Exploring the Gamma Ray Sky

We've all looked at the night sky, and we know, visually, about stars and planets and galaxies, but very few people have a feel for what the gamma ray sky actually looks like.

by Thomas A. Prince

Astronaut Jay Apt stands on board the space shuttle *Atlantis* as the Gamma Ray Observatory (in the background), the heaviest scientific payload ever launched into orbit, prepares to begin its mission. At this point it is still in the grasp of the remote manipulator system.

The following article is adapted from a recent Watson Lecture on gamma ray astronomy.

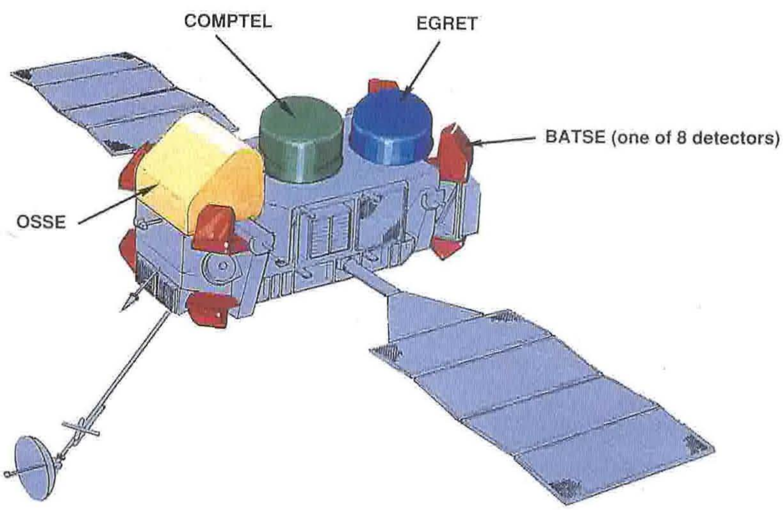
Traveling back and forth to Washington, D. C., for Gamma Ray Observatory meetings, I usually try to do a little work on the airplane. Every so often I'll be sketching some drawings of neutron stars and writing down equations, and all of a sudden I get the distinct feeling that the person in the seat beside me is watching. Then, invariably, a few minutes later they'll ask, a bit sheepishly, "Are you an astronomer or something?" I answer, "No, I'm not an astronomer; I'm a physicist, but I do a lot of work with NASA's space astronomy missions." Then their eyes light up and they say, "Oh, you must be working on the Hubble Space Telescope." I say, "No, I work with the Gamma Ray Observatory," and they say, "Oh, what's that?" So perhaps with this article, which was adapted from a recent Watson Lecture, I can explain to a larger audience, as well as to all potential airplane-seat neighbors, just what the Gamma Ray Observatory is and what we are learning from it.

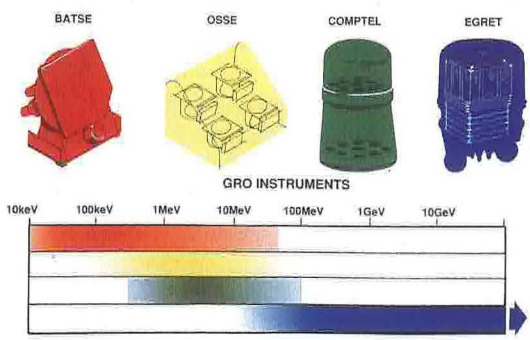
The Gamma Ray Observatory, or GRO, is the second in NASA's program of "Great Observatories" that will observe the sky at various wavelengths. So far, the Hubble Space Telescope, which covers the visible wavelengths, and the Gamma Ray Observatory have been launched. Scheduled for the future are the AXAF telescope, which works in x-ray radiation, and the SIRTF, which operates in the infrared.

Actually, it is understandable why people are more familiar with the Hubble than with GRO. We've all looked through telescopes or binoculars and intuitively have a good feel for what a visual or optical telescope is. But how many of us have a gamma ray detector in our homes? And how many of us know what our pet dog looks like at gamma ray energies? We've all looked at the night sky, and we know, visually, about stars and planets and galaxies, but very few people have a feel for what the gamma ray sky actually looks like.

Gamma rays are radiant energy of the same form as radio waves, infrared, visible light, and x-rays. We can distinguish among these different forms of radiant energy, called electromagnetic radiation, in one of three ways—by wavelength, by frequency, or by energy. Radio waves have long wavelengths; gamma rays, on the other hand, have very short wavelengths—smaller than an atom. Radio waves are relatively low frequency; gamma rays are ultrahigh frequency. Gamma rays have very high energies compared to radio and visible light. For example, visible light has an energy somewhat larger than one electron volt; gamma rays span the range from about 10,000 electron volts—that is, about 10,000 times more energetic than light—to about 10 billion electron volts. Because gamma rays are so energetic, and because their wavelengths are so short, they interact more like particles than like waves, so I'll be discussing them as if they were particles. While visible light essentially has to do with atomic transitions (that is, when you look at a fluorescent light you're really looking at the excitation of atoms), gamma ray radiation often comes from the excitation of nuclei. So visible light is used to learn about the atomic physics of

GRO's four instruments all record the energy and arrival time of each gamma ray although they cover different, but overlapping, energy ranges and provide different views of the gamma ray sky. BATSE can look in all directions; OSSE has a narrower field of view. COMPTEL and EGRET are imaging instruments.





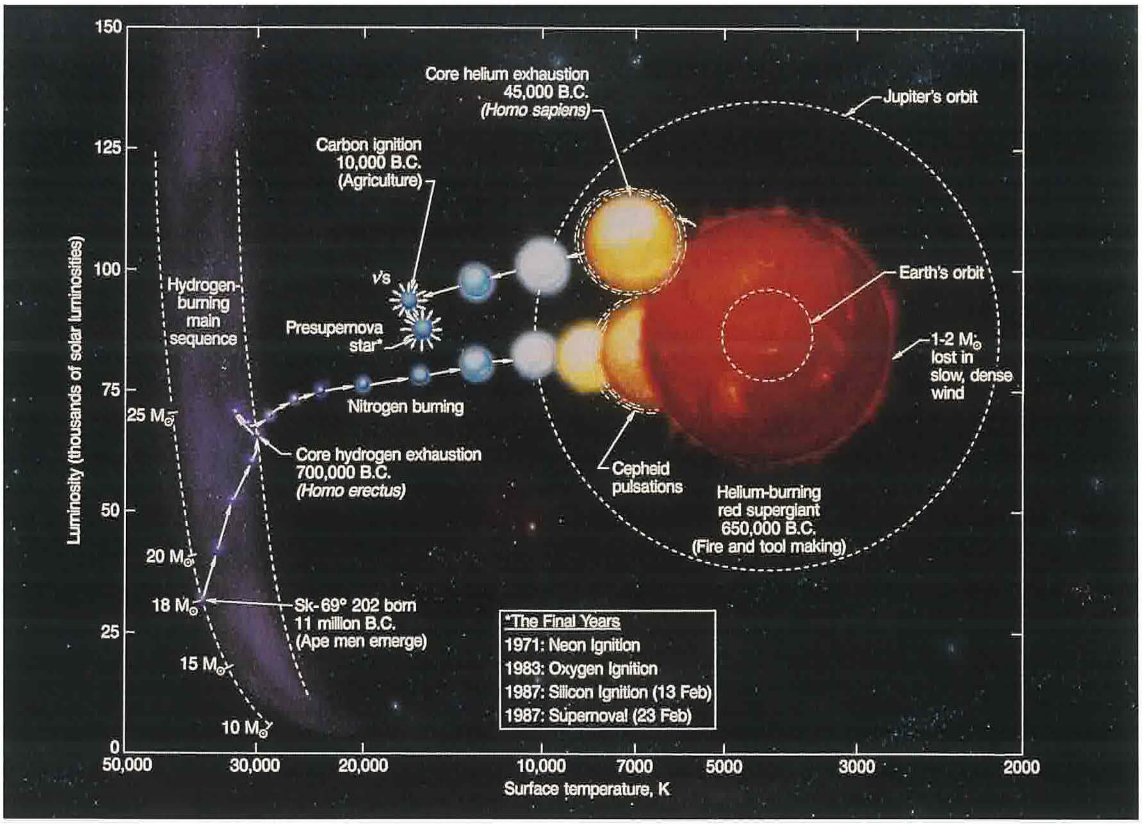
astrophysical sources, and gamma ray radiation will tell us about nuclear processes such as radioactive decay in those sources.

If humans had gamma ray eyes, we wouldn't be able to see much. The air in a room would glow faintly because of trace radioactivity. If we had only gamma ray eyes, we would pretty certainly starve to death. Plants and animals don't show up very well at all, and it would be a lousy way to hunt. But in astronomy, not being able to see gamma rays and learn what they can tell us, is starvation of a different sort. Even gamma ray eyes wouldn't help much, because gamma rays, although they are very energetic, don't penetrate the Earth's atmosphere at all. So we have to send instruments above the atmosphere to observe the radiation. The Arthur Holly Compton Gamma Ray Observatory (its official name) is the most ambitious attempt so far to observe the sky at gamma ray energies.

The Gamma Ray Observatory was launched April 5, 1991, from the space shuttle *Atlantis*. The satellite weighs 35,000 pounds, the heaviest scientific payload ever put into orbit from the shuttle. The GRO has four instruments on board, all of which record the energy and arrival time of each gamma ray, but each with a different scientific goal. Although the instruments are often called telescopes, they're very different from conventional optical telescopes; there are no lenses or mirrors for the gamma ray range. BATSE (Burst and Transient Source Experiment), covering the lowest energy range, consists of eight detectors on the corners of the satellite to look in all directions at all times. OSSE (Oriented Scintillation Spectrometer Experiment) looks at a much smaller field of view at somewhat higher energies. Neither of these two produces an actual picture of the gamma ray sky. But COMPTEL (Compton Telescope) is an imaging instrument. It looks at a still higher energy range and has about a 40-degree field of view, while EGRET (Energetic Gamma Ray Experiment Telescope) is an imaging instrument, which holds down the most energetic end of the gamma ray range.

Now that I've described the GRO instruments, I'd like to turn to the observations. Many of the interesting results I'll be discussing are quite new, some as recent as this winter.

Probably the most familiar gamma ray source is our own sun. But although the sun dominates our sky in the visible wavelength, it's almost completely dark at gamma ray wavelengths, even if we observe it from space. Occasionally, though, a solar flare erupts, suddenly releasing magnetic energy in a loop on the sun. That



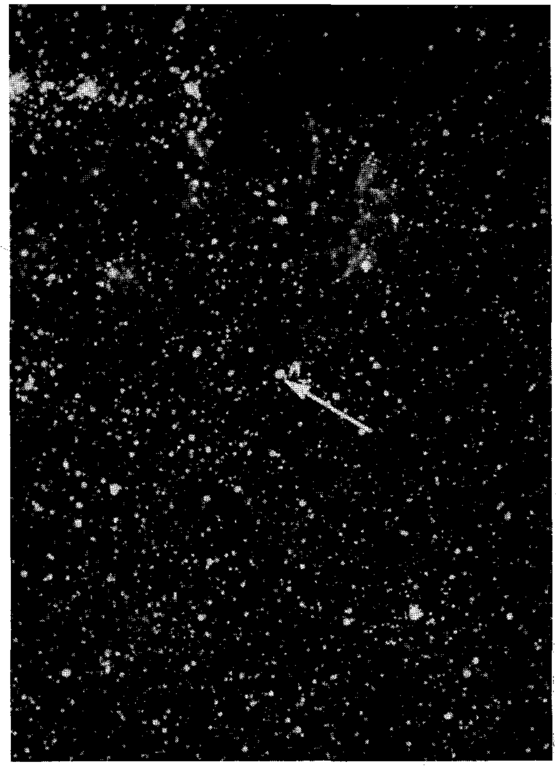
The life history of the star that produced Supernova 1987A began 11 million years ago with a blue star about 20 times the mass of our sun. First it burned hydrogen, then swelled up into a helium-burning red giant. When it ran out of helium and started burning carbon 12,000 years ago, it shrank back into a blue star. Ignition of the next elements—neon, oxygen, and silicon—took place only in the last 15 years before the supernova explosion. (Illustration courtesy of Tom Weaver and Stan Woosley.)

energy accelerates particles, which bombard the nuclei in the sun's atmosphere, causing emission of gamma rays. The four instruments on GRO have studied some of the most intense solar flares ever observed on the sun. These studies have shown that the sun, although a very normal star, can accelerate gamma rays up to almost the highest energies observable by the Gamma Ray Observatory. This brings up the question of whether, if the sun can throw out gamma rays like this, other normal stars can also be seen at gamma ray energies. Unfortunately the answer is no. We can see the sun because it's so close to us, but not any other ordinary stars. Instead, the GRO will be looking for sources of gamma rays from much more exotic objects: supernovae, neutron stars, and black holes.

The study of supernovae was one of the primary scientific objectives of the Gamma Ray Observatory, in particular of the OSSE and COMPTEL instruments. A supernova is, quite simply, the death of a star, and in that death a tremendous amount of energy is released. A star that explodes in a supernova can suddenly become brighter than the entire galaxy that it's in. A particularly important supernova occurred five years ago (precisely at 7:35 a.m. on February 23, 1987). Supernova 1987A was the closest, brightest, and best studied supernova since the invention of the telescope.

It takes a star, for example one about 20 times the mass of the sun, a long time to get into a state where a supernova can occur. The life history of that star is pretty much a story of the struggle between gravitation, which is trying to collapse the star into a tiny ball, and the nuclear reactions burning in its core, which create the energy and pressure that puff the star up. The star starts out by burning hydrogen into helium, the fusion reaction in its core. But of course it has to run out of hydrogen eventually, so it starts burning helium, making carbon in the process. When it runs out of helium, it starts burning the carbon; when it runs out of carbon, it starts burning neon, then oxygen, then silicon. And then it stops, because when you burn silicon in a nuclear reaction in the core, you create iron. Iron is a very stable nucleus, and you can't get any net energy from burning it to form heavier elements. This is the state that the star is in just before going supernova. It has a core of silicon and iron that weighs about twice as much as the sun. It's roughly the size of the Earth and is just sitting there accumulating iron, which it can no longer burn.

Above is a picture of what astrophysicists think is the life history that led to Supernova 1987A. The star started out about 11 million years ago as a blue star roughly 20 times the mass of the sun, then began burning hydrogen, swelled up, and became a red giant star that would have fried any earthlike planet near it. At that time it was burning helium. When it ran out of helium, it started burning carbon, ending up as a blue star again. The neon-oxygen-silicon burning took place very fast—forming the core of silicon and iron in only about the last 15 years before going supernova. When enough iron accumulat-

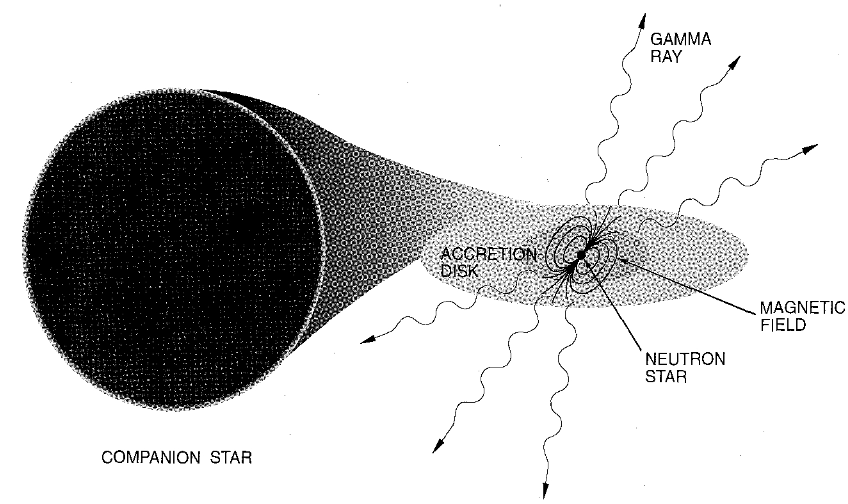
Supernova 1987A—before and after. Before, it was an ordinary blue star in the Large Magellanic Cloud named Sanduleak -69°202. On February 23, 1987, it died in an explosion that released a tremendous amount of energy, mostly in the form of neutrinos. A fraction of a percent of the energy goes into producing radioactive elements that are identifiable by gamma ray detectors. (Photograph from the Anglo-Australian Observatory by David Malin.)

ed, the core could no longer hold up its own weight, the atoms got crushed, and the entire core collapsed in less than a second to an object about 25 miles across. So here's something that weighs a little less than twice as much as the sun collapsing into an object about twice the size of Pasadena. As you might expect, in that process it releases a tremendous amount of energy—more energy than our own sun has emitted in its entire lifetime as a normal star.

Most of this energy from a supernova, 99 percent in fact, shoots out as a form of radiation called neutrinos. Neutrinos can pass through matter very easily. Supernova 1987A is so far away that its light took about 170,000 years to reach us. But even from that unimaginable distance, more than a trillion neutrinos produced in that event passed through each one of us. These neutrinos, the 99 percent of a supernova's energy, are a story in themselves, but I want to track the other 1 percent, because that's the energy that's interesting to gamma ray astronomers. That 1 percent explodes out in a shock wave, which first heats up the material of the overlying star that *hasn't* collapsed—heats it up so much that it can start producing nuclear reactions and radioactive material and heavier elements. Then the rest of the energy goes into blowing all that stuff out into interstellar space. This material has elements in it such as carbon, oxygen, nitrogen, and traces of metals—precisely the elements that we're all made of. This is no coincidence. The stuff we are made of was once cooked up inside a massive star and ejected in a supernova explosion. The same material condensed to form our solar nebula, and here we are. We would not be here if it weren't for supernovae.

But meanwhile, back to the gamma rays, it turns out that the nuclear processes that occur when the shock wave passes through the materials in the star create a lot of radioactive elements or radioactive tracers, such as nickel, cobalt, titanium, sodium, and aluminum. The radioactive material produced in a single supernova is equivalent to a mass that's about 25,000 times the mass of the Earth. Because so much radioactivity is created, it's observable by gamma ray detectors. When a nucleus of, say, cobalt 56 decays radioactively, it emits a gamma ray of a very specific energy. When we see increases in intensity at that particular energy, we can say we have detected radioactivity, and we can measure how much cobalt 56 was actually produced.

One of the long-term objectives of the Gamma Ray Observatory is to detect radioactivity from elements produced in supernovae, be they a couple of months old, a couple of years old, or even a couple of million years old, and from that to map out the distribution of radioactivity that has been produced by supernovae in our galaxy. Because Supernova 1987A, however, offered such an unparalleled opportunity to observe the radioactivity of a supernova in progress, it became one of the Gamma Ray Observatory's first targets. Just this January, GRO scientists discussed the possibility that the OSSE detector may for the first time be seeing direct evidence of the rare isotope cobalt 57. We think that right now, at this stage of its evolution, the supernova is being powered by the decay of cobalt 57 instead of



When a neutron star resulting from a supernova happens to have a companion star that has swelled into a red giant, the neutron star's strong gravitational field can suck material from its companion into an accretion disk. A neutron star with a strong magnetic field can pull some of the material in the disk onto its poles, creating hot spots of radiation that show up as the star rotates. The neutron star is then detectable as a pulsar.

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cobalt 56, which powered the supernova early on. The detection of this isotope will be fundamental to the understanding of the supernova at these late stages, four to five years after the explosion.

Now I'd like to consider not what was ejected, but what was left behind. When the core collapsed, it left a very condensed, very hot blob sitting there. Eventually it cooled and became an object about 12 miles across, about the size of Pasadena, 1-1/2 times the mass of the sun. Because it's composed, not of atoms, but almost purely of nuclei (and in particular neutrons), we call it a neutron star. GRO data are being combed very agressively right now, searching for radiation signatures of the neutron star that was born out of Supernova 1987A. It hasn't been detected so far, but it will be an exciting discovery when and if it is.

How many neutron stars are produced by supernovae like this? Predictions say that perhaps two or three occur per century in a galaxy like our own. That doesn't seem like much, but in astrophysical terms time is fairly long—for a galaxy that has been around for billions of years, two or three per century adds up pretty quickly. Probably 100 million or more neutron stars have been produced in our galaxy over its history. But we don't see that many of them; why not?

An old neutron star just sits out there; it's dark; it's relatively cold; it's not producing any energy of its own, so it's essentially unobservable. But in rare instances the neutron star can be detected. Sometimes a star that goes supernova happens to exist in a binary system with a companion star. This companion star can start out as a blue star and then gradually swell up to be a red giant. When it does so, the neutron star resulting from a supernova can literally suck the material off the companion star with its strong gravitational field, and put it into an accretion disk, where it spirals in toward the neutron star. Some neutron stars have very strong magnetic fields, very much stronger than anything we're used to on Earth, which can catch material in the accretion disk and funnel it down onto the star's polar caps. Since the neutron star is only the size of Pasadena, this stuff actually falls on a surface about the size of the Caltech campus. The matter hits the surface of the neutron star at speeds approaching the speed of light, dumping a tremendous amount of energy onto that surface and heating these spots up to temperatures as much as 10,000 times greater than the temperature of the sun. If the rotation axis of the neutron star is misaligned with the magnetic axis, then the hot spots that are being created at the polar caps of the neutron star rotate in and out of our field of view. What we can see are pulses of radiation coming at us—one pulse for each time the hot spot circles around. Hence, this type of neutron star is called a pulsar, and it's something we *can* detect.

With detectors such as BATSE on GRO a group of us at Caltech (including John Grunsfeld, a senior research fellow, and grad students Deepto Chakrabarty and Bill Detlefs) are looking for very regular pulses of radiation. We're searching a broad range of periods and frequencies of this radiation. We've been quite successful so far, and have detected 11 pulsar systems. Because these

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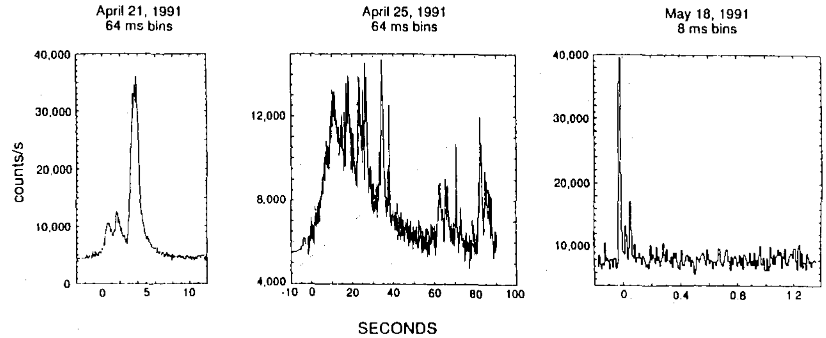
Seen from the shuttle Atlantis before final launch last April, the Gamma Ray Observatory glides over the coast of Mauritania and Senegal in West Africa.

systems turn on and off irregularly, on time scales of days, weeks, and months, they're hard to catch in the act. You might watch in a particular direction for one of them with a telescope for a long time and not see anything, and then a month later, after you got tired of looking, it might turn on. The beauty of the BATSE detectors, which look in all directions at once, is that you can detect a pulsar as soon as it turns on and study it for the entire time it's active. By doing such studies we hope to determine such things as the magnetic field of the neutron star, and perhaps its mass. And we certainly want to know the details about how mass can be sucked off the companion star and onto the neutron star.

Another target for the Gamma Ray Observatory is black holes. The same type of process that leads to the formation of neutron stars can also create black holes, with the difference that a neutron star can form from a star about 20 times the mass of the sun, while a black hole requires a star that's more than 40 times the mass of the sun. Because it has a more massive core, when a star this size goes supernova, there's more mass compacted in that dense blob that forms when it finally collapses. If enough matter gets packed in there, it will have such a strong gravitational field that a black hole is produced. But how can we see a black hole? It has the same type of visibility problems as a neutron star—it's just sitting out there in space, and it's *black*. If the black hole happens to be in orbit around a companion star, however, just as with a neutron star, matter can be sucked onto the black hole to form an accretion disk and spiral in. As the matter spirals toward the black hole, it gains energy and heats up, emitting radiation in the process. It turns out that it's very hard to tell a black hole, which has no magnetic field, from a neutron star that happens to have a very weak magnetic field. Scientists have spent a lot of time trying to tell the difference between them, and some of us think that the Gamma Ray Observatory may be able to detect one distinct signature of a black hole. We think that black holes may be able to produce a very hot bubble of electrons and positrons close by. As the hot bubble expands because of its high temperature, the electrons and positrons can combine and annihilate each other (because they are matter and antimatter). When this occurs, they produce gamma rays close to an energy of 511 thousand electron volts. By looking for radiation at that energy we can determine whether or not systems that we think might be black holes are really emitting this signature of electron-positron production. The Gamma Ray Observatory's OSSE is the best detector yet with the potential to observe this phenomenon, and with it we hope to learn a lot about discriminating between black holes and neutron stars.

Probably the most interesting results to come out of GRO so far involve gamma ray bursts. These were discovered in the late sixties by a series of satellites monitoring the nuclear test ban. They were searching for evidence of clandestine nuclear weapons tests, evidence that included gamma ray bursts. Indeed, they *did* see gamma ray bursts, but, it was determined eventually that they weren't coming from Earth

Gamma ray bursts come in all shapes and sizes, from less than a second long to tens of seconds long. These are three that BATSE detected early in the GRO mission.



—rather, they were coming from space. Since that information was declassified in 1973, the astronomical community has proposed and carried out a large number of experiments to determine the origin of these gamma ray bursts. The bursts come in all shapes and sizes—some less than a second long, and some tens of seconds long. The largest of them can be the brightest source of gamma rays in the sky for the brief time that they occur.

The Gamma Ray Observatory has given us the best data yet on these bursts. Gamma ray bursts, as observed by the BATSE detectors (which look out from the observatory's eight corners), happen about once per day. Both BATSE and COMPTEL can determine the rough arrival directions of the gamma rays. In addition, by comparing the time of arrival of the burst at the Gamma Ray Observatory with its time of arrival at very distance spacecraft (for instance, Ulysses, which is out near Jupiter), we can tell very accurately the direction where the burst actually came from. Oddly enough, when astronomers look at the spot where a burst came from, they find nothing astounding whatsoever. It's almost invariably a patch of sky empty of any interesting objects.

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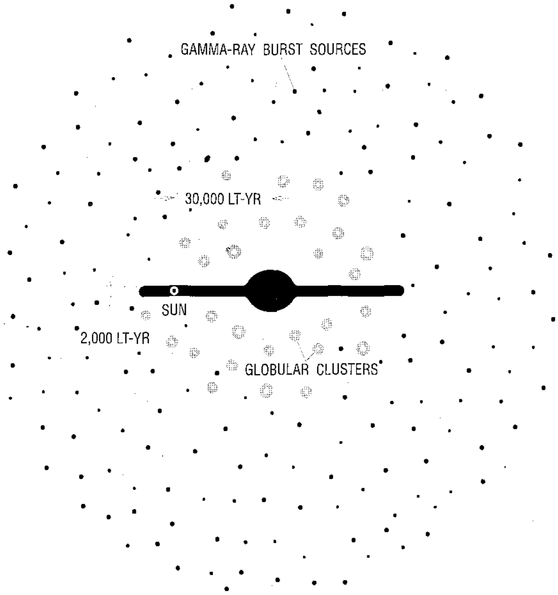
What could these bursts be, and where do they come from? Before the launch of the GRO, the general consensus of the scientific community was that gamma ray bursts were due to old, dead neutron stars, which are normally dark. Astrophysicists had proposed various models by which dead neutron stars could actually create gamma-ray bursts—neutron star-quakes, collisions with asteroids or comets, or release of magnetic field energy, analogous to solar flares. Before the GRO, detectors were able to see only the brighter gamma ray bursts, which were randomly scattered in every direction across the sky. Using our visible-light intuition, such a random distribution is what you would expect from objects in our own galaxy—relatively close to us. When you look, for example, at the brightest stars (that is, the closest ones), they seem to be sprinkled randomly about, but as they get fainter and fainter (that is, farther away), you start seeing them line up with the plane of the galaxy. The plane of the galaxy is familiar to us as the Milky Way that we see in the night sky.

Analogous to what we see in the visible, we expected that the Gamma Ray Observatory's sensitive detectors would reveal a deficit of the faintest (farthest away) bursts, namely in directions out of the galactic plane, and that the observable faint bursts, like faint stars, would lie along the galactic plane. Very early in the GRO mission it was indeed found that there was a deficit in the number of faint bursts. But the chief surprise is that the prediction concerning their distribution was *not* borne out. Rather than being lined up in the galactic plane, the faintest bursts are distributed all over the sky. The fact that we see a deficit of faint bursts clearly means that we are seeing out to the edge of their distribution. But the fact that the faint bursts that we do see are uniformly scattered across the sky means that there is no preferred direction and that, therefore, their distribution doesn't seem to have anything to do with the plane of our galaxy.



GRO data show that gamma ray burst sources may be distributed in a halo around our galaxy, which, if the bursts are indeed from old neutron stars, provokes a mystery as to how the neutron stars might have gotten out there.

Many bursts and their positions have been cataloged, and yet we have no firm idea where they really are, how far away they are, or what they are.

This has put astrophysicists in a quandary. We've known about these bursts—the brightest objects in the gamma ray sky when they go off—for almost a quarter of a century. Many bursts and their positions have been cataloged, and yet we have no firm idea where they really are, how far away they are, or what they are. I don't think there's any other object in astrophysics that has been studied so intensely but about which so little is definitely known.

Three theories have been suggested to explain the new data from GRO: that the bursts are very close to us; that they are moderately far away; and that they are very, very far away. The first is probably everybody's least favorite choice. In this instance it's been proposed that perhaps the gamma ray bursts are coming from a uniform and randomly distributed crowd of comets around the solar system. Unfortunately no one has come up with a good explanation of how you can make gamma ray bursts with nearby comets.

The second possibility involves old neutron stars, which was also the pre-GRO favorite explanation. We are, however, forced to the conclusion that if there is an edge to the distribution of gamma ray burst sources, then it must be uniformly distributed across the sky. So instead of having all the burst sources lined up in the plane of the galaxy, we may have to put them out in a halo around it. The immediate question that arises is that if old neutron stars are creating the gamma ray bursts, why are they way out in a halo when presumably they were all produced via supernova explosions from massive stars in the plane of our galaxy? Were they ejected out of the plane into the halo? Was there at one time a halo of massive stars around our galaxy that produced lots of neutron stars?

I'm still betting on the galactic halo model, but a lot of scientists favor the idea that puts these gamma ray bursts very far away—way outside of our galaxy. We know from the GRO data that there is an edge to their distribution; where is there a natural edge once you go outside of our galaxy? Well, there's the "edge" of the universe—the Big Bang. When you look out with powerful telescopes, you're looking further and further back in time, toward the beginning of the universe. How far out do the gamma ray bursts have to be in order to explain all the data? It turns out that they would have to be distributed over a good fraction of the entire universe. That means that the gamma ray bursts would have to be truly cosmological in origin. Some suggestions for the kind of objects that could possibly put out enough energy to do this include a neutron star orbiting another neutron star or even a neutron star orbiting a black hole. In certain cases the neutron star orbiting another neutron star emits gravitational radiation, spiraling the two stars closer and closer to each other until they merge. Such an event would release as much energy as a supernova. Quite a few people are excited about this explanation, but I am skeptical. It's going to take a lot more work on the data from GRO and on new types of data to unravel this question, but so far the distribution of gamma ray bursts has been the Gamma Ray Observatory's most exciting discovery.

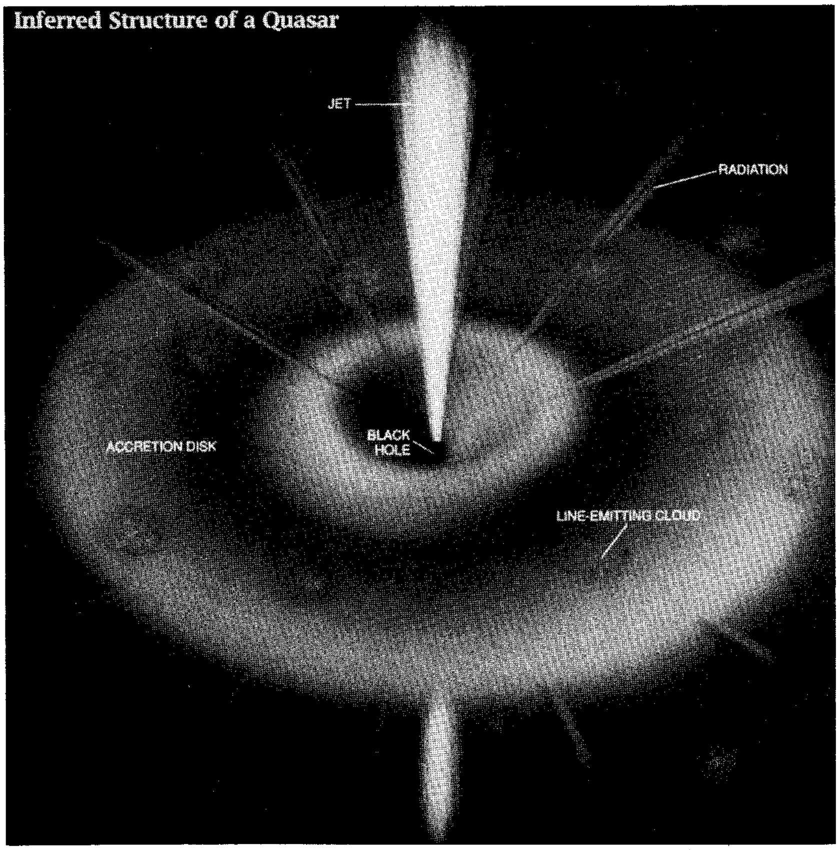
The second most important discovery from

The GRO mission, not even a year old, has already been highly successful, yielding new discoveries and raising some intriguing questions.

GRO concerns quasars—quasi-stellar objects that can be ten billion light-years or more away from us. It's generally thought that quasars are powered by black holes, not ones that weigh perhaps 10 times as much as the sun, as I discussed earlier, but black holes that might be as much as 10 million times the mass of the sun, or even larger. Quasars are very efficient emitters of radiation. EGRET, the highest energy telescope on the GRO, was trained on the site of the quasar nearest to us, called 3C273, which had been detected at gamma ray energies before. EGRET did detect a very definite peak of gamma ray emission, indicating clearly that it had seen a source in the general direction of 3C273. But although the Gamma Ray Observatory was pointed directly at 3C273, the location of the strong source was quite a bit off it. In fact, this was an entirely different quasar, called 3C279, which is far more distant than 3C273. It turned out to be the farthest, brightest, and most luminous gamma ray object ever detected. Just recently the EGRET telescope detected four more quasars. So it seems that the massive black holes that may lurk in the centers of quasars are very efficient gamma ray producers. I anticipate further interesting GRO results on quasars in the future.

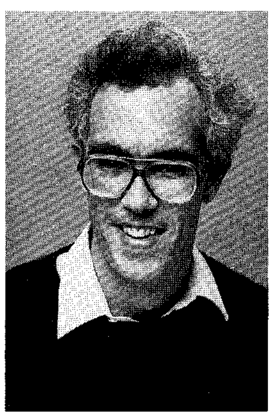
The GRO mission, not even a year old, has already been highly successful, yielding new discoveries and raising some intriguing questions. It is giving us our first really good look at the gamma ray sky.

Perhaps this article will help make gamma rays more familiar, although they will never beat visible light in a popularity contest. But at least if you ever end up sitting next to me on a plane, you won't have to wonder what a gamma ray observatory is. Rather, you can ask, "Have they found out where those gamma ray bursts are coming from yet?" □



From "The Quasar 3C 273" by Thierry J.-L. Courvoisier, E. Ian Robinson. Copyright June 1991 *Scientific American,* Inc. All rights reserved.

Recent GRO data may provide clues to the nature of quasars (quasi-stellar objects), which are thought to be powered by black holes 10 million times the mass of the sun. These black holes are thought to produce jets that can be intense sources of gamma radiation.



Tom Prince, associate professor of physics, has been a member of the Caltech faculty since 1979, after receiving his BS from Villanova in 1970 and his PhD from the University of Chicago in 1978. His group has been active in the development of imaging gamma ray telescopes. Currently he's chairman of the NASA GRO Users Group, and also has been instrumental in the growth of parallel supercomputing at Caltech.