very early stage. Earlier Japanese and Soviet satellite experiments found what looked like cyclotron-resonance structure in about 10% of all their gamma bursts.

Although the other three instruments aboard the Compton Gamma Ray Observatory are limited-field-of-view detectors more concerned with longer-lived gamma sources, they can occasionally provide complementary information on a gamma burst, *if* they happen to be looking in the right direction when BATSE detects an event. The Energetic Gamma Ray Experiment Telescope is essentially a flying spark-chamber assembly capable of measuring gamma energies up to 30 GeV. Its field of view is about 20°×20°. EGRET recorded 200-MeV gammas in one particularly bright BATSE event last May. Comptel, an imaging telescope sensitive to gammas from 1 to 30 MeV, always points in the same direction as EGRET. Its field of view is a full steradian. Comptel can determine the angular position of a burst event to within 1°. OSSE, the Oriented Scintillation Spectrometer Experiment, is optimized to detect gammas from 100 keV to 10 MeV. Its four central detector modules are particularly sensitive to the spectral signatures of radioactive elements in longer-lived sources. But each of these modules is surrounded by a massive anticoincidence shield of crystal scintillator that can provide particularly fine time resolution for any gamma burst to which it happens to have a clear line of sight.

Like BATSE, each of these other gamma-detector systems aboard the GRO is, by virtue of its size and design, an order of magnitude more sensitive to faint sources than any previous instrument of its kind.

—BERTRAM SCHWARZSCHILD

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