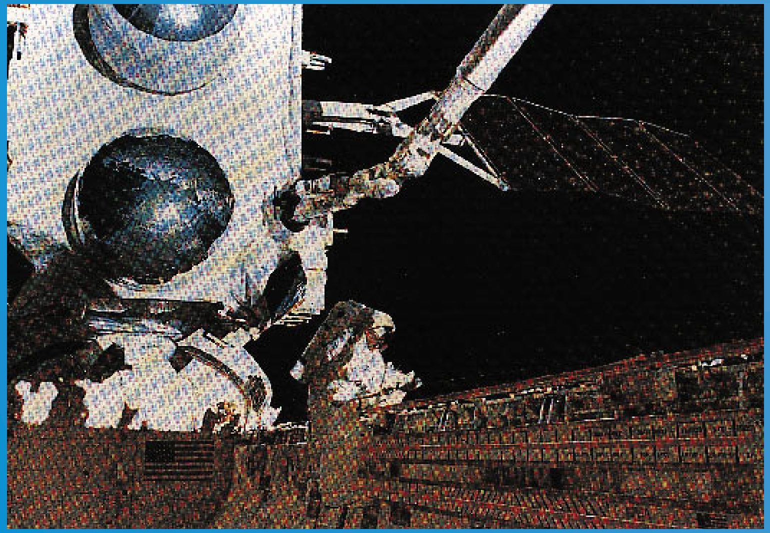
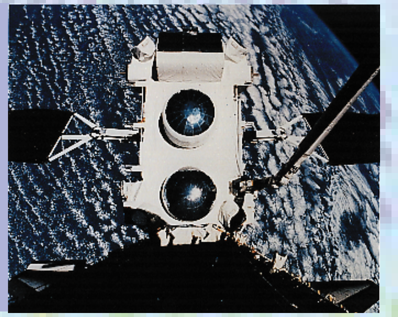
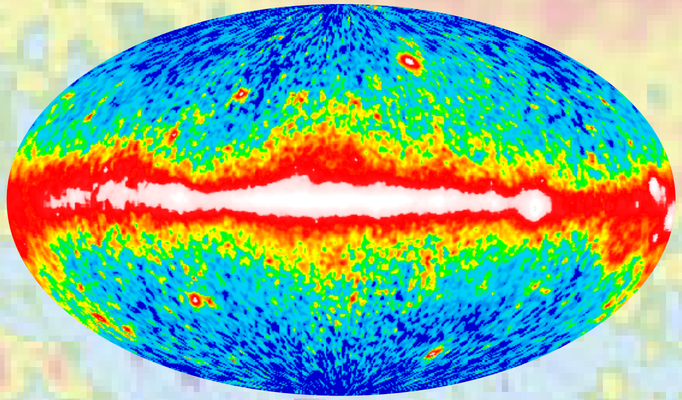




Gamma-Ray Astronomy in the Compton Era



National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland

"Who is there, who has not asked himself, 'What is this world around me?' Rocks, trees, people — what are the parts of which they are made, and how are these parts put together? Light, radio waves, x-rays — what are these radiations?"

A.H. Compton

Compton Observatory Science Highlights: Gamma-ray Bursts

✸ The discovery that gamma-ray bursts come uniformly from all directions in the sky indicates that the bursts are not confined to our Milky Way galaxy, but are probably due to huge explosions in the distant reaches of the universe.

✸ The careful measurements of gamma-ray burst brightness has revealed that there are surprisingly few dim bursts being measured. Assuming that dimmer bursts come from further away implies that the burst distribution has an outer edge.

✸ The detection of high-energy gamma rays hours after the bursts indicates some kind of lingering activity must be occurring in the sources after the initial fireball.

Compton Observatory Science Highlights: Galactic Sources

✸ An increase in the number of detected gamma-ray pulsars from 2 to 7 — this has resulted in much greater understanding of the basic physics of these rapidly rotating neutron stars.

✸ The discovery of the "Bursting Pulsar", an exotic object near the galactic center which is unlike any previously known gamma-ray emitter.

✸ A large increase in the number of mysterious, unidentified gamma-ray sources both in and out of the plane of the Milky Way galaxy.

✸ The discovery, with the help of x-ray observations, that the previously unidentified source known as Geminga is a gamma-ray pulsar. This could be an important clue to the nature of several other unidentified sources.

Compton Observatory Science Highlights: Diffuse Emission

✸ The mapping of the Milky Way galaxy using the 26Al isotope uncovered surprising localized enhancements in emission. This has important consequences for how chemical elements are created in our galaxy.

✸ Extensive studies of electron/positron annihilation radiation from the center of the galaxy.

✸ The discovery of gamma-ray line emission from the supernova remnant Cas A. This is also very important for the synthesis of elements.

✸ The discovery of gamma-ray lines from the Orion complex of diffuse gas clouds. These lines are probably caused by energetic cosmic rays interacting with local gas.

Observatory Science Highlights: Extragalactic Sources

✸ The emergence of blazar Active Galactic Nuclei (AGN) — highly variable cores of distant galaxies — as a primary source of cosmic gamma rays at the highest energies.

✸ Sensitive measurements of the energy distribution for another type of active galaxy known as Seyfert galaxies, which show that the production of gamma-ray photons dies out at much lower energies than previously thought.

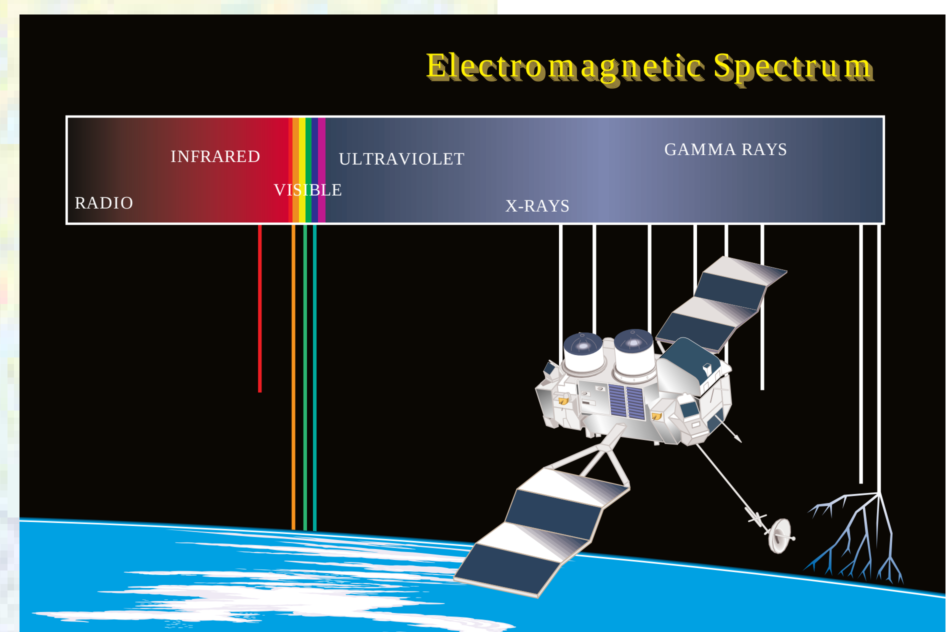
✸ The detection of diffuse gamma-ray emission from the Large Magellanic Cloud, a nearby galaxy whose gamma-ray flux indicates that cosmic rays are galactic in origin — helping to solve a longstanding problem in high-energy astrophysics.

Gamma-Ray Astronomy in the Compton Era: Introduction

Looking into the night sky, one sometimes feels that the visible Universe is a calm, comfortable place. NASA's Compton Gamma Ray Observatory looks at a very different cosmos. This is the Universe viewed through gamma-ray photons, the highest energy portion of the electromagnetic spectrum. This is a place of explosive energy, cosmic particle accelerators, and exotic environments such as collapsed stars and mysterious bursters. A place of nuclear decays, particle collisions, extraordinary temperatures, and violent explosions. For the first time, the entire sky has been comprehensively studied using this high-energy radiation. From the Sun to the furthest galaxies — from diffuse clouds of interstellar gas to the cores of powerful, gigantic black holes — the Compton Observatory has reshaped the way scientists view nature.

Each gamma-ray photon (which is the basic "piece" of light, much like electrons are one of the basic pieces of normal matter), carries at least 10,000 times the energy of a common photon of visible light. This energy is usually measured in electron-volts (or eV). A typical optical photon has around 2 or 3 eV's of energy. The gamma-ray spectrum begins at energies of around 50,000 eV (or 50 keV) and extends up to 1 TeV (1,000,000,000,000 eV) or even higher! The window provided by gamma-ray astronomy gives researchers valuable information about a wide variety of astrophysical phenomena, information which is impossible to get by other means. The high-energy part of the electromagnetic spectrum reveals information about nuclear interactions and decays, about how elementary particles are created and accelerated in astrophysical sources, and clues to the origin of cosmic rays. Gamma rays are not easily scattered or destroyed. So once created, gamma rays can provide unambiguous information about very important astrophysical environments. Over the years, astrophysicists have realized that in order to fully understand nature, one must observe in as many ways possible to provide a unified view. With the launch of the *Compton* mission, gamma-ray astronomy has, for the first time, become an integral part of this multi-wavelength approach.

This success did not come quickly or easily. Gamma-ray astronomy is a very difficult discipline to pursue for several reasons. First, it cannot be accomplished from the ground like radio or optical astronomy. The earth's atmosphere is opaque at gamma-ray energies. Cosmic gamma rays are absorbed high up in the atmosphere. Only at the highest energies are gamma rays detectable from the ground, through the large showers of particles caused by interaction with the atmosphere. Also, gamma rays are scarce. Even the brightest sources emit relatively few photons at these energies as compared to other energy bands. The Crab pulsar, a bright source, emits about one gamma-ray photon for every 10,000 optical photons. Finally, the cosmic gamma-ray



TOP: Arthur Holly Compton, the Nobel Prize winning American physicist for whom the Gamma Ray Observatory is named.

LEFT: Gamma rays occupy the highest energy portion of the electromagnetic spectrum. Only at the highest energies do remnants of the cosmic gamma rays survive to ground level.

signal is partially masked by a similar signal from cosmic rays – elementary particles which have a uniform distribution on the sky and often affect detectors in ways similar to gamma rays. Given these constraints, the only way to get useful information is to make very large, complex detectors and fly them above the Earth's atmosphere.

As a result of these difficulties, it has taken several decades for gamma-ray astronomy to fulfill its promise. Theoretical studies dating back to the 1950's emphasized the value of gamma-ray astronomy. Pioneering instruments, which paved the way for later satellite-borne experiments, were flown on rockets and more frequently in high-altitude balloons throughout the 1960's and 70's, a practice that survives today as a way to test new instrumentation. These vehicles provide only short observations, insufficient to carefully observe nature at gamma-ray wavelengths. The first real inroads came with the pioneering space-borne missions of the 1970's like the SAS 2 and COS–B missions which provided truly fundamental results in this field. These instruments explored the nature of diffuse gamma-ray emission, provided detailed observations of the first known gamma-ray pulsars, and uncovered a population of unidentified gamma-ray emitters which still puzzle scientists today.

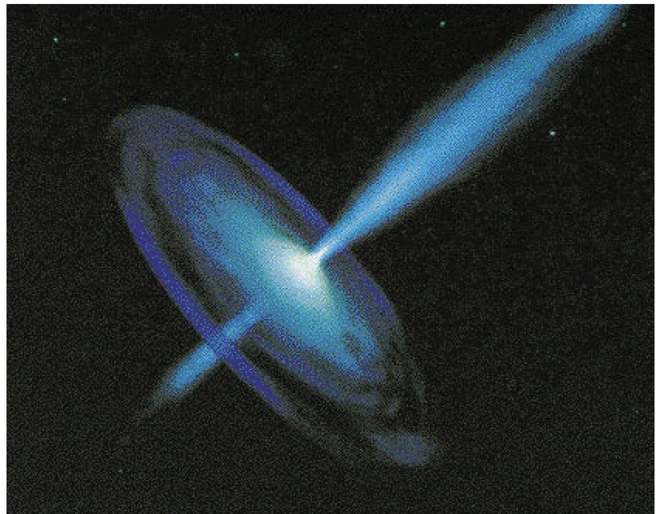
Sometimes early progress came in more unexpected ways. As far back as 1968 the Vela satellites — created to monitor the Earth's atmosphere for nuclear explosions — detected brief bursts of gamma rays of cosmic origin coming from random directions on the sky. Networks of subsequent satellites carrying gamma-ray burst detectors established in the inner solar system since 1976 have produced source locations for these transients using wavefront arrival timing analysis (a method analogous to triangulation of ships at sea). However, searches of these source locations have produced no obvious counterparts to the gamma-ray bursts at any other wavelength.

Whether the source of gamma rays was expected or not, knowing how gamma rays are produced is the key to understanding what they reveal about a source. Nature creates gamma rays in a variety of ways. If the temperature of the environment is high enough — around 100 million degrees Celsius — they can be produced in a manner similar to less energetic x-ray radiation. These so-called thermal photons are often produced as a result of an explosive event such as a supernova. They are also produced through powerful gravitational interactions such as when a black hole or neutron star is capturing matter from a companion star. The detection of gamma-ray photons produced in this way yields valuable information about how compact stars interact with their environments and the energy budget of these sources.

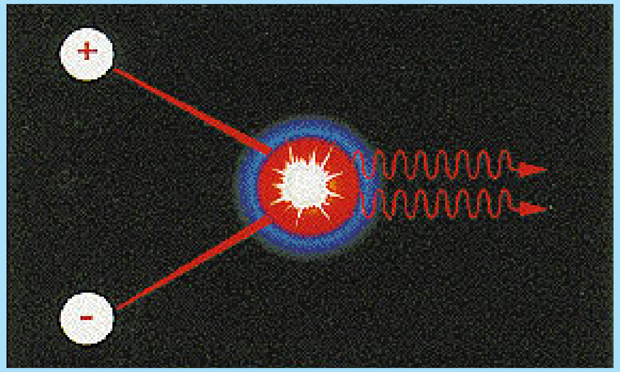
One of the original goals of gamma-ray astronomy research was to study cosmic sources of radiation created by atomic nuclei. These nuclear lines are the emission of photons at characteristic energies and are typically produced as a result of normal radioactive decay or through interactions of particles with nuclei. Just like the more familiar optical lines caused by the electron transitions in atoms, nuclear lines represent the much more energetic transitions and interactions of protons and neutrons inside the atomic nucleus. Gamma rays produced in this manner give scientists valuable information about how elements are created and destroyed in our galaxy and beyond.

Gamma rays are also produced by other "nonthermal" processes. This term implies that the photons are the results of fundamental interactions between elementary particles or between these particles and other photons, rather than being emitted by a hot, thermal "stew" of plasma. These types of interactions occur in very special environments. Sites like the incredibly high magnetic fields of young neutron stars or the powerful jets of radiation emanating from a gigantic black hole. The main processes taking place have names like pair annihilation (particles and antiparticles destroying each other with the result being gamma-ray emission), Compton scattering (wherein a charged particle collides with a photon — changing the energy and direction of the photon), and synchrotron emission (the photons emitted when relativistic charged particles travel in a magnetic field).

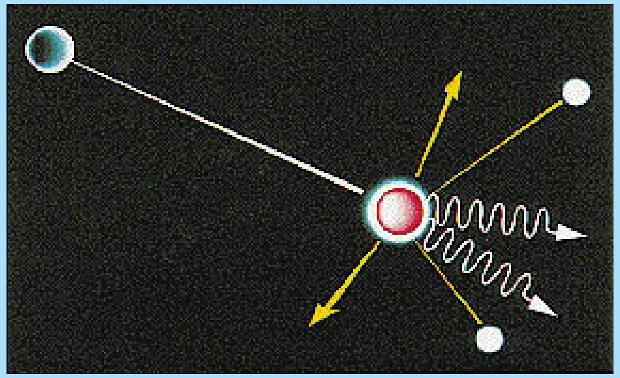
The means by which gamma-ray photons are created are also related to how these photons are detected. The nonthermal processes are the key to how instruments detect high-energy photons. Unlike optical and x-ray photons, gamma rays cannot be focussed by a mirror — they simply pass through thin materials. Paradoxically, one of the reasons gamma rays are valuable is that they are less affected by their environment than lower energy photons, thus providing a more pristine view of the source. Interactions within gamma-ray detectors such as pair creation, Compton scattering and nuclear excitation — those processes which give rise to the photons at the cosmic source — are used to measure the time of gamma-ray arrival and energy. Gamma-ray instrumentation relies on detection techniques developed in the world of high-energy physics. Phototubes . . . spark chambers . . . scintillators . . . collimators . . . these are some of the terms in the lexicon of gamma-ray instrument builders. Putting all these devices together into a coherent mission to investigate the unexplored gamma-ray universe was the challenge of the Compton Gamma Ray Observatory Project.



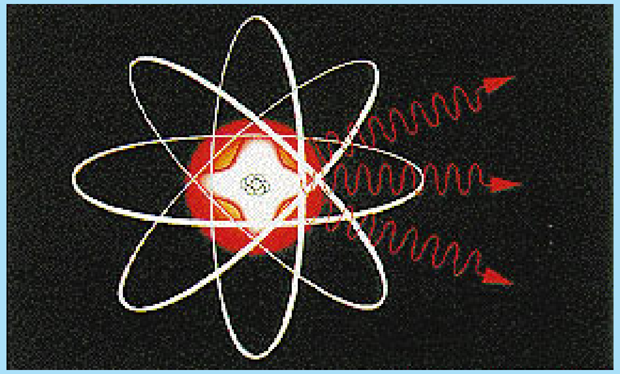
An accretion disk and jet associated with the center of an active galaxy — a gamma-ray quasar. Such objects are an important component of the gamma-ray sky.



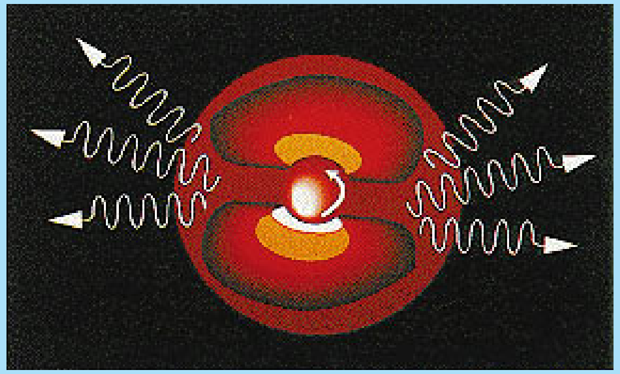
Matter-antimatter annihilation



Particle-particle collisions



Radioactive nuclei



Cyclotron radiation

Some of the fundamental physical interactions which result in gamma-ray line emission. Other processes can produce gamma rays over broad energy ranges.

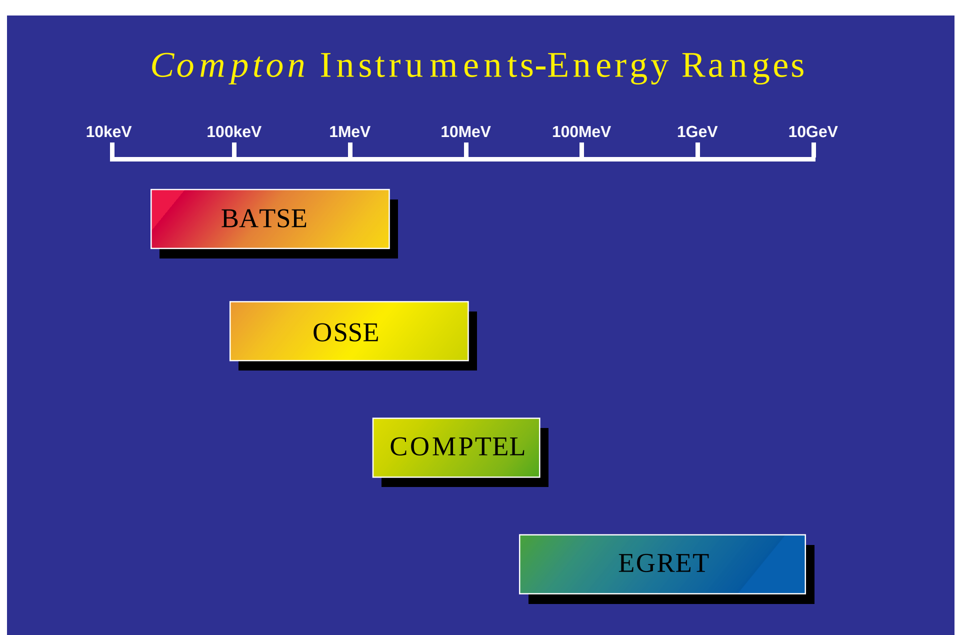
The STS 37 space shuttle launch which carried the Compton satellite into orbit. Compton, at 17 tons, is the largest scientific payload carried by the shuttle.

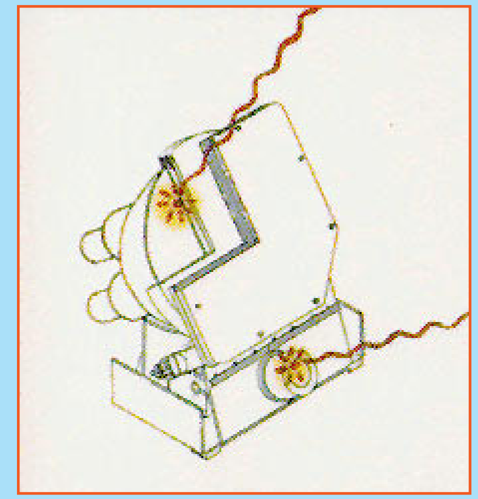
Gamma-Ray Astronomy in the Compton Era: The Instruments

A 14-year effort of scientific vision, careful instrument design, spacecraft engineering, and mission development culminated in the 1991 space shuttle launch of Compton. Since launch, the Compton project has exceeded expectations, providing high-quality science data to over 750 scientists from 23 countries. The international scope of the Compton mission is also revealed through the instrument builders — the United States, the Federal Republic of Germany, the Netherlands and the United Kingdom all contributed. The four onboard science instruments combine to provide complementary capabilities for mapping the gamma-ray sky, probing the energy distribution of individual sources, and monitoring the sky for time variable phenomena.

These capabilities were intended to solve some of the outstanding questions earlier missions had posed — questions about the nature of gamma-ray bursts, about the behavior and number of gamma-ray emitting pulsars and active galaxies — and perhaps most importantly, to watch for the unexpected. The enhancements in sensitivity of the *Compton* instruments over previous experiments hold the key to this progress. To detect more gamma rays, one simply needs larger instruments. The size of the *Compton* instruments, the benefits of a long mission, and anticoincidence techniques which prevent cosmic rays from mimicking gamma-ray signals have allowed *Compton*'s instruments to make significant contributions to high-energy astrophysics. While there is some overlap in capabilities, each of the four instruments has special design characteristics which allow them to perform unique and valuable science.

The Compton instruments cover more than six orders of magnitude in energy in a complementary manner.





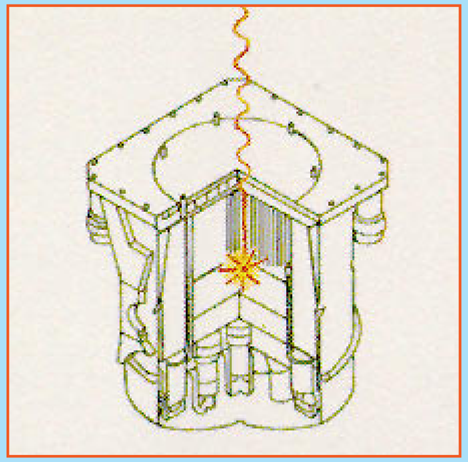
BATSE - the all-sky monitor for Compton is designed to detect gamma-ray bursts and search the sky for other transient emission.

BATSE

BATSE – the Burst and Transient Source Experiment – is the all-sky monitor for *Compton*. This experiment uses eight independent detectors, one at each corner of the satellite, resulting in a continuous view of those parts of the sky not blocked by the Earth. The individual modules use scintillators as the active detection element. Scintillators are large crystals, in the BATSE case made of sodium iodide, which convert the energy of the gamma ray into visible light. Photomultipliers viewing the crystal then detect the visible photons. The strength of the resulting electronic signal is the record of the gamma-ray energy. BATSE can detect photons in the range of about 20 keV to 1 MeV. This instrument has the capability to detect many gamma rays in small periods of time, allowing scientists to study the temporal structure of gamma-ray bursts. While an individual BATSE module cannot record the direction of the incident gamma rays, the relative strengths of the burst signal in each module result in an approximate triangulation of the burst position.

The origin of gamma-ray bursts remains the longest unsolved mystery in modern astronomy. Hundreds of gamma-ray bursts were detected prior to the launch of the Compton Gamma Ray Observatory, but few clues to their nature have been forthcoming. One of BATSE's primary objectives is to study these sources by mapping their positions on the sky and by measuring their brightness, spectra and temporal development. Their time profiles are particularly enigmatic, lasting a few tens of milliseconds to hundreds of seconds, each burst exhibiting a unique and complex evolution of brightness with time. Since *Compton*'s launch, approximately one gamma-ray burst per day has been detected by BATSE. In addition, BATSE has the capability of performing long-term monitoring of other types of gamma-ray sources. Many objects emit photons in the same energy band as gamma-ray bursts, including accreting neutron stars and black holes, some radio pulsars and active galaxies. BATSE provides a valuable capability for detecting changes in flux associated with these objects over a large range of timescales and helps scientists understand the mechanisms responsible for their high-energy emission.

BATSE also uses its gamma-ray burst design capabilities to provide valuable data on the hard x-ray emission from solar flares.

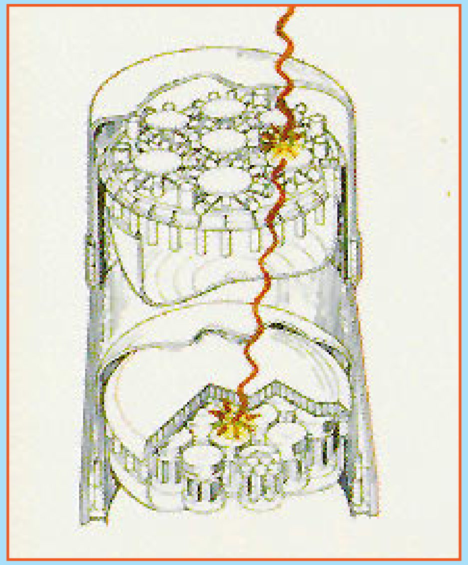


OSSE provides sensitive spectral measurements of individual gamma-ray point sources.

OSSE

OSSE – Complementing BATSE is the Oriented Scintillator Spectrometer Experiment (OSSE) which provides the capability of detecting sources in the band from 50 keV to about 10 MeV. OSSE is composed of four independent modules, each a collimated scintillator. Collimation refers to the practice of placing a baffle on the detector to reduce the field-of-view. This allows the detector to concentrate on a single source. The independent modules of OSSE can also view a background region simultaneously for comparison with the source region. This comparison allows OSSE to detect sources which are much weaker than those routinely observable with BATSE. In addition, OSSE provides very good spectral capabilities over its entire energy range. This allows for sensitive searches for features which are important diagnostics of source environments.

These spectral features are the primary science objectives for OSSE. There are many types of features OSSE can look for. Gamma-ray lines, which are enhancements in the numbers of photons detected around some characteristic energy, are the main type. An example of such a line is the 511 keV line associated with the pair annihilation of electrons and positrons (the electron's antiparticle). Other types include lines from nuclear decays or interactions, and cyclotron lines which are caused by the effect of very strong magnetic fields on gamma-ray emitting particles. OSSE is sensitive to other spectral features such as changes in the continuum emission from gamma-ray sources. Most gamma-ray sources have a smooth distribution of strength of emission (flux) versus energy. By finding variations in this distribution, a great deal is learned about the source environment. OSSE has the capability to identify such features which in turn are crucial to understanding the basic physics involved.

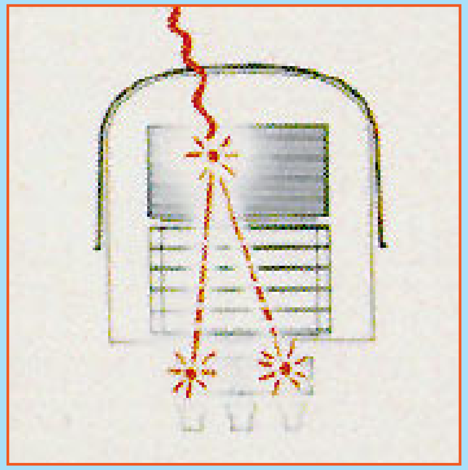


The COMPTEL instrument has provided the first comprehensive study of the universe in the 1 - 30 MeV energy range.

COMPTEL

Unlike BATSE and OSSE, the Imaging Compton Telescope – COMPTEL – is an imaging detector. This experiment allows scientists to make images of the gamma-ray sky, albeit at a reduced resolution as compared to optical astronomy, over the energy range from about 1 to 30 MeV. This experiment employs a novel design where gamma rays are Compton scattered in the top detector and absorbed in the lower detector. By tracing backwards the path of the scattered gamma ray from top to bottom and measuring the total energy deposited in the detectors, the location of the cosmic gamma ray on the sky is found to lie on an circle and not at a point as seen by a traditional detector. The intersection of "event circles" from many photons determines the location of the gamma-ray source in the sky.

The COMPTEL energy range is important to nuclear astrophysics. Nuclear reactions occur during cataclysmic events such as novae, which are nuclear explosions on the surface of a white dwarf or other compact star, or supernovae, which are totally catastrophic stellar explosions. During these events, nuclear reactions fuse together the light elements of helium, carbon, nitrogen, and oxygen into the heavier elements of aluminum, nickel, and iron while releasing gamma rays in the 0.5 - 5 MeV energy range. Many of these heavier elements are then ejected into interstellar space as radioactive isotopes, which then decay into stable isotopes releasing neutrons and gamma rays. This energy range has historically been a very difficult one to work in. COMPTEL does a good job of bridging the gap between more traditional detectors like OSSE and EGRET.



EGRET is the highest energy experiment onboard Compton with sensitivity up to 30 GeV.

EGRET

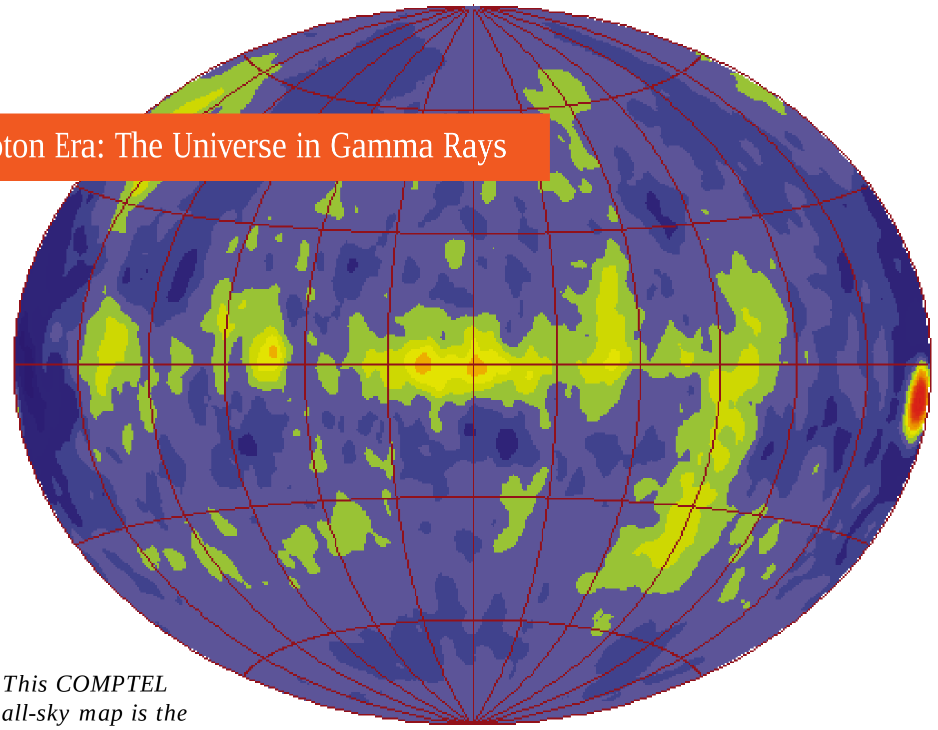
The Energetic Gamma-Ray Experiment Telescope (EGRET) is sensitive to photons in the energy range from 20 MeV to 30 GeV, the highest energies accessible by the *Compton* instruments. Like COMPTEL, EGRET is an imaging instrument. The basic instrument design is that of a spark chamber, technology which is borrowed directly from high-energy physics. The cosmic gamma ray enters the instrument and interacts with absorber material. At these energies, pair production is the dominant process. The gamma ray is converted into an electron/ positron pair. As this pair travels through the gas-filled chamber, sparks are detected in electrified wires which criss-cross the chamber. The spark chamber essentially takes a picture of the trail of the pair as they pass through the instrument. These tracks lead back to the incident direction of the cosmic photon, allowing EGRET to image the sky. Once the pair exit the chamber, they are absorbed by a scintillator which gives a good estimate of the total pair energy, and hence the energy of the incident photon.

EGRET is in the tradition of previous spark chamber experiments which have detected pulsars and active galaxies as high-energy gamma-ray sources. The improved sensitivity of EGRET, however, allows for much more detailed study of such objects. EGRET is also intended to perform detailed studies of diffuse gamma-ray emission. This emission is the result of interactions of cosmic rays with interstellar material, the study of which provides important information about the origin of cosmic rays. There are also many gamma-ray sources detected at EGRET energies which are unidentified at any other energy. No known counterpart exists for these sources and uncovering their identity is another important aspect of EGRET science.

Beyond their individual capabilities, the CGRO instruments work together to provide an even more comprehensive study of nature. For instance, BATSE can provide signals to the other three instruments which allow them to respond, with tailor-made instrument configurations, to solar flares or gamma-ray bursts. EGRET, COMPTEL, and OSSE often observe the same object simultaneously, affording tremendous potential for further understanding of detected sources. The CGRO instruments often observe sources simultaneously with other satellite- or ground-based observatories to provide a truly comprehensive view. This approach, called multi-wavelength astronomy, gives scientists the most complete information about our universe. Ultimately, however, the gamma ray view by itself has proven to be pretty spectacular!

Gamma-Ray Astronomy in the Compton Era: The Universe in Gamma Rays

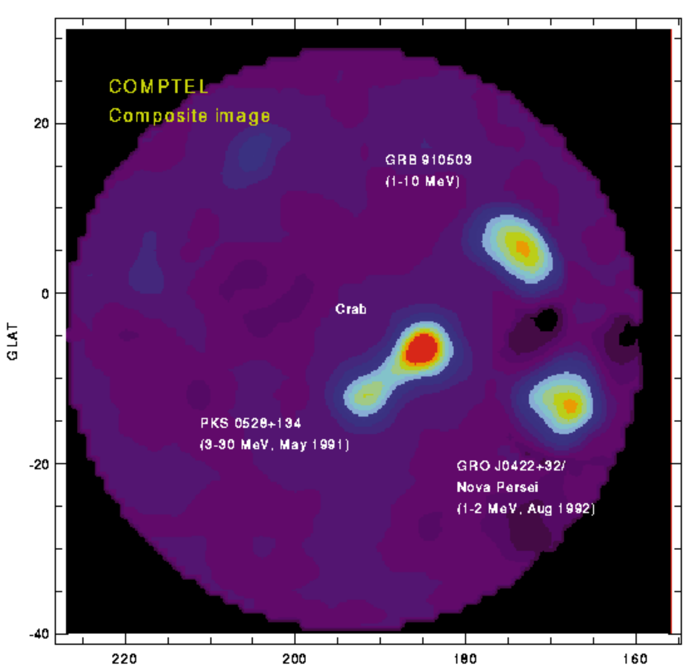
The Compton instruments combine to provide many different views of the high-energy universe. Perhaps the most interesting, and one representing a primary mission goal for Compton, is the all-sky survey. The first two and one half years were devoted to viewing the entire gamma-ray sky with the two imaging detectors, EGRET and COMPTEL. The remarkable images which resulted from this survey show for the first time what the sky looks like over the medium (1-30 MeV) and high (>100 MeV) energy ranges.



This COMPTEL all-sky map is the first ever at MeV energies. This image complements the EGRET all-sky map which is shown on the front cover.

The dominant feature is the wide strip across the middle of the image which is the gamma-ray glow of the Milky Way. This is shown particularly well by the EGRET map on the front cover. This diffuse emission gives astronomers insight into the interactions of cosmic rays and interstellar material. Unfortunately, this emission also makes it more difficult to detect point sources of gamma rays which lie in the galactic plane. The other main feature of these maps is the occasional island of enhanced emission seen over the diffuse background. These are the gamma-ray emitting pulsars and galaxies which are of considerable interest to astronomers. Many of these point sources are not obvious from simply inspecting the map. For instance, the EGRET point source catalog contains 157 individual sources. Advanced statistical methods are required to distinguish the weaker sources from mere fluctuations and to make the best estimates of the source characteristics such as true location, total flux, and variability.

For a more detailed look, we can focus in on a smaller region of sky. The anticenter region (so-called because it is 180 degrees away from the direction to the galactic center) is a good place to start. The COMPTEL image of the anticenter shows four different types of objects which represent the variety of the gamma-ray sky. The Crab pulsar, the active galaxy PKS 0528+134, the transient gamma-ray source GRO J0422+32, and the gamma-ray burst GRB 910503 were all detected by COMPTEL in this region. Much of the sky is similar, look closer and you will find several sources, each with distinct characteristics. It is worth spending a little time discussing all these types of sources in more detail to understand the contributions of the *Compton* instruments.

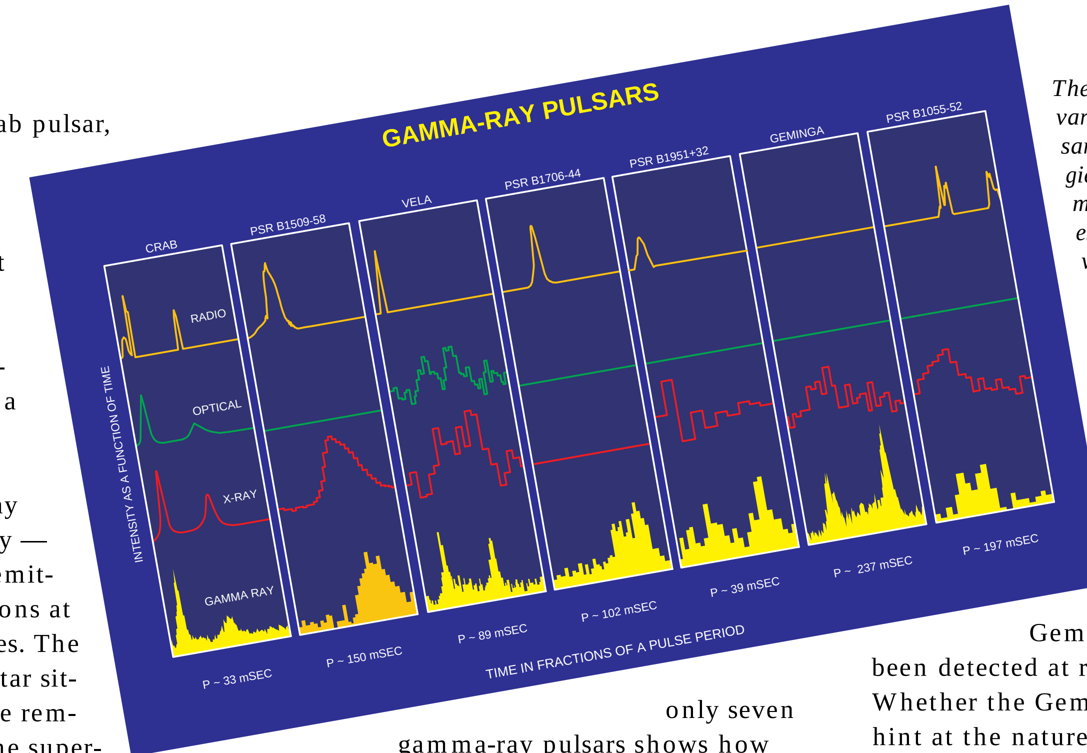


The COMPTEL view of the galactic anticenter. The diversity of the gamma-ray sky is apparent even from this limited region.

Pulsars

The Crab pulsar, which is one of the most important objects in the sky at any wavelength, is a standard candle of gamma-ray astronomy — strongly emitting photons at all energies. The neutron star sitting in the remnant of the supernova which dominated the sky in 1054 A.D. is rotating 30 times per second. With each rotation a beam of gamma rays sweeps past the Earth creating the effect of pulsations. Pulsars have been likened to spinning magnets. This description, although somewhat accurate, hides the complexity that exists in the incredibly strong magnetic fields associated with neutron stars and the unknown structure of the collapsed star. Careful study of the gamma-ray energy distribution, and pulse shape of the Crab pulsar have supplied needed information about how gamma-ray pulsars work.

Before *Compton*, only two gamma-ray pulsars were known, the Crab and Vela pulsars. There are now seven: PSR 1509-58, PSR 1706 44, PSR 1055-52, PSR 1951+32 and Geminga all being added to the list. The names of most of these are based on coordinates from radio observations. In fact, there are around 550 radio pulsars known at this time. The fact that there are only seven gamma-ray pulsars shows how special the environment must be to create gamma rays. The gamma-ray pulsars tend to be of the young, rapidly-spinning variety. Each pulsar has unique characteristics and the pulse shapes can be highly dependent on the energy range. Knowing why some pulsars emit gamma rays and some don't, how the pulse shapes in each energy range arise, and what the gamma-ray photons say about the structure and environment of the neutron star, are at the heart of gamma-ray pulsar research.



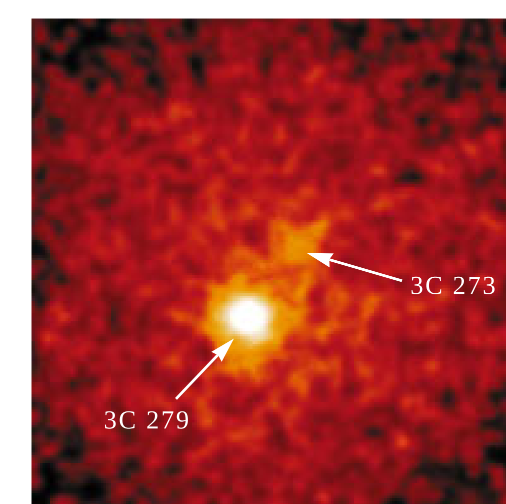
The folded light-curves of various gamma-ray pulsars at different energies. A straight line means no known pulses. Explaining the variety of pulse shapes and energy dependencies is a challenge to theorists.

The whimsically named Geminga is of a somewhat different nature. The name, which means "is not there" in a certain Italian dialect, refers to the fact that there was no apparent counterpart at any other wavelength to the very strong gamma-ray source first detected in the 1970's. Geminga was one of the large class of unidentified gamma-ray sources, the nature of which is still largely unknown. In Geminga's case, however, EGRET observations verified the x-ray detection of pulsations in the flux from Geminga, positively identifying it as a gamma-ray pulsar. Oddly, Geminga still has not been detected at radio wavelengths. Whether the Geminga story is a hint at the nature of the other unidentified sources or simply an anomaly is an important area of current research.

Active Galaxies

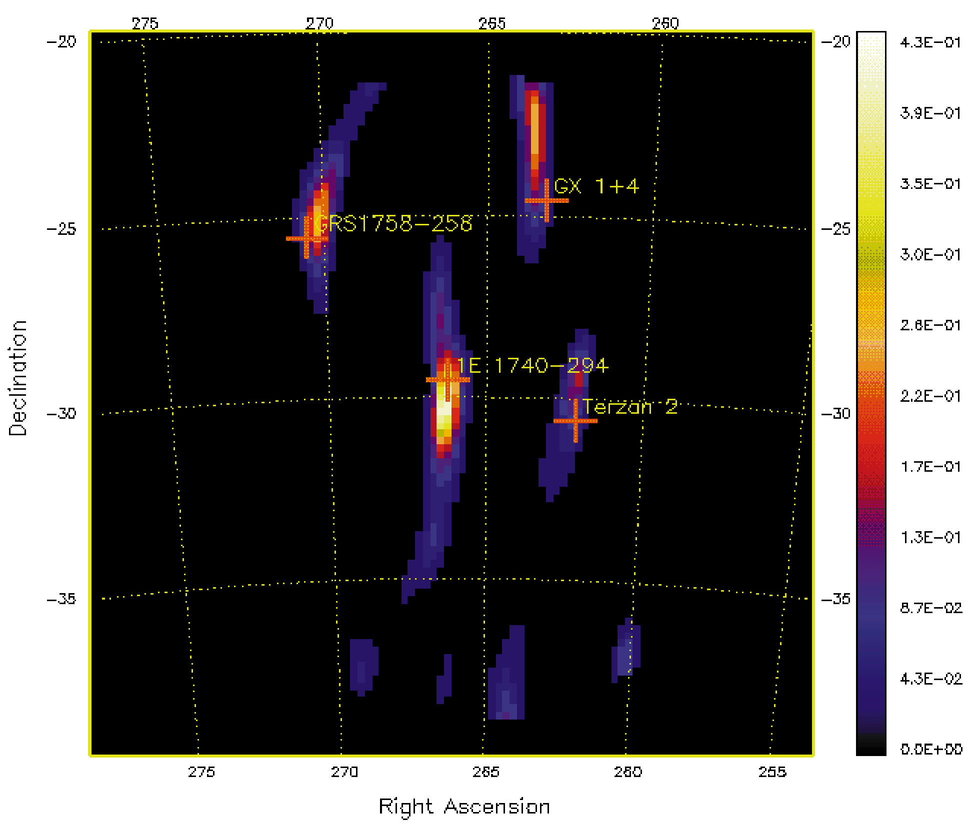
Back to our anticenter image, just slightly away from the Crab, the gamma-ray emitting active galaxy known as PKS 0528+134 is also

One of the first Compton surprises was the EGRET detection of the gamma-ray blazar 3C 279. The only previously detected gamma-ray blazar, 3C 273 can be seen to be weakly emitting.



clearly detected in the COMPTEL energy range. Active galaxies represent the largest class of gamma-ray emitters. These sources are incredibly powerful but are also highly variable. Look once and it is there, look again and there is no emission. This variability is because of the physics of the region surrounding the gigantic black hole presumed to power the active galactic nuclei. Emission from these "Blazar" AGN are believed to come from the jets of relativistic particles emanating out from "a central engine". Such jets are seen in radio maps of these sources. *Compton* studies of active galaxies have been one of the greatest successes of the mission. Over 50 Blazar-type AGN have been detected by the EGRET instrument alone.

A second type of AGN, known as Seyfert galaxies, also comprise an important class of gamma-ray emitting AGN. About 17 of these galaxies, which are much closer to the Milky Way than Blazars, have been detected mainly by the OSSE instrument. In the theoretical unified view of gamma-ray emission from active galaxies, Seyferts differ from Blazars in part because we are viewing them from a different angle, so that we are looking through the galaxy rather than looking face on as in the Blazars. In this way, the jet emission is less important than emission more closely associated with the inner regions of the galaxy itself. The OSSE instrument has found that the average spectrum of the Seyfert galaxies is well-described by this sort of picture. Unexpectedly, the Seyfert spectrum falls off much more quickly than previously thought. Previous observations suggested that Seyfert emission extended up to the MeV range. The average Seyfert spectrum indicates otherwise. This is an important clue to the inner workings of AGN.



The center of our galaxy is populated by many low-energy, rapidly changing gamma-ray sources. BATSE monitoring helps to unravel the mystery of these sources.

Accreting Galactic Sources

Back in our own galaxy, the COMPTEL source named GRO J0422+32 is a system known as a x-ray nova. This is an example of a third type of gamma-ray source — studied mostly with OSSE and BATSE — accreting galactic binary systems. The name describes the system well: a pair of stars, one normal and the other collapsed into a neutron star or black hole, are in orbit around one another. Depending on the mass of the companion star and the evolutionary history of the system, there can be relatively steady emission of low-energy gamma rays, or episodic emission whenever the pair are at their closest orbital approach. Studies of such objects have been aided by the sensitivity and long mission of *Compton*.

Another example of these systems can be found by looking at the center of our own galaxy. While not an imaging instrument in the classical sense, BATSE does monitor the entire sky. As the *Compton* satellite orbits, sources are alternately hidden and revealed by the Earth. Techniques can be used to calculate a coarse image of the sky using this information. The image of the galactic center calculated using this technique shows that these low-energy gamma-ray emitters are numerous. OSSE and BATSE observations continue to provide information on such topics as the definition of the binary orbit, the strength of the neutron star magnetic field, and the basic physics of accretion.

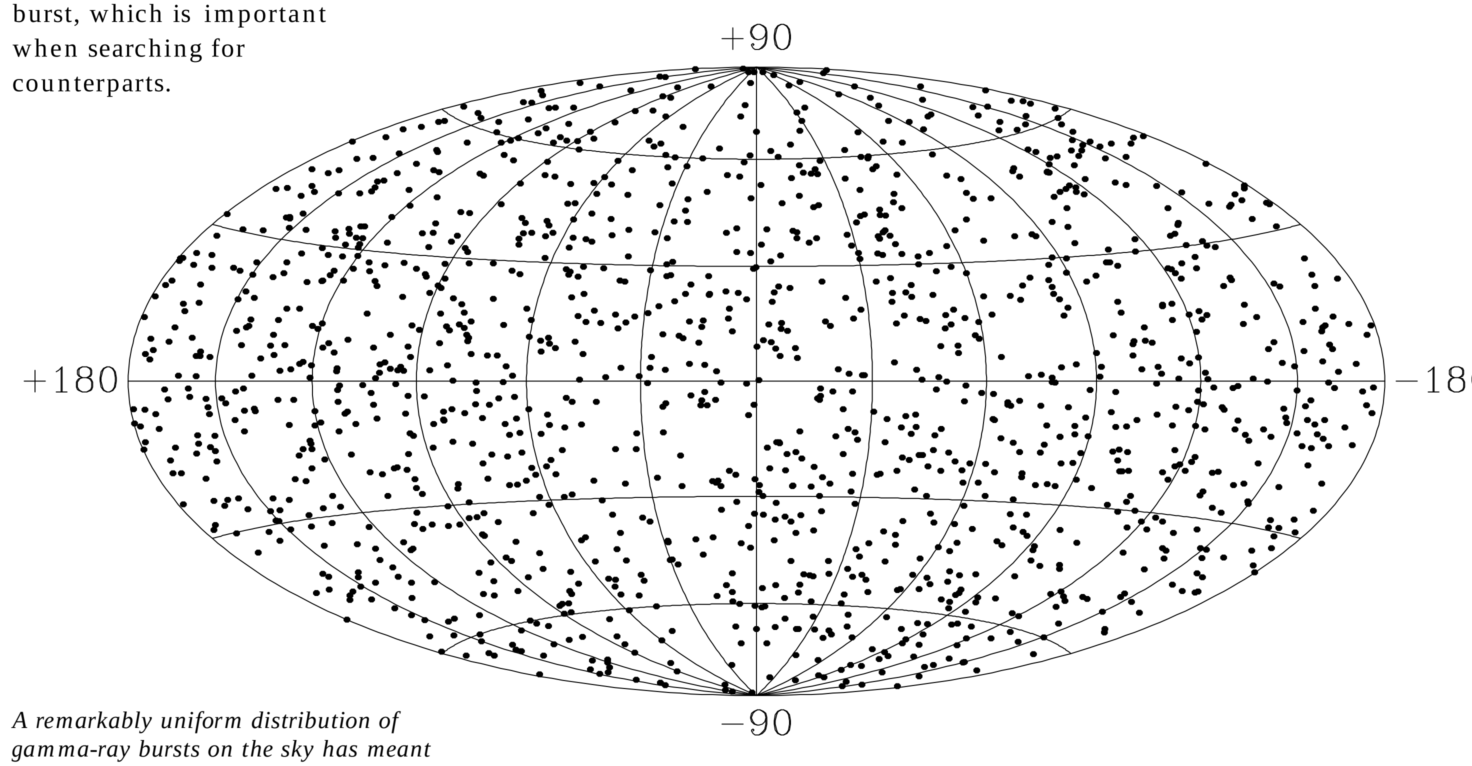
Gamma-Ray Bursts

The final source in the anticenter image is that of a gamma-ray burst. Normally, BATSE provides the only information on bursts. Once in a while, however, one of the imaging instruments can see the high-energy tail of a gamma-ray burst and actually image the burst emission. This information is quite valuable, allowing for a better localization of the burst, which is important when searching for counterparts.

Before the launch of *Compton*, the consensus of the astronomical community was that gamma-ray bursters must be a class of neutron star, born in the supernova explosions of dying massive stars that inhabit regions near the plane of our galaxy. BATSE was expected to reveal a clustering of burst directions near the galactic plane. Furthermore, the neutron stars were expected by some investigators to produce repeated burst performances.

BATSE, which detects about one burst per day, has not confirmed this galactic disk hypothesis. Instead, the celestial distribution of more than 1400 BATSE burst localizations is completely uniform on the sky, and no convincing evidence for repetitions has been found. The burst directions appear to be unassociated with luminous matter as far away as the Virgo supercluster of galaxies, with which our Milky Way galaxy is peripherally connected.

These are just a few of the images of our universe that *Compton* has provided astronomers. There is much more to the gamma-ray sky than this. Enhanced emission from diffuse clouds of gas, supernova remnants, and nearby normal galaxies are also detectable. Such static images give a somewhat misleading impression — perhaps the most important characteristic of the universe seen by *Compton* is that it is dynamic and unpredictable.

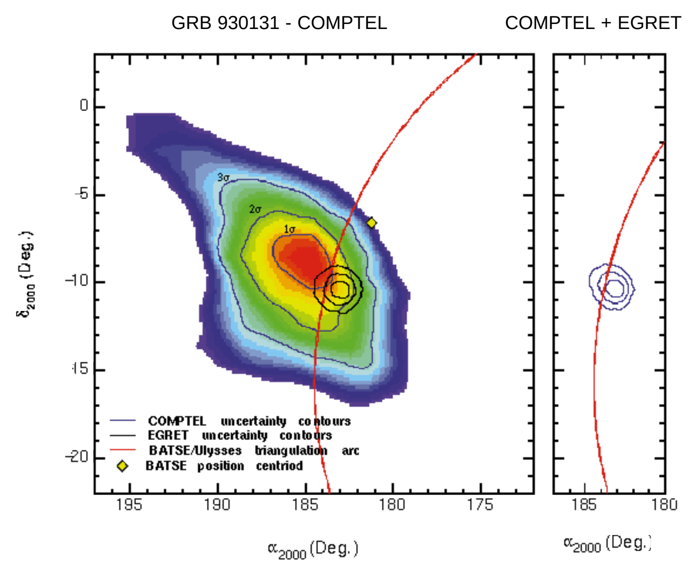


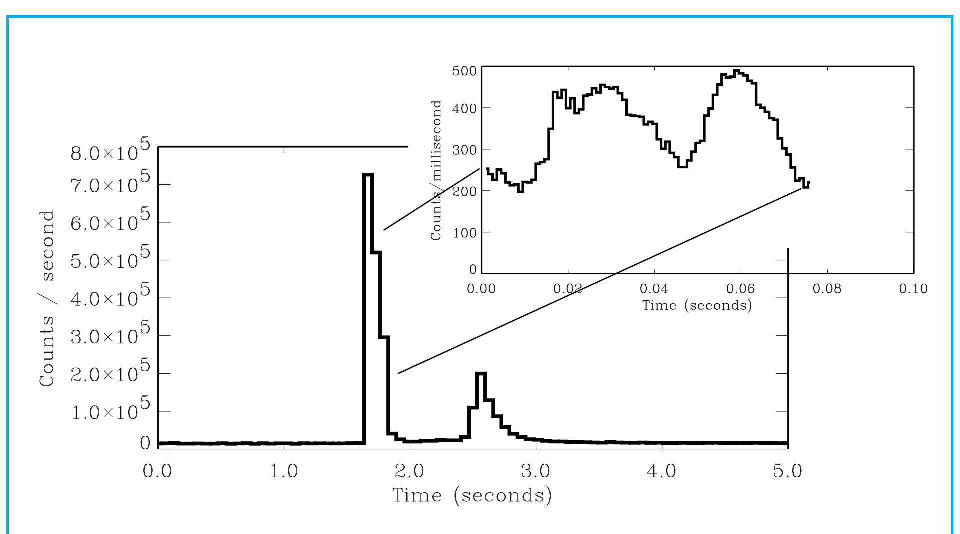
A remarkably uniform distribution of gamma-ray bursts on the sky has meant trouble for models of bursts based upon galactic objects. A galactic population would preferentially show a clustering along the galactic plane.

We have known since the 1970's that the gamma-ray sky is variable. Only since Compton have we realized the tremendous richness of the high-energy sky. Supernovae, x-ray novae, active galaxies, the Sun, bursts — the sky is constantly changing. The flux from an individual source can often change by an order of magnitude or more.

No other sources, however, match gamma-ray bursts for their extraordinary behavior. For example, while millions of TV viewers watched the Superbowl on January 31, 1993, the wavefront of a very intense gamma-ray burst passed across the Earth and was detected by all four instruments on *Compton*. This burst was briefly more than 1000 times brighter than the rest of the gamma-ray sky. As seen by BATSE at low gamma-ray energies, 10 keV to a few MeV, the intense part of the burst consisted of a few short, closely spaced pulses lasting only about one second. EGRET also detected this initial phase of the burst, but quite unexpectedly, emission was seen to persist almost one minute later at high gamma-ray energies, 100 MeV to several GeV, where EGRET is most sensitive. This "Superbowl Burst" was also seen by a detector on the Ulysses spacecraft, allowing the location to be refined well beyond the positional uncertainty of most gamma-ray bursts. Unfortunately, the ephemeral character of gamma-ray bursts makes it difficult to identify the source of the burst. There are many typical celestial objects within even the smallest burst location error circle. Unless a flash of light at other energies, say radio or optical energies, is seen simultaneously with the gamma-ray burst, it is extremely difficult to argue for any of the candidates. This is what makes the problem of gamma-ray bursts so difficult. At this time, we must rely almost exclusively on the gamma-ray information alone.

For example, the burster distance or emission pattern is constrained by the presence of high energy gamma-rays such as those detected in the Superbowl Burst. The more distant the gamma-ray burst source is, the higher its intrinsic luminosity, and correspondingly the higher the gamma-radiation density within the source itself. In a very dense radiation field these high-energy photons can collide and annihilate. The survival of GeV photons against gamma-gamma annihilation implies either that the sources must be very close by — less than tens of light-years distant — so that the gamma-radiation field is not too dense, or that the radiation is highly collimated or "beamed", thereby avoiding collisions between the gamma rays and allowing their exit from the source. Thus the gamma-ray bursters may effectively be enormously powerful cosmic beam machines.

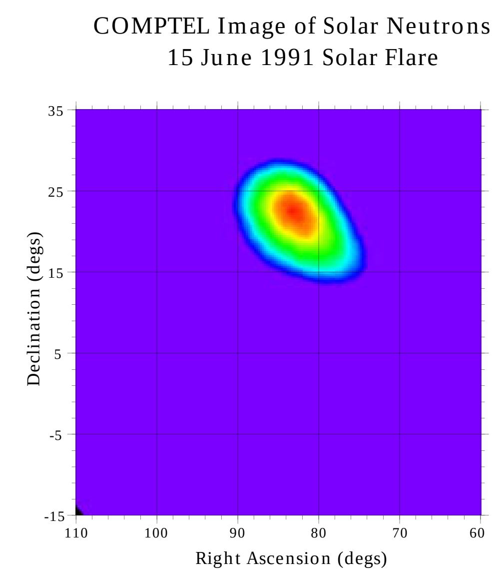


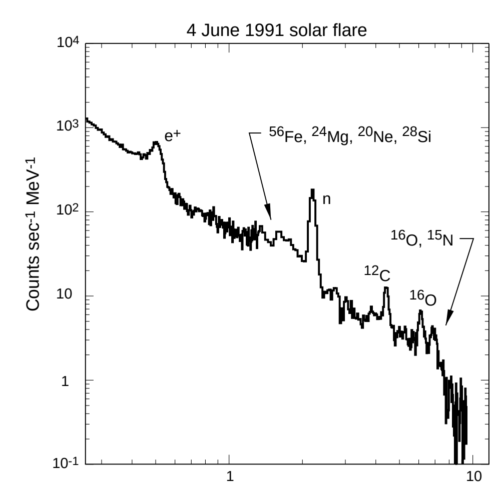


Lightcurve of the "Superbowl Burst" showing complex structure at different timescales. Understanding the wide variety of burst time profiles and durations are part of the mystery of gamma-ray burst astrophysics.

LEFT: Localization of the Superbowl Burst. Since it was detected by all four Compton instruments as well as another spacecraft, this location is particularly good. Even the best burst locations, however, have not yet resulted in the identification of an object responsible for a burst.

BELOW: Details in the OSSE solar spectrum help identify the nature of particle acceleration during solar flares. The COMPTEL image is a remarkable picture of the Sun in the "light" of neutrons.





While not as mysterious as gamma-ray bursts, solar flares can be just as exciting. Most normal stars are not candidates for study by *Compton* instruments, but the Sun is so close by that even weak emission can be detected. In the case of solar flares, which are highly energetic bursts of radiation from the Sun due to acceleration of particles in loops formed in the outer solar atmosphere, the same capabilities BATSE uses to detect cosmic gamma-ray bursts are used for flare studies. Flare activity is related to the so-called solar cycle, an approximately 11-year period during which solar activity (and hence flares and sunspots) go through relative maxima and minima. The launch of *Compton* came shortly after such a solar maximum. Luckily, solar activity was still at a very high level and valuable observations were made. *Compton* will still be in orbit during the next solar maximum.

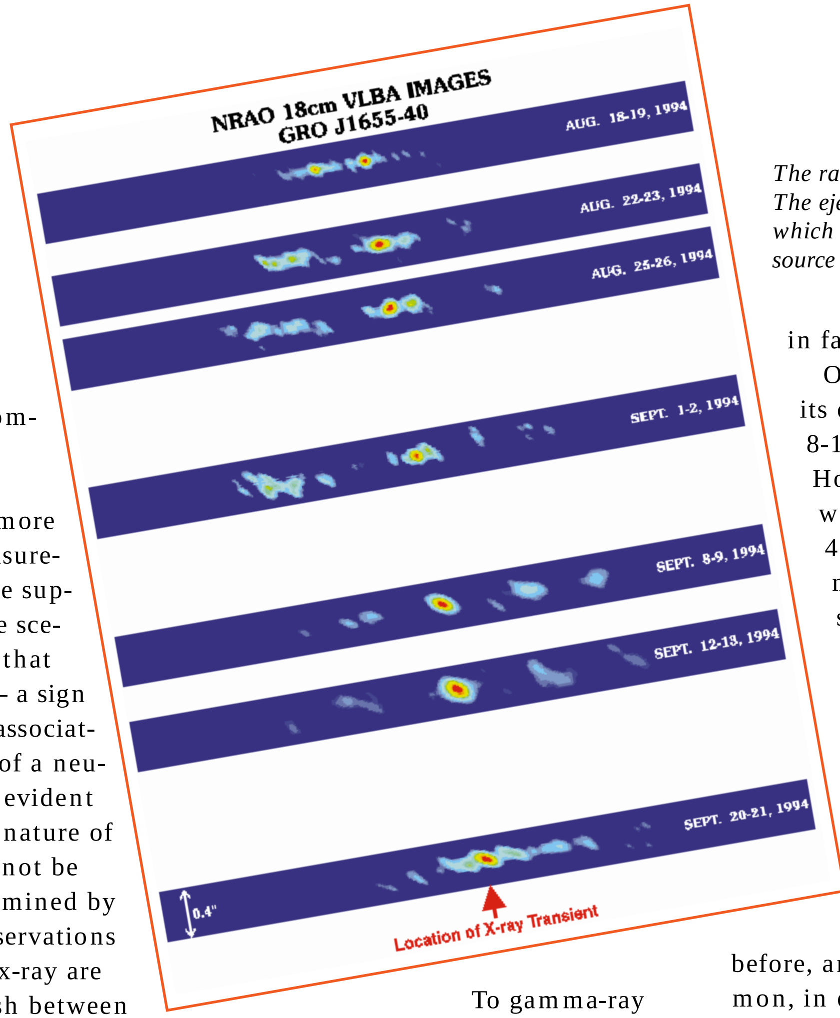
Much has been learned about the fundamentals of particle acceleration in solar flares from *Compton* observations. Gamma-ray observations can also provide information on which elements are present in the ambient coronal gas. By studying the gamma-ray time history of flares, and correlating the gamma-ray emission with observations at other wavelengths, it has been discovered that particles are accelerated for much longer periods of time than just the impulsive beginning of the flare. An example of such a flare was detected on June 4, 1991. EGRET, COMPTEL, and OSSE all detected evidence for particle acceleration lasting for several hours.

This flare was one of the few energetic enough to be detected by all the *Compton* experiments. These broadband observations are very important. Perhaps one of the most intriguing observations yet made by *Compton* is the COMPTEL detection of neutron flux from a solar flare. Neutrons interact in the COMPTEL instrument in a manner similar to that of gamma rays. Usually, neutrons are removed from the data as contaminants. During a flare, however, solar neutrons are actually a valid signal considered worthy of study. As a result, not only can COMPTEL construct an image of the Sun in the light of gamma rays, but an actual image of the Sun using neutron flux can be formed! This is a remarkable achievement. Neutrons decay with a half life of 5 minutes, so it is unlikely that any other astrophysical systems could ever be detected via neutron flux.

GRO J1655-40: A Galactic Transient

Most sources which exhibit time variability are a little less spectacular than bursts, but just as important. For example, in late July of 1994, BATSE began to detect a strong, previously unknown source of low-energy gamma radiation from the direction of the southern constellation Scorpius. The source, dubbed GRO J1655-40, rapidly increased in brightness, becoming, over the course of about 10 days, among the brightest sources in the sky in BATSE's sensitivity range. But what was it? Its "light curve", which is a term astronomers use in referring to the source brightness as a function of time, vaguely resembled that of previously known transient objects which consist of a neutron star orbiting a very luminous, hot, young star. On the other hand its spectrum, which is simply the number of photons emitted versus photon energy, resembled that of another class of transient objects which consist of a much dimmer, cooler, old star orbiting a black hole.

In either case it is accretion onto the compact object which is responsible for the gamma-radiation. A more accurate spectral measurement using OSSE gave support to the black-hole scenario, as did the fact that periodic pulsations — a sign that the radiation is associated with the rotation of a neutron star — were not evident in the data. The true nature of GRO J1655-40 could not be unambiguously determined by *Compton* alone — observations at radio, optical and x-ray are required to distinguish between the likely possibilities, or perhaps reveal some unexpected alternative.



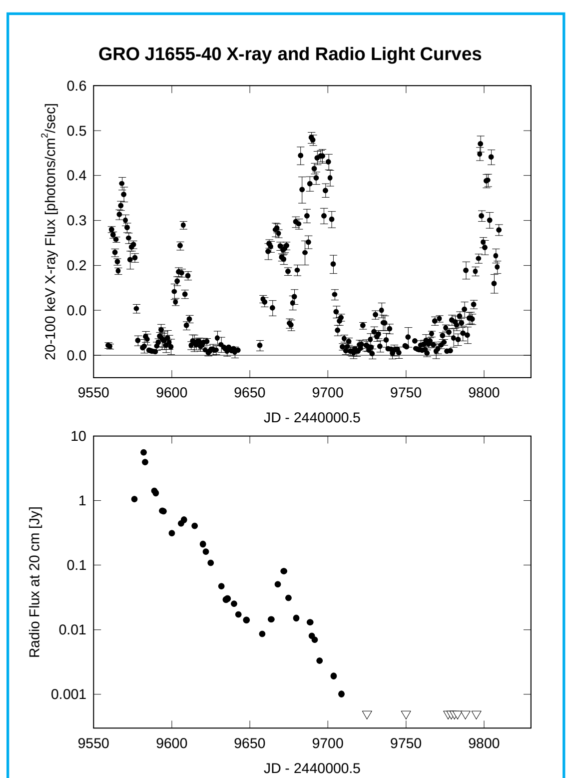
The radio images of GRO J1655-40. The ejection of "blobs" of material which stream away from the central source can be discerned.

To gamma-ray astronomers, or for that matter to scientists in general, the prospect of finding the unexpected is often the most exciting endeavor!

For GRO J1655-40, the team of gamma-ray astronomers using CGRO, radio astronomers using the Very Large Array (VLA – an array of radio telescopes mounted in an 22-mile long "Y" shaped configuration on the desert of New Mexico), and astronomers working in the visible domain using telescopes in the Chilean Andes were not disappointed! What they discovered was that GRO J1655-40 did in fact contain a black hole.

Optical studies showed that its orbital period was 2.6 days; 8-12 hours is more typical. However, the real surprise was in the radio. GRO J1655-40 was found to be ejecting matter in highly collimated streams in a direction nearly perpendicular to the plane of its binary orbit. Astronomers call such streams of matter, "jets", in analogy to the stream of water emitted from the nozzle of a high-pressure water hose.

Jets had been seen before, and are in fact quite common, in extremely distant, energetic objects known as "quasars". However, in our own galaxy, there are only a few examples of jet-producing sources. What made GRO J1655-40 all the more interesting was that time-lapsed sequences of observations revealed that the jet-ejection velocities approached the speed of light; 92% of the speed of light to be precise! Einstein's theory of relativity dictates that no material object move with a velocity that exceeds the speed of light, so GRO J1655-40 appeared to be hurling large quantities of material into space at 92% of the "cosmic speed limit". Actually not quite: scientists studying quasars had noted in the 1970's that a combination of projection effects and relativity can produce the illusion of motion at, or even exceeding the speed of light, but it still remains a hard and fast truth that physical matter never really exceeds the speed of light.



The BATSE time history of gamma-ray emission from the transient source GRO J1655-40 as compared to the radio lightcurve.

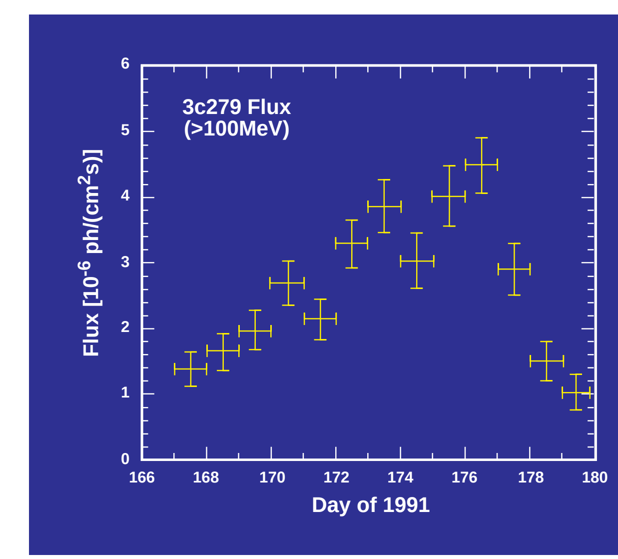
In any case, an enormous amount of energy is required to generate and sustain the jets seen in GRO J1655-40. Since it is much closer to home than the distant quasars — about 10,000 light years as opposed to about 1,000,000,000 light years — scientists infer that it is far less luminous and fills a much smaller volume of space than a quasar. This means, among other things, that it evolves more rapidly — on time scales of days rather than decades or longer! As such, GRO J1655-40 affords scientists a unique opportunity to study how jets are formed and how they evolve over time. With the combination of nearly continuous monitoring of the gamma-ray emission provided by BATSE, and frequent observations in the radio, evidence linking the accretion process and jet formation has been revealed for the first time! It was found that jet-ejection episodes followed gamma-ray "flares" by 5-10 days. Because of the larger distances to quasars, the analogous effect could take decades to observe.

Combined radio, optical, ultraviolet and x-ray studies of GRO J1655-40, and about a half-dozen other transients believed to contain black holes, have provided an unprecedented wealth of information. Additional transients are likely to occur within the lifetime of *Compton*, and undoubtedly, more surprises will be forthcoming.

Quasars: Cosmic Engines

Surprises have been business as usual for *Compton*. In the first few weeks of the mission, the instruments pointed to the Virgo region to observe the only active galaxy ever seen to shine at gamma-ray energies greater than 100 MeV — a quasar called 3C 273. An ordinary galaxy mainly shines with the visible light emitted by its billions of stars. But many galaxies are bright at other wavelengths: radio, infrared, x-ray, or even gamma-ray. The energy from such an active galaxy may arise from bursts of star formation, a collision with another galaxy, or perhaps even a massive central black hole. When such active galaxies lie at extreme distances, their apparent size is so small they appear like a star. In this case, they may be known as a quasi-stellar object, or quasar. Despite the fact that quasars lie in the outer reaches of the universe, they are still detectable by our telescopes. This implies, given their great distances, that they are among the most energetic phenomena in the universe.

The observation of 3C 273 surprised scientists because the bright gamma-ray source they expected to see was several degrees away from the position of 3C 273! It turned out that they were in fact detecting 3C 279, a similar type of quasar. 3C 273 was weakly detectable in the same image but the bright emission from an unanticipated source set the tone for the *Compton* mission. The variability of the gamma-ray quasars are shown by the light curve of 3C 279 during this period. The rise in intensity over a few days and then the flux plummeting back down is not atypical of gamma-ray quasars. Starting with the unexpected detection of gamma rays from the object known as 3C 279, EGRET has detected over 50 additional gamma-ray quasars, some at distances of a billion light years from Earth. Many of them are highly variable, extremely powerful cosmic accelerators. For example, the observed flux from 3C 279 implies a total luminosity over 10,000 times that of the total luminous output of our entire galaxy, assuming the emission is isotropic, that is, uniform in all directions. Most scientists however, now consider this very unlikely and believe that the emission is "beamed", or directed into a narrow cone. The quasars that EGRET detects are the ones that are fortuitously directed towards us. Like the galactic object GRO J1655-40, the variability of the gamma-ray quasars provide scientists the opportunity to carefully monitor emission at many wavelengths, providing a unified picture of the gamma-ray source. The ever-changing gamma-ray sky makes this approach necessary.



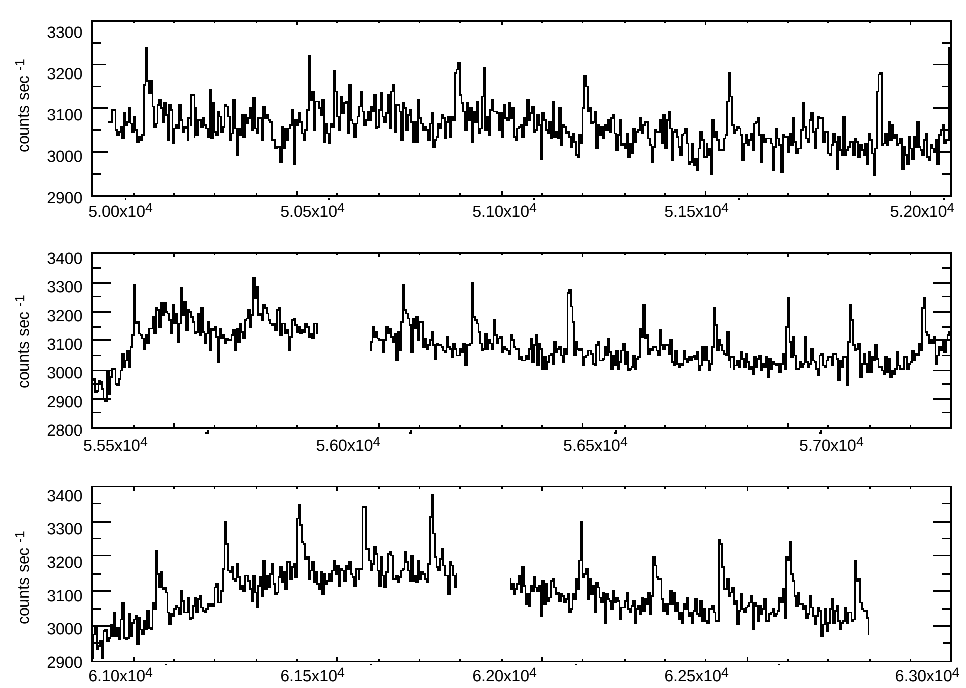
Lightcurve for the EGRET observation of 3C 279. This bright, variable quasar was the first of over 50 to be detected.

Gamma-Ray Astronomy in the Compton Era: The Future

We have only touched on a few of the scientific investigations Compton continues to perform. A large number of exciting and important investigations remain to be done during the coming years of the Compton mission. As with many good experiments, the Compton instruments have revealed new questions for every old question they have answered. Only by exploring the universe, can we truly find how much we have to learn.

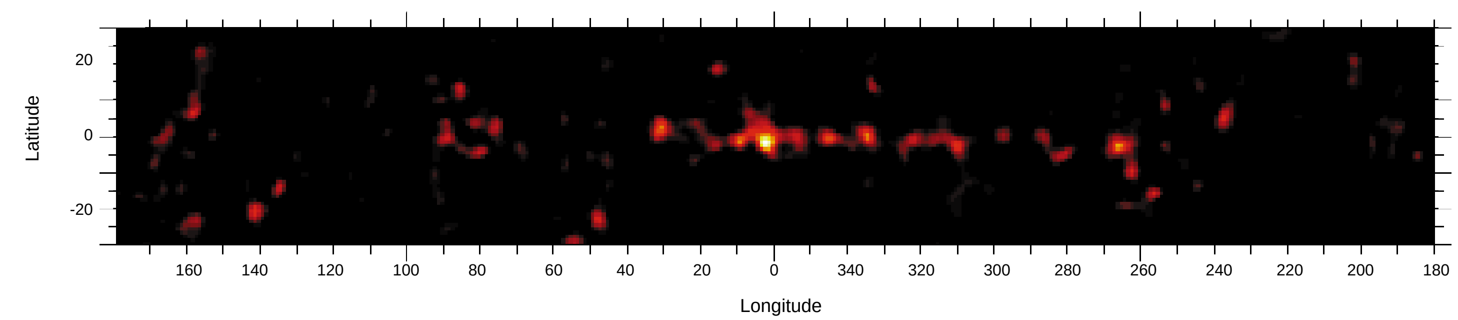
Solving the gamma-ray burst mystery is a prime example. The use of real-time telemetry data from BATSE and COMPTEL may help to locate gamma-ray bursts rapidly and communicate localizations to optical and radio observatories which can then search for burst counterparts. This means that the signal coming down from the spacecraft itself is immediately checked for the presence of a gamma-ray burst. A system to support such efforts called BACODINE, for BATSE COordinates DIstribution NEtwork, has been implemented by a team of scientists. This real-time alert system currently notifies 25 observatories operating 31 instruments covering radio, optical, and TeV energies (10^{12} electron volts; ground-based gamma-ray observatories detect showers of particles created by the absorption of the initial gamma ray in the Earth's atmosphere, a technique available only at the highest energies). Several of these instruments are fully-automated with rapid-slewing capabilities. The burst positions are computed within about 5 seconds following burst detection by BATSE and distributed to the participating observatories within seconds. Hopefully, such real-time observations in longer wavelength bands will detect the "Holy Grail" of gamma-ray burst astrophysics — a counterpart to the gamma-ray burst emission — and help solve the mystery.

The dynamic evolution of the gamma-ray sky makes scientists realize that any day could bring something new. On December 2, 1995, BATSE began to detect bursts of low-energy gamma rays from a direction within a few degrees of the center of our galaxy. These bright flashes of radiation repeat every few minutes. This train of bursts continued to be detected, although at a slower rate of about one per hour for the next two months. This was a new type of bursting galactic source, named GRO J1744-28, which would turn out to be even more remarkable than first thought. While some accreting galactic sources have shown bursting behavior, particularly at x-ray energies, and other accreting galactic sources are x-ray pulsars — emitting x-rays at the rotational period of the neutron star, it was soon discovered that this source was not only bursting, but it was emitting regular pulses as well! About twice per second. This "Bursting Pulsar" is unlike any other known astrophysical object. Is this a completely unique object or simply the first of a new class? Maybe it is an example of a source in a brief stage of evolution which will not be seen for a very long time. How can theories created to separately explain bursters and pulsars be modified to explain this object? What will other wavelength bands tell us?



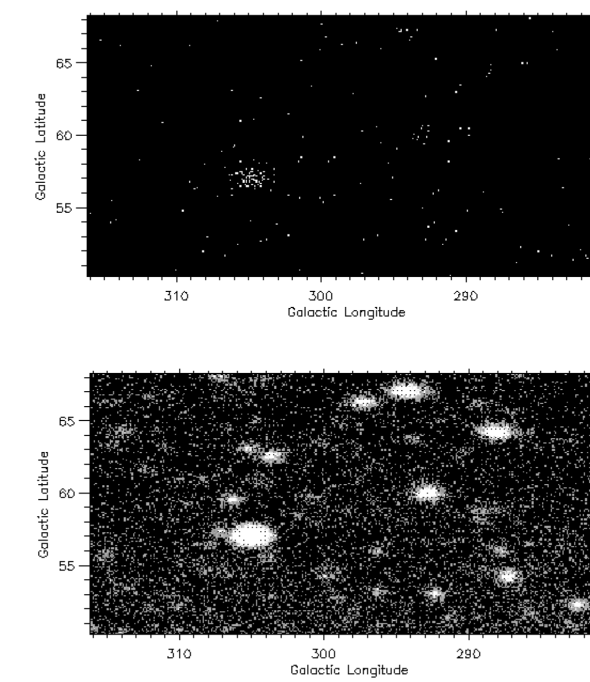
Early time history of the "Bursting Pulsar" showing some of the thousands of bursts seen from this unique source.

COMPTEL Map of Galaxy at 1.8 MeV



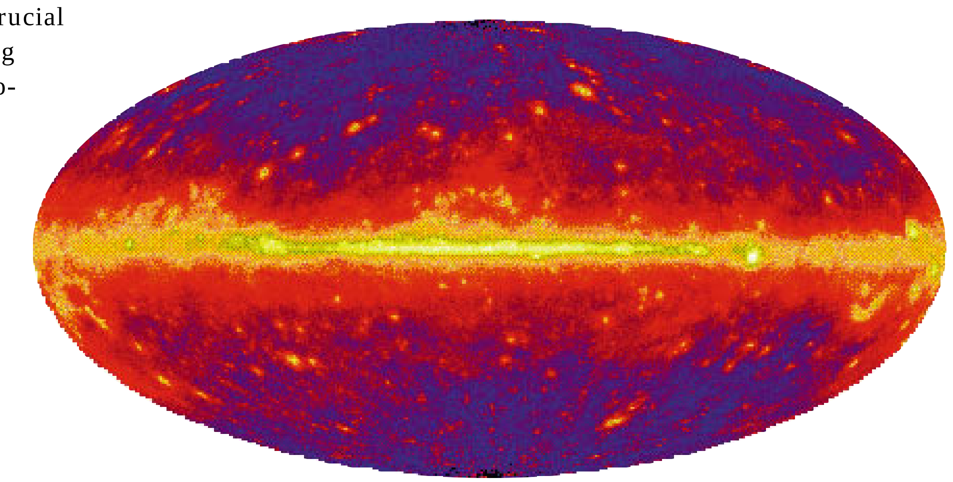
ABOVE: Determining the source of enhancements, obvious in this map of the 1.8 MeV gamma-ray line from 26Al, is a continuing project for the COMPTEL and OSSE experiments.

BELOW: A simulated comparison of the Virgo region which contains 3C 279 as seen above 1 GeV by EGRET (top) as compared to GLAST (bottom). The development of better telescopes is driven by the need to explain current results.



Aside from surprises like GRO J1744-28, there are many other possible discoveries which await the final years of the *Compton* mission. In the next few years, a new supernova in a nearby galaxy is a possibility. Observations of gamma-ray lines will constrain models of explosive nucleosynthesis — the theory of how heavy elements are created in our galaxy. Additional observations of our own galaxy may reveal more areas of line emission which can probe the supernova rates in our own galaxy. Further mapping of the diffuse emission from our galaxy will provide crucial information regarding the transport and production of cosmic rays.

Other important studies that can be accomplished include deep observations at high galactic latitudes to detect ever fainter quasars, multiwavelength observations with ground-based observatories which will be used to further refine our understanding of gamma-ray emitting galaxies, the search for more hidden pulsars similar to Geminga, and collecting more and more gamma-ray bursts in the hope that we can constrain models of gamma-ray burst emission.



The simulated all-sky view as seen by the proposed GLAST experiment. The detail in a one-year mission is greatly enhanced over the EGRET results.

Beyond Compton

It is a paradox that successful missions can create new questions as efficently as they provide answers for the old questions. Such is the nature of the scientific enterprise — you often don't realize how little you know! Science is in a constant search for better techniques to analyze and interpret old data. New experiments which take advantage of advanced technology or better understanding of the space environment are always in development.

Proposed instruments such as GLAST (which stands for Gamma-ray Large Area Space Telescope) would provide an order of magnitude improvement in sensitivity over the already successful EGRET instrument. GLAST is an example of the possible improvements in detector technology which can provide a much more detailed view of the gamma-ray sky. The GLAST concept utilizes advanced silicon-strip particle detector technology and would operate in the 10 MeV to 300 GeV energy range. The goals of an instrument like GLAST are to collect more photons using larger area and thereby provide higher spatial resolution (to better estimate source locations), and to have better energy resolution (to better estimate the source spectrum), enabling even more detailed study of the high-energy emission of active galactic nuclei, neutron stars, and diffuse radiations which comprise much of the gamma-ray sky. Other missions such as the European-based INTEGRAL (for INTErnational Gamma-Ray Astrophysics Laboratory) mission, which is scheduled to launch in the year 2001, will provide images of the universe in the important energy range from 20 keV to about 10 MeV. INTEGRAL will provide very sensitive energy resolution over this range of nuclear transitions, where many interesting gamma-ray lines may be seen in cosmic sources.

No matter the nature of the instruments to follow, the Compton Gamma Ray Observatory has given scientists an incredible view of the universe. The breadth of scientific results that continue to come from the *Compton* instruments are revealing the wonder and power of the most energetic processes occurring in nature. The journey of exploration which began with the first ancient astronomers has now come to the point where we are using the tools of elementary particle physics to probe astrophysical sites so exotic that they would have been unimaginable a few decades ago. Where we go from here is limited only by our imaginations and our determination to understand the universe and our place in it.

A conception of the INTEGRAL spacecraft. Future missions would build on the Compton legacy.

Glossary

accretion - the process whereby matter from a normal star or diffuse cloud is captured by a compact companion such as a black hole or neutron star

Active Galactic Nuclei (AGN) - a term used to describe the central region of a distant galaxy which can appear to be a pointlike source of strong gamma-ray emission. AGN are generally thought to be due to supermassive central black holes accreting nearby matter

BATSE - Burst and Transient Source Experiment, the *Compton* instrument operating from 15 keV to 1 MeV; the instrument primarily intended to detect bursts, flares, and to monitor long-term emission from other sources

black hole - a star which has evolved to the point where the self-gravity of the star cannot be balanced by any other nuclear or electromagnetic forces. The result is the complete collapse of the star to a point or singularity

blazar - a type of distant AGN which often appears to be a pointlike source of bright, highly variable radiation

collimator - a structure which is used to narrow the field-of-view of a gamma-ray detector

COMPTEL - the Imaging Compton Telescope, which operates in the 1 - 30 MeV energy range and is useful for imaging and the detection of nuclear lines

Compton scattering - The dominant particle interaction process at MeV energies wherein a photon scatters off of an electron, energizing the electron and changing the trajectory of the photon

cosmic ray - refers to high-velocity elementary particles such as electrons or protons or atomic nuclei which fill much of interstellar space

COS–B - a European gamma-ray experiment operated from 1975-1982. Sensitive over much the same energy range as the EGRET experiment

cyclotron emission - the gamma-ray emission from electrons in a strong magnetic field. Quantum mechanical effects make this type of emission quantized at discrete energies

diffuse emission - gamma-ray emission which is not confined to a point source. Typically due to the interactions of cosmic rays with interstellar material. Sometimes refers to emission from extended sources such as supernova remnants

EGRET - the Energetic Gamma-Ray Experiment Telescope which operates from 30 MeV to 30 GeV

electron-volt - a unit of electromagnetic energy, sufficient to excite atoms to emit visible light, keV = 1,000 eV, MeV = 1,000 keV, GeV = 1,000 MeV

flux - a detector-independent measure of the brightness of a gamma-ray source

gamma ray - a photon carrying more energy than an x-ray (more than about 50 electron volts)

gamma-ray burst - brief, intense, random gamma-ray emission from an unknown source

jet - typically a stream of relativistic particles which flows out from a central source

lightcurve - a time history of emission from a gamma-ray source

light-year - a measure of distance travelled by light in one year's time = 9.7×10^{15} meters

neutron star - An end point of stellar evolution wherein the star is supported by the force of repulsion between neutrons; very compact with a radius of about 10 km and mass about 1.4 times the mass of the Sun

nuclear lines - gamma-ray emission centered on a characteristic energy; caused by interactions of particles with atomic nuclei or by transitions within a nucleus

occultation - the technique of measuring the flux of a source by comparing a detector signal while the source is in the field of view to the signal when the source is hidden or occulted by the Earth

OSSE - Oriented Scintillation Spectrometer Experiment, the low-energy gamma-ray instrument on the *Compton* satellite used for detailed study of gamma-ray spectra

pair annihilation - A fundamental interaction between a particle such as an electron and its antiparticle (i.e. a positron) which results in the emission of two photons with the initial pair of particles destroyed. This process dominates other gamma-ray interactions with matter at energies above a few tens of MeV

pair production - the inverse process to pair annihilation where a particle/antiparticle pair are created from two gamma rays photon - the fundamental particle of electromagnetic radiation (light). Photons carry energy proportional to their frequency

pulsar - a subclass of neutron stars characterized by a beam of emission which sweeps around as the neutron star rotates, alternately coming into and going out of the field of view of an observer, thus giving rise to a pulsing effect

phototube - an electronic device which converts a photonic signal into an electronic signal. Used in gamma-ray astronomy instrumentation to detect the arrival and energy of an incident photon

positron - anti-particle of the electron. Capable of mutually annihilating with an electron to emit characteristic radiation around 511 keV

SAS 2 - a pioneering spark-chamber instrument like EGRET launched in 1972

scintillator - a crystal which detects gamma rays by converting the energy into detectable light

Seyfert - a type of AGN which is dominated by a bright, compact blue nucleus

solar flare - a burst-like emission of radiation from proturbances in the Sun's outer atmosphere

spark chamber - a gamma-ray detection device utilizing pair production of the initial photon followed by the detection of a trail of sparks in a grid which follow the trajectory of the resultant electron/positron pair

spectrum - the number of photons a source emits as a function of energy

supernova - the endpoint of stellar evolution whereby the star, having exhausted its nuclear fuel explodes, usually leaving behind a compact object such as a black hole or neutron star

synchrotron emission - radiation emitted by charged particles when accelerated by a magnetic field

thermal Brehmstrahlung - the x- and gamma-ray emission process caused by the collisions of particles in a hot plasma ("braking" radiation)

white dwarf - an evolved, compact star which is supported against self-gravity by the repulsive interaction of electrons

x-ray nova - a binary system where episodic accretion from the companion star to the black-hole companion results in explosive gamma-ray emission which gradually declines over a period of months

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Credits

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Page 1 - artist's illustration of the electromagnetic spectrum.

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Page 4 - launch of the *Compton* Observatory courtesy of NASA

Page 4 - artist's illustration of the *Compton* instruments energy ranges

Page 5 - artist's illustration of the BATSE instruments

Page 6 - artist's illustrations of the OSSE and COMPTEL instruments

Page 7 - artist's illustration of EGRET instrument

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Page 8 - COMPTEL anticenter image courtesy of Max Planck Institute, Germany

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"The progress of the human race in understanding the universe has established a small corner of order in an increasingly disordered universe."

S.W. Hawking