Overview and Goals of the Gamma Ray/XR Project (GR/XR)

Gamma Ray/X-Ray (GR/XR), funded through NASA's ROSES Program, is a three-year project to develop standards-aligned, online curriculum modules for high school students on the history, tools, science, and impact of gamma ray and X-ray astronomy using NASA's mission- and education-related resources.

The high-level goals of this project are to:

- Introduce students to the science, technology, and history of astrophysical research;
- Involve educators and students in underserved communities in the development and evaluation of these materials;
- Promote the use of NASA's astrophysical research to strengthen understanding of basic physics concepts and raise awareness of STEM careers;
- Specifically address NASA's subgoal 3D: Discover the origin, structure, evolution, and destiny of the Universe and search for Earth-like planets.

The purpose of this **Scope** document is to provide a broad context for the four lessons on gamma-ray astronomy (history, tools, science, and impact). The **Scope** document was written by Julia Brazas and Professors Donald Q. Lamb and Donald G. York of the University of Chicago. The audience for this document is the teachers who will use the lessons in the Gamma Ray Astronomy Module.

What are gamma rays and gamma-ray bursts?

Gamma rays have the smallest wavelengths and the most energy of any other photon in the electromagnetic spectrum. The electromagnetic spectrum includes photons in the range of 100 eV to 100,000 eV and wavelengths of 0.01 nanometers and 10^{12} nanometers (10^{-11} meters and 1 kilometer). This range is divided into broad categories of gamma rays, X-rays, ultraviolet, optical, infrared, millimeter and radio, in decreasing order of energy and increasing order of wavelength. Gamma rays that are commonly seen on Earth are created by radioactive decay of nuclei, but in space they are created from charged particles that are accelerated by magnetic or gravitational fields. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium.

Gamma-ray bursts (GRBs) are the most powerful explosions that have occurred in the Universe since the Big Bang. They produce brief, but intense, flashes of gamma radiation that occur about once a day in the observable Universe, and are most likely from objects in galaxies scattered across the Universe. They come from all different directions of the sky and last from a few milliseconds to a few hundred seconds. A gamma ray burst releases energy equal to all of the Sun's energy generated over its 10 billion year lifetime in just a matter of seconds.

GRBs appear first as a brilliant flash of gamma rays that rise and fall in a matter of minutes. These bursts are often followed by afterglows at X-ray, optical, and radio wavelengths. Our recent insights about gamma-ray bursts come largely from studies of the afterglow, although interpretations of the data are still widely debated.

Most observed GRBs are believed to be a narrow beam of intense radiation released during a supernova, as a rapidly rotating, high-mass star collapses to form a black hole. Some bursts, of very short duration, appear to originate from a different process, possibly the merger of binary neutron stars. However, the immediate source of this tremendous energy is unknown.

Gamma-ray astronomy presents unique opportunities to explore the Universe at high energies. Scientists can use observations of the bursts to test theoretical predictions, for instance, about the nature of the last stages of supernovae. Of course, this is unique information, because one cannot bring a supernova into the laboratory to study it. In some cases, it is expected that the observations and the theory will not agree: the theories may need modification, or there may be new physical principles indicated that were not previously accounted for.

The 1960s

On August 6, 1963, after more than eight years of difficult negotiations, the United States, the United Kingdom, and the Soviet Union signed the Limited Nuclear Test Ban Treaty. The Treaty prohibits nuclear weapons tests or other nuclear explosions under water, in the atmosphere, or in outer space; and pledges the signatories to work towards complete disarmament, an end to the armaments race, and an end to the contamination of the environment by radioactive substances.

To monitor compliance with the Treaty, a detection system would be necessary. During nuclear test ban negotiations in Geneva, Switzerland, a young scientist named Stirling Colgate proposed the use of satellites for this purpose. The Soviets agreed, but there was a problem. In 1952 Stirling worked at Livermore National Laboratory in California on hydrogen bomb experiments and had conducted simulations to determine what would happen if an H-bomb exploded in space. He concluded that the result of such an H-bomb explosion would be the release of enormous amounts of X-ray and gamma rays, similar to a supernova. If they sent up a satellite specifically to generate automated alerts as a monitoring system for the detection of the now banned nuclear tests, a gamma-ray burst from a cosmological source might set off the detection device and result in World War III.[1] A satellite system would have to survey the sky for naturally occurring high-energy radiation so that it could be distinguished from nuclear tests. The Soviets agreed. The arrangement spurred research into supernovae by both Russian and American scientists, and fueled the Space Race in the coming years.

In October 1963, the United States Air Force launched the first in a series of satellites inspired by the recently signed nuclear test ban treaty. The primary mission of the satellites was to survey the gamma-ray sky. They were also part of an unclassified research and development program whose goal was to develop the technology to monitor nuclear tests from space and give the U.S. a means of verifying the conditions of the treaty. The satellites were named *Vela*, the Spanish word meaning “to watch”.[2] The Russians, who were first to launch a space satellite called Sputnik 1 in October 1957, followed suit. After the American results were published (1973), they were immediately confirmed in Soviet publications, as discussed below.

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[1] Miller, 2005, 239-240.

[2] Bonnell & Klebesadel, 1996, 977.

The *Vela* satellites were designed and built by teams of workers at the Los Alamos Scientific Laboratory (now called the Los Alamos National Laboratory or LANL). One of the workers was Ray Klebesadel. Ray was a physicist responsible for monitoring Soviet compliance with the Nuclear Test Ban Treaty. The *Vela* satellites carried X-ray, gamma-ray, and neutron detectors along with a variety of other detectors and instruments designed to monitor the space environment.

The satellites were always launched in pairs to an orbit of more than 60,000 miles (96,000 kilometers) above the Earth. The first pair of satellites was orbited on October 17, 1963. By 1967 an advanced version of the satellite had been developed. The new model was equipped with more sophisticated detection instruments and was designed to continually point toward the Earth, unlike the earlier version, which viewed the heavens as well. The advanced pair of *Vela* satellites was orbited on April 28, 1967.

After the first four satellites were up, Ray and his colleagues started to look through the data they sent back to Earth. Primarily, they were looking to make sure everything was working as expected and that nature was not generating any sort of signal that could trick the satellites into thinking a nuclear explosion had occurred. Data from events in space that triggered the detectors were kept and analyzed, a painstaking process that was done without computers. Many of the triggers were determined to be false. Some events appeared to be real, as they occurred simultaneously in different satellites.

In mid-1969, Ray was examining data taken on July 2, 1967. He noticed a spike in the data, a dip, a second spike, and a long, gradual tail off. It was immediately clear to Ray that this was pattern did not indicate a secret nuclear test, but indicated something originating from space. His team checked for possible solar flares and supernovae, and found none.

Why not tell the world immediately? Rather than releasing faulty data, the last two satellite pairs in the series were launched in 1969 and 1970, with improved instrumentation that could better determine the direction of the bursts. These would provide more accurate data to confirm the discovery of GRBs.

Ray’s discovery would be confirmed by two missions launched in 1971. The *IMP-6* satellite, which was intended to study solar flares, gathered detailed spectra of six events that showed the bursts peaked at gamma-ray energies and were not simply the high-energy tail of an X-ray phenomenon. A gamma-ray telescope on board the *Orbiting Solar Observatory 7* was also able to confirm a direction to one of the events, supporting the original conclusion of cosmic origin.

These results, published in 1973, gave GRBs an aura of enhanced mystery. The excitement created in the astronomical community was evidenced by a flurry of publications of instrumental and theoretical papers on the newly discovered "cosmic gamma-ray bursts.” In the following year, data from Soviet *Konus* satellites were published, confirming detection of these gamma-ray bursts.[3]

Over the next 20 or so years, there was a period of continuing observations as the Interplanetary Network, a group of spacecraft equipped with gamma ray burst detectors, roamed the sun and Solar system. A catalog of GRBs was constructed and many theories were discussed as to their origin. Great debates were even held within the astronomical community as to whether the bursts were occurring in

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[3] NASA, undated C.

the Milky Way Galaxy or in other galaxies. The addition of each newly observed burst tended to reveal not much more than that they never repeated from the same source.

The 1990s: A Decade of Debates and Discoveries

The launch of the *Compton Gamma Ray Observatory (CGRO)* on April 5, 1991, aboard the space shuttle *Atlantis,* ushered in a new era of GRB observations. *CGRO* was the second of NASA's Great Observatories. At 17 tons, it was the heaviest astrophysical payload ever flown at the time of its launch.

The Observatory was named in honor of Arthur Holly Compton from the University of Chicago, who won the Nobel Prize for physics in 1927 for work on scattering of high-energy photons by electrons, a process central to the gamma-ray detection techniques of all four instruments. The instruments aboard *CGRO* covered an unprecedented six decades of the electromagnetic spectrum, from 30 keV to 30 GeV. In order of increasing spectral energy coverage, these instruments were the *Burst and Transient Source Experiment (BATSE)*, the *Oriented Scintillation Spectrometer Experiment (OSSE)*, the *Imaging Compton Telescope (COMPTEL)*, and the *Energetic Gamma Ray Experiment Telescope (EGRET).* For each of the instruments, an improvement in sensitivity of better than a factor of ten was realized over previous missions. Within months of its launch, *BATSE* allowed astronomers to monitor the distribution of the gamma-ray bursts across the sky. It was soon clear that they are detected at a rate of about one per day, from all directions.

Prior to the launch of *Compton*, scientists had little information on gamma-ray bursts. In the first few years after the 1973 announcement, at least six different models appeared that accounted for GRBs as events outside our Galaxy. Then there was a decade of “absolute certainty” that GRBs happened inside the Milky Way, probably on old neutron stars. The main reason put forward by the group claiming a local origin was the extreme energy release that is necessary to explain the observed emission from gamma-ray bursts if they are extragalactic. But not everyone agreed.

Great Debates

By 1995 there was still no consensus in the astronomical community as to the source of or distance to GRBs. In fact, two major theories had scientists at odds about whether gamma-ray bursts originated inside or outside of our galaxy.

On April 22, 1995, two professors, Bohdan Paczynski, from Princeton University, and Donald Q. Lamb, from the University of Chicago, debated “The Distance Scale to Gamma Ray Bursts” at the Smithsonian’s Natural History Museum in Washington, D.C. The event occurred 75 years to the week after Heber D. Curtis and Harlow Shapley met in the same auditorium and discussed “The Scale of the Universe,” an event now referred to as “The Great Debate.”

In the 1920 debate, two of the great astronomers of the time presented their opposing viewpoints on an issue of intense interest to the scientific community. The incontrovertible fact to be discussed was that the sky is full of fuzzy patches, then known as nebulae, which often appear as having a spiral shape. Curtis argued that each nebula was an entire galaxy, like the Milky Way, and that the Universe is composed of many galaxies like our own. Shapley argued, on the other hand, that these spiral nebulae were just clouds of stars and gas within the Milky Way, and that the Universe was composed of only one big Galaxy. In Shapley's model, our Sun was far from the center of this Great Universe/Galaxy. Conversely, Curtis placed our Sun near the center of our Galaxy, a relatively small and unremarkable object in the far flung Universe of billions of galaxies. Although the details of the debate included numerous, complicated arguments, the scientists disagreed on the interpretation of the data then available on the nature of the nebulae.

The "Great Debate," held on April 22, 1995, both commemorated the Shapley-Curtis debate and presented another classic scientific disagreement: the distance scale to gamma-ray bursts. It, too, featured another pair of astronomers, champions of opposing viewpoints, who argued over one of the greatest astronomical controversies of the time. Like their counterparts in 1920, the professors based their views partly on theoretical calculations, as well as on the new and detailed measurements from the largest and most sophisticated telescopes of their time, especially *BATSE*. Bohdan Paczynski (1940-2007) defended the idea that the origins of gamma-ray bursts were cosmological; thus, GRBs were billions of light years away. Poised on the opposing side of the argument was Don Lamb. He argued that the gamma-ray sources originated in the halo of our own Milky Way galaxy. As evidence, Don presented both theoretical calculations and observational data placing GRBs at the outer edges of our Galaxy.

The debates, held 75 years apart, provided a glimpse into the reasoning processes of eminent scientists engaged in a great controversy for which the evidence on both sides was fragmentary and partly faulty.[4] The debates also demonstrated how difficult it is to be both first and right in science. It is frequently productive to make an intelligent scientific guess based on reasonable information, even if it might turn out wrong later. Such a guess might lead to testable predictions that could lead to increased understanding.[5] And like the discovery of gamma rays by Paul Villard, and Ray Klebesadel's discovery of cosmic gamma ray bursts chance and readiness would soon step in to help resolve the debate over distance.

In the meantime, another mystery that vexed astronomers was the discovery of two kinds of gamma-ray bursts—short and long—using data from BATSE. Astronomers were fairly certain that typical long GRBs lasting several seconds were caused by the collapse of massive stars, signaling the birth of black holes. But dimmer, short GRBs lasting only milliseconds seemed to be of possibly a different nature.

1997-1999: The Breakthrough Years

Although there had been a long debate concerning whether gamma-ray bursts came from the Milky Way Galaxy or much further away, the years 1997 through 1999 provided observations with uncontroversial evidence that GRBs come from the distant reaches of the cosmos. By observing the position of the GRB after the burst disappeared, astronomers found that there were visible galaxies that hosted the GRBs.

When gamma-ray bursts were first discovered they seemed to only emit radiation in the gamma portion of the spectrum. For several years physicists had expected these bursts to be followed by a longer-lived afterglow at longer wavelengths, such as radio waves, X-rays, and even visible light. Although the

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[4] Shu, 1982, 286.

[5] http://antwrp.gsfc.nasa.gov/htmltest/gifcity/pl_why.html;
http://antwrp.gsfc.nasa.gov/htmltest/gifcity/pl_prg2.html;
http://antwrp.gsfc.nasa.gov/htmltest/gifcity/cs_why.html

explosion only lasts for a few seconds, the afterglow of a GRB can linger for weeks or even months. The afterglow follows a path down the electromagnetic spectrum, first mostly emitting gamma-rays, and then radiating either X-rays or X-radiation, and so on, all the way down to radio waves. Eventually, the afterglow fades completely from our view. Because the afterglow is much longer-lived than the initial explosion, various types of telescopes can be used to study the afterglow.

GRBs had only been observed at gamma wavelengths, which were normally visible only to detectors on satellites, but this was about to change. The pursuit of the afterglow came after an Italian-Dutch satellite named *BeppoSax* detected a gamma-ray burst and its x-ray afterglow on February 28, 1997. The *Gamma-Ray Burst Monitor (GRBM)* and one of the *Wide Field Cameras (WFCs)* on board the satellite -- originally designed to study X-rays -- detected a burst that astronomers would name *GRB 970228*, referring to the year (1997), month (February) and day of the month (28) of the discovery. Within a few hours, the *BeppoSAX* team determined the burst's position within 3 arcminutes.

Dr. Jan van Paradijs (1946-1999), a scholar at The University of Alabama in Huntsville and professor of astronomy at the University of Amsterdam, received a tip that *BeppoSax* had detected a burst and its x-ray afterglow. After a flurry of phone calls, Jan was given its approximate position in the sky by the astronomers operating the satellite. When he discussed the information with two of his students, one of them reminded Jan that he had scheduled observing time that night, for another purpose, on a large, remotely operated telescope in the Canary Islands. The team turned the telescope to the spot in the sky indicated by *BeppoSax* and discovered the visible light afterglow. The discovery enabled astronomers to determine the distance to the gamma-ray burst, showing that it exploded billions of light-years away and not nearby, as some scientists believed. Astronomers quickly generalized that most GRBs were extragalactic. This ultimate explanation resulted from an effort spanning 34 years, costing billions of dollars, and involving military and civilian institutions and scientists and engineers from all over the world.

Another breakthrough happened as a result of the April 25 1998, single-peaked-GRB, which was also detected by the *GRBM* aboard *BeppoSAX*. This GRB originated in the direction of the constellation Telescopium, deep in the southern sky, in a galaxy a mere 125 million light years away - cosmically speaking, our “backyard.” The story of this long burst, named *GRB 980425* (found on April 25, 1998) by the astronomers, is an unusual one. It was closer than any other gamma-ray burst for which a distance had been determined and was 1000 to 1,000,000 times dimmer than normal bursts. It also began to challenge previously held views that supernovae and gamma-ray bursts were unrelated.

Immediately after reports about the April 25 burst had been received, astronomers at *La Silla Observatory* in Chile took some images of the region of the sky where the gamma-rays were observed. The astronomers quickly noticed that a new, comparatively bright star, right on the arm of a small spiral galaxy, appeared in exactly the same location merely a day after the burst. During the following weeks and months, astronomers obtained images through various filters to determine the brightness in different colors, as well as detailed spectra. These observations soon showed the object to be an unusually bright supernova. The new supernova received the official designation *SN 1998bw*.

From a careful study based on these observations, it was concluded that *SN 1998bw* underwent an exceptionally powerful explosion, more violent than most other supernovae observed so far. It was also unusual in the sense that very strong radio emission was observed within a few days after the explosion

- normally this only happens after several weeks. In fact, at radio wavelengths, *SN 1998bw* was the brightest supernova ever observed and is the current record-holder at radio wavelengths.

The proximity of the host galaxy and the supernova's brilliant light also helped scientists pinpoint the location of the gamma-ray burst and allowed them to observe and study the environment around it. Images from the *Hubble Space Telescope (HST)* (named for Edwin P. Hubble of the University of Chicago) allowed astronomers to determine that the source of the burst did not lie at the center of the faint galaxy, but was offset, most likely in the disk population of normal stars. This seemed to rule out the possibility that the bursts are powered by massive black holes now known to be at the center of most galaxies, and suggested the products of typical stellar evolution, such as colliding neutron stars or core collapse supernovae, as GRB candidates. A galaxy like our own Milky Way could produce a bursting object every few million years, an explosion that for a few seconds outshines the entire galaxy.[6] Considering the entire sky, with its billions of galaxies, evidently with the right detectors, the Universe would appear as a Christmas tree full of twinkling lights.

The next big breakthrough in understanding GRBs occurred when an enormously powerful event was detected on January 23, 1999, designated *GRB 990123*. It was observed with an unprecedented range of wavelengths and timing sensitivities. A small automated optical telescope responded to alerts from orbiting gamma-ray and X-ray telescopes to begin observing the GRB within 22 seconds of the burst’s onset, while the GRB was still on-going. Subsequent observations took place over the next few weeks in the gamma-ray, ultraviolet, optical, infra-red, millimeter, and radio wavelengths. The object was determined to have a redshift of 1.6, putting it at a cosmological distance and implying a staggering energy release. In fact, if the energy were emitted equally in all directions, twice the rest mass energy of a neutron star would be required.

With *GRB 990123*, scientists saw for the first time visible light emitted during a gamma-ray burst explosion. A day or so after *GRB 990123*, astronomers used the 10-meter *Keck II* telescope on Mauna Kea, in Hawaii, to analyze ultraviolet and visible light from the fading afterglow. Although the burst originated billions of years ago and was 9 billion light years away, the object was so bright that observers on Earth could have seen it with a pair of binoculars, if they had tried.

2000-2010: The Years of Insight

The study of the afterglow helped scientists determine the distances to gamma-ray bursts, but the sources of GRBs are still the subject of intense theoretical speculation. The 21st century missions to study GRBs are contributing to theories and models that change as more data are collected. At the same time, unexpected phenomena appear that can support or change ideas, possibly leading to new scientific theories and models.

GRBs are grouped into two categories based on their emission duration: short and long. Short-duration GRBs are believed to be the violent merger of two neutron stars, or possibly a neutron star and a black

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[6] http://www.aao.gov.au/local/www/sne/98bw/98bw.html; http://www.eso.org/public/outreach/press-rel/pr-1998/pr-15-98.html; http://www.spacetelescope.org/news/html/heic0003.html; http://imagine.gsfc.nasa.gov/docs/science/how_l1/how_bursts.html

hole. The result is an intense energy burst lasting fewer than 2 seconds. Long GRBs are associated with the core collapse of massive stars that generate a jet of gamma rays followed by lower-energy afterglow.

Short-duration GRBs are significantly dimmer than long-duration ones, by a factor of 10, and fewer of them have been detected. In addition, short bursts have relatively more higher-energy gamma rays than longer bursts. Finally, there is also evidence that in long bursts energy is converted into gamma rays at a steady rate, while in short bursts, the energy conversion rate appears to decrease as the burst progresses.

Selected Missions

The first space mission entirely dedicated to gamma-ray bursts was *HETE*, the *High Energy Transient Explorer*. The *HETE-1* satellite was launched in 1996 from a Pegasus rocket but had an unfortunate end. Although the rocket achieved the right orbit, its third stage failed to release *HETE-1* and another satellite onboard, and as a result, both satellites were unable to function as designed and died within a day of launch due to lack of solar power[7].

Launched in 2000, *HETE-2* began a two-year mission to detect gamma-ray bursts, determine their location, and relay that information within milliseconds of reception to other astronomers, who could then focus telescopes on the burst to collect photons in the visible, infrared, and radio wavelengths. A unique feature of *HETE-2* was that data were analyzed onboard the satellite by powerful processors that provided rapid detection of GRBs and, for the first time, the determination of the GRB position. This was computed in a matter of seconds and transmitted to a network of VHF receivers on the ground, allowing for the distribution of accurate GRB positions within tens of seconds of the trigger, rather than hours, as with the *BeppoSax* satellite.

The *Swift Gamma-ray Burst Explorer*, launched in 2004, is a multi-wavelength observatory carrying three instruments: the *Burst Alert Telescope (BAT)*, the *X-ray Telescope (XRT)*, and the *Ultraviolet/Optical Telescope (UVOT).* The primary scientific objectives of the mission are to determine the origin of gamma-ray bursts and to pioneer their use as probes of the early Universe. Unlike many other instrument names, *Swift* is not an acronym. The telescope was given the name of a highly aerial small bird, the swift, because of the telescope's ability to respond swiftly to a burst event, in a protocol similar to *HETE-2*. *Swift* can rapidly respond to newly detected GRBs and disseminate data. As soon as the *BAT* discovers a new GRB, *Swift* rapidly relays its 1-4 arcminute position estimate to the ground and triggers an autonomous spacecraft slew to bring the burst within the field of view of *XRT* and *UVOT* to follow-up the afterglow.

Launched June 11, 2008, the *Fermi Gamma-ray Space Telescope* (formerly known as GLAST, the Gamma-ray Large Area Space Telescope) has an imaging gamma-ray telescope vastly more capable than instruments flown previously, as well as a secondary instrument to augment the study of gamma-ray bursts: the *Large Area Telescope (LAT)* and the *Gamma Ray Burst Monitor (GBM)*. The telescope was named in honor of Enrico Fermi, who, like Compton, was from the University of Chicago and who won the Nobel Prize for physics in 1938 for his work on the artificial radioactivity produced by neutrons, and for nuclear reactions brought about by slow neutrons.

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[7] Vedrenne & Atteia, p. 135.

Insights

Together, the *HETE*, *Swift* and *Fermi* missions brought insights into the nature of gamma-ray bursts.

In 2003, *HETE-2* provided solid evidence linking long GRBs to the collapse of massive stars, which signal the births of black holes. *GRB 030329* was among the brightest optical afterglows ever seen, more than three magnitudes brighter than the famous optical afterglow of *GRB 990123*. In addition, the burst source and its host galaxy lie very nearby, at a redshift of z = 0.167. Typically, GRBs occur at z= 1-2, so the likelihood that the source of an observed burst should be as close as this one is one in several thousand. About 10 days after the *GRB 030329*, the spectral signature of a Type IC supernova emerged, designated by scientists as *SN 2003dh*. The clear detection of the supernova in the afterglow or *GRB 030329* confirmed decisively the connection between GRBs and core collapse-type supernovae.[8]

On July 9, 2005, *HETE-2* detected a short gamma-ray burst *GRB 050709*. It rapidly and accurately broadcast the location of the burst, allowing the *Chandra X-ray Observatory* (named for Subrahmanyan Chandrasekhar, a Nobel Laureate from the University of Chicago), the *Hubble Space Telescope* and ground-based telescopes to identify the burst's X-ray afterglow, and, for the first time, the optical afterglow of a short burst, which provided the clues needed to track the burst to its host galaxy. The distinctive signature is that of two neutron stars or a neutron star and a black hole merging, followed by a colossal explosion. The collision happened about two billion years ago, creating an energy show so brilliant that we can witness it eons later.

On April 23, 2009, *Swift* discovered a gamma-ray burst lasting 10 seconds located in the constellation Leo. At a redshift of z = 8.2, the burst is the current record holder for the most distant observed GRB, as well as the most distant object of any kind. *GRB 090423* is also the oldest known object in the Universe, as the light from the burst took approximately 13 billion years to reach Earth. The event occurred roughly 630 million years after the Big Bang, confirming that massive stellar births (and deaths) did indeed occur in the very early Universe.[9]

In its first year of operations, the *GBM* onboard *Fermi* observed low-energy gamma rays from more than 250 bursts (compared to 9 GRBs detected *Swift* in its first year); the *Large Area Telescope (LAT)* observed 12 of these bursts at higher energy than they had been detected before. The first high-energy gamma-ray burst was one for the record books. The explosion, designated *GRB 080916C*, occurred on September 16, 2008, in the constellation Carina, and is the most powerful gamma-ray burst ever recorded. As seen from Earth, the explosion had more power than 9,000 supernovae (if the energy was emitted equally in all directions). The gas jets emitting the initial gamma rays moved at a minimum velocity of 99.9999% the speed of light, making this blast the most extreme as of that date.

Fermi also captured more than 1,000 discrete sources of gamma rays, five times the number previously known. Blazars, distant galaxies whose massive black holes emit fast-moving jets of matter toward us, are by far the most prevalent source, now numbering more than 500. *Fermi* also found a number of

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[8] Lamb et al, 2004, 425-426.

[9] http://en.wikipedia.org/wiki/GRB_090423

gamma ray sources in our own Galaxy: 46 pulsars and two binary systems where a neutron star rapidly orbits a hot, young star.

The Future of Gamma Ray Astronomy

The sensitivity of a spaced-based telescope is limited in the number of photons it can collect by its size. Satellite gamma-ray observatories are not large enough to be sensitive to most gamma-ray sources above 100 GeV because the number of photons generally decreases with increasing energy. The same is true of ground-based telescopes, but they can be made large enough to collect the few photons that make it to Earth and, usually, the larger a telescope's collecting area, the fainter are the objects it can detect. Furthermore, ground-based telescopes are much cheaper to build.

Such ground-based telescopes are among the recent instruments being used to study the universe at higher energies. The *Very Energetic Radiation Imaging Telescope Array System* (*VERITAS*) is an array of 4, 12-meter optical telescopes designed to study gamma rays at in the very high energy range of 50 GeV - 50 TeV. These telescopes observe the Cherenkov light emitted by showers of secondary particles (mostly electrons and positrons) that are produced when gamma-rays interact in the Earth’s atmosphere. By studying the shower images, scientists can infer the presence of cosmic rays in space that signal very high-energy events, such as exploded stars, distant active galaxies, and the presence of dark matter.

The *High Energy Stereoscopic System* (*HESS*) is another ground-based system of Imaging Atmospheric Cherenkov Telescopes that investigate cosmic gamma rays in the 100 GeV to 100 TeV energy range. The name *HESS* is also intended to pay homage to Victor Hess, who received the Nobel Prize in Physics in 1936 for his discovery of cosmic radiation. The instrument allows scientists to explore gamma-ray sources with intensities at a level of a few thousandths of the flux of the Crab Nebula, the brightest steady source of gamma rays in the sky.

At even higher energies (beyond 10^{20} eV), the *Pierre Auger Cosmic Ray Observatory* is dedicated to studying cosmic rays, the most energetic and rarest of particles in the Universe. As with gamma rays, when a cosmic ray particle strikes the Earth's atmosphere, it creates a shower of lower energy secondary particles, and these are observed to reach the ground. In fact, about a hundred of these secondary particles pass through our bodies every second. But as the energy level increases, the number of particles becomes more and more rare. At 10^{19}eV, only about two particles per square mile arrive at the upper atmosphere per year. Above 10^{20}eV, only about two particles per square mile arrive each century. As energy levels increase, larger collecting areas are needed to detect the few particles that ultimately reach Earth. To find and measure these rare events, a high-energy cosmic ray study needs a truly giant detector, like the 35-mile by 35-mile detector in Malargüe, Argentina, where it occupies an area as large as the state of Rhode Island. Even with an array so large, *Auger* detects cosmic rays and gamma rays that are so energetic they occur at the rate of only a few a year.

So as we begin the 21st century, the study of gamma rays is growing to include the study of even higher energies, thanks to a generation of space and ground-based observatories that together have an almost uninterrupted sensitivity across an incredible range of photon energies, with a factor of nearly one million from the least energetic gamma rays that can be detected by *Fermi Gamma-ray Space Telescope* to the most energetic cosmic rays detected by *Auger Cosmic Ray Observatory*.

The Impact of Gamma Ray Astronomy

Nature's most powerful explosions, gamma-ray bursts, tell us about the history of heavy metal production, when the first stars formed long after the Big Bang.

What have we learned in more than 40 years of intensive study of gamma rays and gamma-ray bursts?

Gamma-rays have over 1,000,000 times more energy than visible light photons. Because they are so energetic, it takes extreme conditions to create them. Thus, the detection of gamma-ray alert us to stellar activity – the birth of stars, the formation of neutron stars, solar flares, and black holes–and makes more of the Universe "visible" to us. Gamma-ray astronomy reveals differences between stars that end their lives as supernova and hypernova, the explosions which produce the element that make up everything in the Universe, and further provides insight into the nature of light and matter. These events in turn reveal more about the physics of the Universe.

As the most energetic form of radiation, detection of gamma-ray also help us to understand the size and age of the Universe, because when we detect a burst, we see light that has travelled from the observable edges of time and space. Knowing the distance to GRBs informs our understanding of the size, and age, of the Universe. Further, studying GRBs helps us to understand physics at extreme conditions that cannot be replicated in earthly laboratories.

Studies of gamma-ray bursts shed light on other topics in cosmology not directly related to the bursts themselves, as when *Fermi* detected a short gamma-ray burst, designated *GRB 090510*. Ground-based studies show the event took place in a galaxy 7.3 billion light-years away. Of the many gamma-ray photons *Fermi*'s *LAT* detected from the 2.1-second burst, two possessed energies differing by a factor of a million. Yet after traveling some seven billion years, the pair arrived just nine-tenths of a second apart, providing rare experimental evidence that space-time is smooth as Einstein assumed.[10] The assumption has rarely been tested.

Putting the facts together, astrophysicists have narrowed the field to two promising theories for the origin of GRBs: the merging of two neutron stars and collapsar/hypernova. The truth may lie somewhere between these two theories -- for example, the short bursts may be from neutron star mergers while the long bursts may be from collapsar/hypernovae. However, it may also be that GRBs originate from something that astronomers haven't considered yet.

Astronomers think short-duration GRBs are not related to supernova, meaning the collapsar/hypernova model is not applicable to them. Rather, they think short GRBs are produced by other phenomenon involving the collision and coalescence of compact objects, such as neutron stars, although other possibilities exist. These include some variation of the core-collapse of a dying star, which would mean short duration GRBs are in fact related to the collapsar/hypernova model.

If a short GRB is due to merging neutron stars, then it should produce powerful bursts of gravitational radiation. Although Albert Einstein included gravitational waves in his 1916 General Theory of Relativity,

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[10] http://www.scientificblogging.com/news_releases/grb_080916c_most_extreme_gammaray_blast_ever_we_know_about; http://www.nasa.gov/mission_pages/GLAST/news/first_year.html

these waves have never been measured directly. Short GRBs, 10 times closer to Earth than long GRBs, likely emit gravitational waves that will be detectable for the first time by future instruments.

As data accumulate, astronomers will learn more about the evolution of massive stars, which explode as supernovae. If gravitational waves, predicted by Einstein's Theory of Relativity, are ever detected, the GRBs will probably be the light posts that tell us the location of where the waves are coming from. Such a discovery would then shed light on the details of the collapse of supernovae to black holes, and the merger of stellar mass black holes to produce the massive black holes that are the source of quasars.

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