

23.6: The Mystery of the Gamma-Ray Bursts

Learning Objectives

By the end of this section, you will be able to:

- Give a brief history of how gamma-ray bursts were discovered and what instruments made the discovery possible
- Explain why astronomers think that gamma-ray bursts beam their energy rather than it radiating uniformly in all directions
- Describe how the radiation from a gamma-ray burst and its afterglow is produced
- Explain how short-duration gamma-ray bursts differ from longer ones, and describe the process that makes short-duration gamma-ray bursts
- Explain why gamma-ray bursts may help us understand the early universe

Everybody loves a good mystery, and astronomers are no exception. The mystery we will discuss in this section was first discovered in the mid-1960s, not via astronomical research, but as a result of a search for the tell-tale signs of nuclear weapon explosions. The US Defense Department launched a series of *Vela* satellites to make sure that no country was violating a treaty that banned the detonation of nuclear weapons in space.

Since nuclear explosions produce the most energetic form of electromagnetic waves called *gamma rays* (see Radiation and Spectra), the *Vela* satellites contained detectors to search for this type of radiation. The satellites did not detect any confirmed events from human activities, but they did—to everyone's surprise—detect short bursts of gamma rays coming from random directions in the sky. News of the discovery was first published in 1973; however, the origin of the bursts remained a mystery. No one knew what produced the brief flashes of gamma rays or how far away the sources were.

From a Few Bursts to Thousands

With the launch of the Compton Gamma-Ray Observatory by NASA in 1991, astronomers began to identify many more bursts and to learn more about them (Figure 23.6.1). Approximately once per day, the NASA satellite detected a flash of gamma rays somewhere in the sky that lasted from a fraction of a second to several hundred seconds. Before the Compton measurements, astronomers had expected that the most likely place for the bursts to come from was the main disk of our own (pancake-shaped) Galaxy. If this had been the case, however, more bursts would have been seen in the crowded plane of the Milky Way than above or below it. Instead, the sources of the bursts were distributed *isotropically*; that is, they could appear anywhere in the sky with no preference for one region over another. Almost never did a second burst come from the same location.

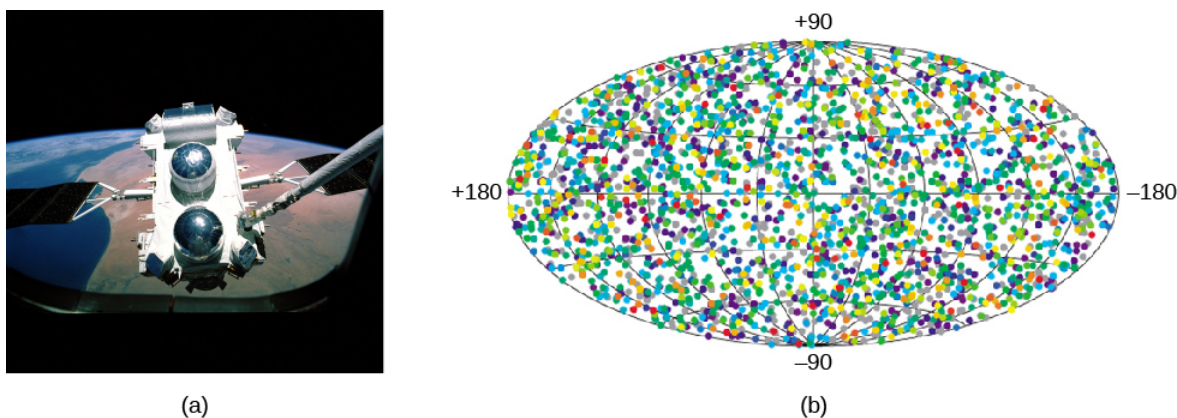


Figure 23.6.1 Compton Detects Gamma-Ray Bursts. (a) In 1991, the Compton Gamma-Ray Observatory was deployed by the Space Shuttle Atlantis. Weighing more than 16 tons, it was one of the largest scientific payloads ever launched into space. (b) This map of gamma-ray burst positions measured by the Compton Gamma-Ray Observatory shows the isotropic (same in all directions), uniform distribution of bursts on the sky. The map is oriented so that the disk of the Milky Way would stretch across the center line (or equator) of the oval. Note that the bursts show no preference at all for the plane of the Milky Way, as many other types of objects in the sky do. Colors indicate the total energy in the burst: red dots indicate long-duration, bright bursts; blue and purple dots show short, weaker bursts.

To get a good visual sense of the degree to which the bursts come from all over the sky, watch this short animated [NASA video](https://www.nasa.gov/visualizing/gamma-ray-bursts/) showing the location of the first 500 bursts found by the later *Swift* satellite.

For several years, astronomers actively debated whether the burst sources were relatively nearby or very far away—the two possibilities for bursts that are isotropically distributed. Nearby locations might include the cloud of comets that surrounds the solar system or the halo of our Galaxy, which is large and spherical, and also surrounds us in all directions. If, on the other hand, the bursts occurred at very large distances, they could come from faraway galaxies, which are also distributed uniformly in all directions.

Both the very local and the very distant hypotheses required something strange to be going on. If the bursts were coming from the cold outer reaches of our own solar system or from the halo of our Galaxy, then astronomers had to hypothesize some new kind of physical process that could produce unpredictable flashes of high-energy gamma rays in these otherwise-quiet regions of space. And if the bursts came from galaxies millions or billions of light-years away, then they must be extremely powerful to be observable at such large distances; indeed they had to be among the biggest explosions in the universe.

The First Afterglows

The problem with trying to figure out the source of the gamma-ray bursts was that our instruments for detecting gamma rays could not pinpoint the exact place in the sky where the burst was happening. Early gamma-ray telescopes did not have sufficient *resolution*. This was frustrating because astronomers suspected that if they *could* pinpoint the exact position of one of these rapid bursts, then they would be able to identify a counterpart (such as a star or galaxy) at other wavelengths and learn much more about the burst, including where it came from. This would, however, require either major improvements in gamma-ray detector technology to provide better resolution or detection of the burst at some other wavelength. In the end, both techniques played a role.

The breakthrough came with the launch of the Italian Dutch *BeppoSAX* satellite in 1996. *BeppoSAX* included a new type of gamma-ray telescope capable of identifying the position of a source much more accurately than previous instruments, to within a few minutes of arc on the sky. By itself, however, it was still not sophisticated enough to determine the exact source of the gamma-ray burst. After all, a box a few minutes of arc on a side could still contain many stars or other celestial objects.

However, the angular resolution of *BeppoSAX* was good enough to tell astronomers where to point other, more precise telescopes in the hopes of detecting longer-lived electromagnetic emission from the bursts at other wavelengths. Detection of a burst at visible-light or radio wavelengths could provide a position accurate to a few *seconds* of arc and allow the position to be pinpointed to an individual star or galaxy. *BeppoSAX* carried its own X-ray telescope onboard the spacecraft to look for such a counterpart, and astronomers using visible-light and radio facilities on the ground were eager to search those wavelengths as well.

Two crucial *BeppoSAX* burst observations in 1997 helped to resolve the mystery of the gamma-ray bursts. The first burst came in February from the direction of the constellation Orion. Within 8 hours, astronomers working with the satellite had identified the position of the burst, and reoriented the spacecraft to focus *BeppoSAX*'s X-ray detector on the source. To their excitement, they detected a slowly fading X-ray source 8 hours after the event—the first successful detection of an afterglow from a gamma-ray burst. This provided an even-better location of the burst (accurate to about 40 seconds of arc), which was then distributed to astronomers across the world to try to detect it at even longer wavelengths.

That very night, the 4.2-meter William Herschel Telescope on the Canary Islands found a fading visible-light source at the same position as the X-ray afterglow, confirming that such an afterglow could be detected in visible light as well. Eventually, the afterglow faded away, but left behind at the location of the original gamma-ray burst was a faint, fuzzy source right where the fading point of light had been—a distant galaxy (Figure 23.6.2). This was the first piece of evidence that gamma-ray bursts were indeed very energetic objects from very far away. However, it also remained possible that the burst source was much closer to us and just happened to align with a more distant galaxy, so this one observation alone was not a conclusive demonstration of the extragalactic origin of gamma-ray bursts.

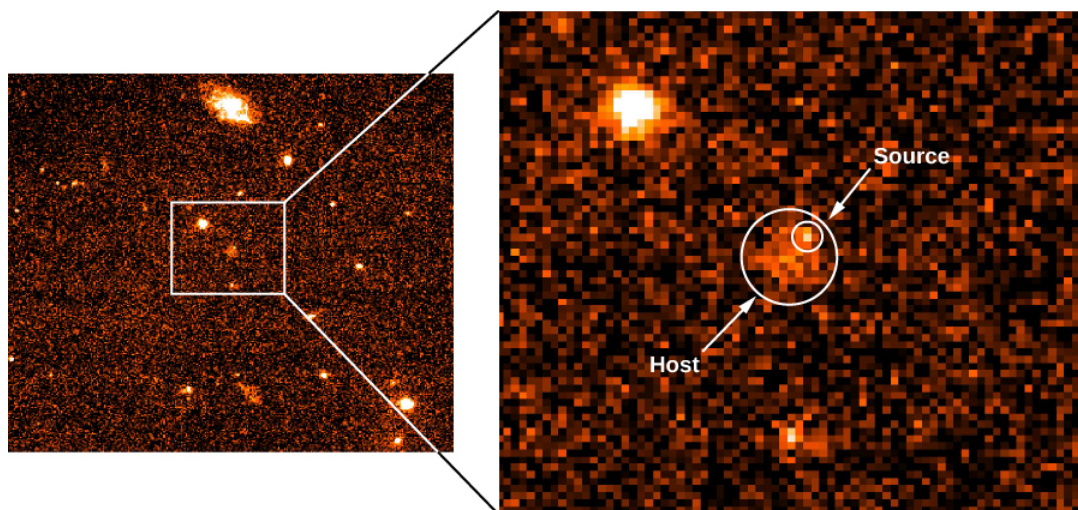


Figure 23.6.2: Gamma-Ray Burst. This false-color Hubble Space Telescope image, taken in September 1997, shows the fading afterglow of the gamma-ray burst of February 28, 1997 and the host galaxy in which the burst originated. The left view shows the region of the burst. The enlargement shows the burst source and what appears to be its host galaxy. Note that the gamma-ray source is not in the center of the galaxy.

On May 8 of the same year, a burst came from the direction of the constellation Camelopardalis. In a coordinated international effort, *BeppoSAX* again fixed a reasonably precise position, and almost immediately a telescope on Kitt Peak in Arizona was able to catch the visible-light afterglow. Within 2 days, the largest telescope in the world (the Keck in Hawaii) collected enough light to record a spectrum of the burst. The May gamma-ray burst afterglow spectrum showed absorption features from a fuzzy object that was 4 billion light-years from the Sun, meaning that the location of the burst had to be at least this far away—and possibly even farther. (How astronomers can get the distance of such an object from the Doppler shift in the spectrum is something we will discuss in Galaxies.) What that spectrum showed was clear evidence that the gamma-ray burst had taken place in a distant galaxy.

Networking to Catch More Bursts

After initial observations showed that the precise locations and afterglows of gamma-ray bursts could be found, astronomers set up a system to catch and pinpoint bursts on a regular basis. But to respond as quickly as needed to obtain usable results, astronomers realized that they needed to rely on automated systems rather than human observers happening to be in the right place at the right time.

Now, when an orbiting high-energy telescope discovers a burst, its rough location is immediately transmitted to a *Gamma-Ray Coordinates Network* based at NASA's Goddard Space Flight Center, alerting observers on the ground within a few seconds to look for the visible-light afterglow.

The first major success with this system was achieved by a team of astronomers from the University of Michigan, Lawrence Livermore National Laboratory, and Los Alamos National Laboratories, who designed an automated device they called the *Robotic Optical Transient Search Experiment (ROTSE)*, which detected a very bright visible-light counterpart in 1999. At peak, the burst was almost as bright as Neptune—despite a distance (measured later by spectra from larger telescopes) of 9 billion light-years.

More recently, astronomers have been able to take this a step further, using wide-field-of-view telescopes to stare at large fractions of the sky in the hope that a gamma-ray burst will occur at the right place and time, and be recorded by the telescope's camera. These wide-field telescopes are not sensitive to faint sources, but ROTSE showed that gamma-ray burst afterglows could sometimes be very bright.

Astronomers' hopes were vindicated in March 2008, when an extremely bright gamma-ray burst occurred and its light was captured by two wide-field camera systems in Chile: the Polish "Pi of the Sky" and the Russian-Italian TORTORA [Telescopio Ottimizzato per la Ricerca dei Transienti Ottici Rapidi (Italian for Telescope Optimized for the Research of Rapid Optical Transients)] (Figure 23.6.3). According to the data taken by these telescopes, for a period of about 30 seconds, the light from the gamma-ray burst was bright enough that it could have been seen by the unaided eye had a person been looking in the right place at the right time. Adding to our amazement, later observations by larger telescopes demonstrated that the burst occurred at a distance of 8 billion light-years from Earth!

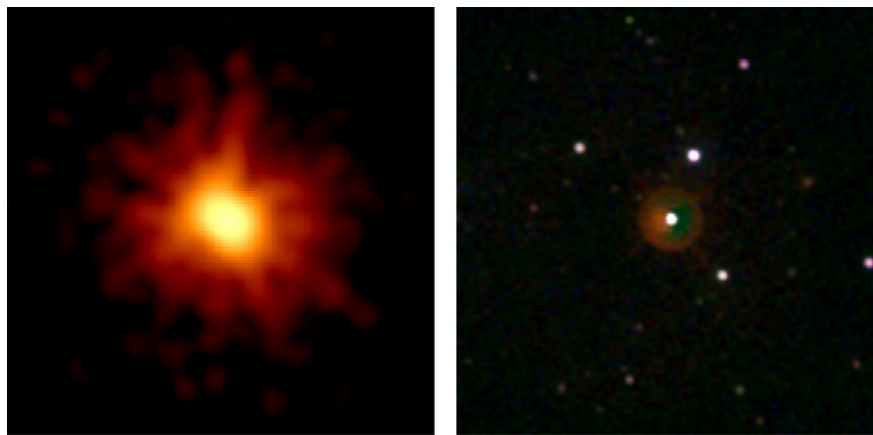


Figure 23.6.3: Gamma-Ray Burst Observed in March 2008. The extremely luminous afterglow of GRB 080319B was imaged by the Swift Observatory in X-rays (left) and visible light/ultraviolet (right).

To Beam or Not to Beam

The enormous distances to these events meant they had to have been astoundingly energetic to appear as bright as they were across such an enormous distance. In fact, they required so much energy that it posed a problem for gamma-ray burst models: if the source was radiating energy in all directions, then the energy released in gamma rays alone during a bright burst (such as the 1999 or 2008 events) would have been equivalent to the energy produced if the entire mass of a Sun-like star were suddenly converted into pure radiation.

For a source to produce this much energy this quickly (in a burst) is a real challenge. Even if the star producing the gamma-ray burst was much more massive than the Sun (as is probably the case), there is no known means of converting so much mass into radiation within a matter of seconds. However, there is one way to reduce the power required of the “mechanism” that makes gamma-ray bursts. So far, our discussion has assumed that the source of the gamma rays gives off the same amount of energy in all directions, like an incandescent light bulb.

But as we discuss in Pulsars and the Discovery of Neutron Stars, not all sources of radiation in the universe are like this. Some produce thin beams of radiation that are concentrated into only one or two directions. A laser pointer and a lighthouse on the ocean are examples of such beamed sources on Earth (Figure 23.6.4). If, when a burst occurs, the gamma rays come out in only one or two narrow beams, then our estimates of the luminosity of the source can be reduced, and the bursts may be easier to explain. In that case, however, the beam has to point toward Earth for us to be able to see the burst. This, in turn, would imply that for every burst we see from Earth, there are probably many others that we never detect because their beams point in other directions

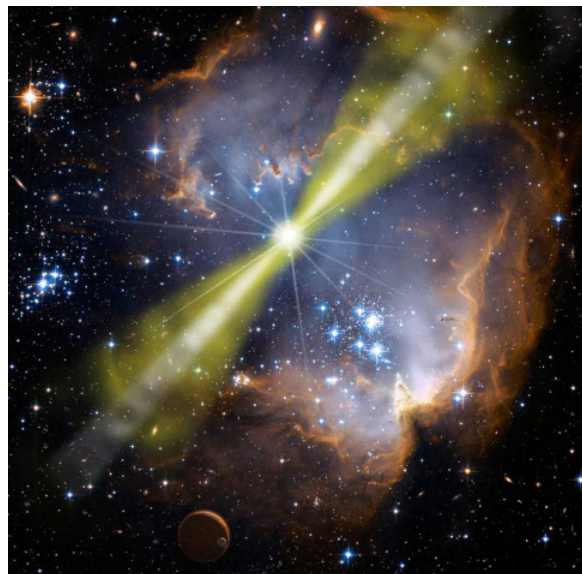


Figure 23.6.4: Burst That Is Beamed. This artist's conception shows an illustration of one kind of gamma-ray burst. The collapse of the core of a massive star into a black hole has produced two bright beams of light originating from the star's poles, which an observer pointed along one of these axes would see as a gamma-ray burst. The hot blue stars and gas clouds in the vicinity are meant to show that the event happened in an active star-forming region.

Long-Duration Gamma-Ray Bursts: Exploding Stars

After identifying and following large numbers of gamma-ray bursts, astronomers began to piece together clues about what kind of event is thought to be responsible for producing the gamma-ray burst. Or, rather, what kind of *events*, because there are at least two distinct types of gamma-ray bursts. The two—like the different types of supernovae—are produced in completely different ways.

Observationally, the crucial distinction is how long the burst lasts. Astronomers now divide gamma-ray bursts into two categories: short-duration ones (defined as lasting less than 2 seconds, but typically a fraction of a second) and long-duration ones (defined as lasting more than 2 seconds, but typically about a minute).

All of the examples we have discussed so far concern the long-duration gamma-ray bursts. These constitute most of the gamma-ray bursts that our satellites detect, and they are also brighter and easier to pinpoint. Many hundreds of long-duration gamma-ray bursts, and the properties of the galaxies in which they occurred, have now been studied in detail. Long-duration gamma-ray bursts are universally observed to come from distant galaxies that are still actively making stars. They are usually found to be located in regions of the galaxy with strong star-formation activity (such as spiral arms). Recall that the more massive a star is, the less time it spends in each stage of its life. This suggests that the bursts come from a young and short-lived, and therefore massive type of star.

Furthermore, in several cases when a burst has occurred in a galaxy relatively close to Earth (within a few billion light-years), it has been possible to search for a supernova at the same position—and in nearly all of these cases, astronomers have found evidence of a supernova of type Ic going off. A type Ic is a particular type of supernova, which we did not discuss in the earlier parts of this chapter; these are produced by a massive star that has been stripped of its outer hydrogen layer. However, only a tiny fraction of type Ic supernovae produce gamma-ray bursts.

Why would a massive star with its outer layers missing sometimes produce a gamma-ray burst at the same time that it explodes as a supernova? The explanation astronomers have in mind for the extra energy is the collapse of the star's core to form a spinning, magnetic black hole or neutron star. Because the star corpse is both magnetic and spinning rapidly, its sudden collapse is complex and can produce swirling jets of particles and powerful beams of radiation—just like in a quasar or active galactic nucleus (objects you will learn about Active Galaxies, Quasars, and Supermassive Black Holes), but on a much faster timescale. A small amount of the infalling mass is ejected in a narrow beam, moving at speeds close to that of light. Collisions among the particles in the beam can produce intense bursts of energy that we see as a gamma-ray burst.

Within a few minutes, the expanding blast from the fireball plows into the interstellar matter in the dying star's neighborhood. This matter might have been ejected from the star itself at earlier stages in its evolution. Alternatively, it could be the gas out of which the massive star and its neighbors formed.

As the high-speed particles from the blast are slowed, they transfer their energy to the surrounding matter in the form of a shock wave. That shocked material emits radiation at longer wavelengths. This accounts for the afterglow of X-rays, visible light, and radio waves—the glow comes at longer and longer wavelengths as the blast continues to lose energy.

Short-Duration Gamma-Ray Bursts: Colliding Stellar Corpses

What about the shorter gamma-ray bursts? The gamma-ray emission from these events lasts less than 2 seconds, and in some cases may last only milliseconds—an amazingly short time. Such a timescale is difficult to achieve if they are produced in the same way as long-duration gamma-ray bursts, since the collapse of the stellar interior onto the black hole should take at least a few seconds.

Astronomers looked fruitlessly for afterglows from short-duration gamma-ray bursts found by *BeppoSAX* and other satellites. Evidently, the afterglows fade away too quickly. Fast-responding visible-light telescopes like ROTSE were not helpful either: no matter how fast these telescopes responded, the bursts were not bright enough at visible wavelengths to be detected by these small telescopes.

Once again, it took a new satellite to clear up the mystery. In this case, it was the *Swift Gamma-Ray Burst Satellite*, launched in 2004 by a collaboration between NASA and the Italian and UK space agencies (Figure 23.6.5). The design of *Swift* is similar to that of *BeppoSAX*. However, *Swift* is much more agile and flexible: after a gamma-ray burst occurs, the X-ray and UV telescopes can be repositioned automatically within a few minutes (rather than a few hours). Thus, astronomers can observe the afterglow much earlier, when it is expected to be much brighter. Furthermore, the X-ray telescope is far more sensitive and can provide positions that are 30 times more precise than those provided by *BeppoSAX*, allowing bursts to be identified even without visible-light or radio observations

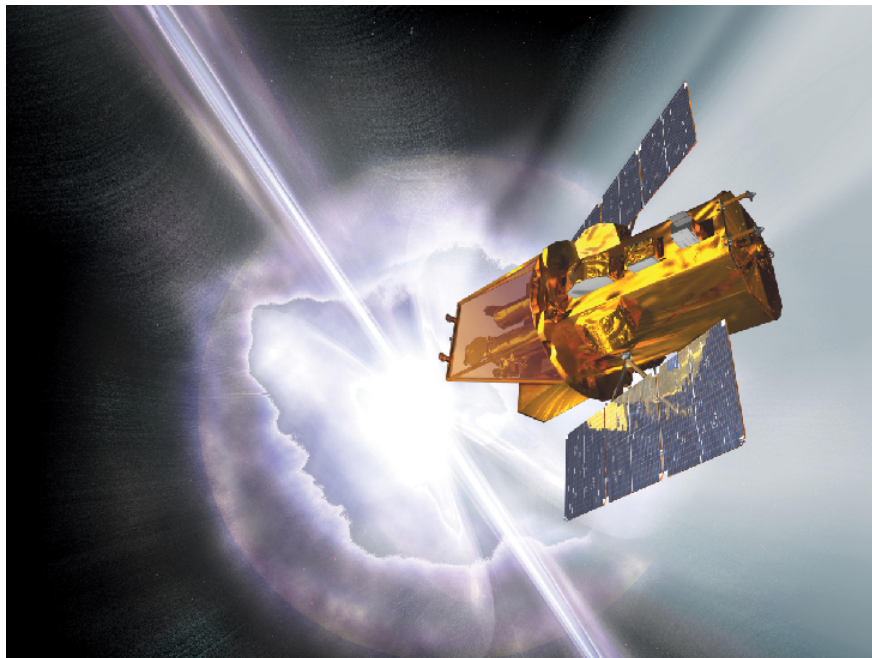


Figure 23.6.5: Artist's Illustration of Swift. The US/UK/Italian spacecraft Swift contains on-board gamma-ray, X-ray, and ultraviolet detectors, and has the ability to automatically reorient itself to a gamma-ray burst detected by the gamma-ray instrument. Since its launch in 2005, Swift has detected and observed over a thousand bursts, including dozens of short-duration bursts.

On May 9, 2005, *Swift* detected a flash of gamma rays lasting 0.13 seconds in duration, originating from the constellation Coma Berenices. Remarkably, the galaxy at the X-ray position looked completely different from any galaxy in which a long-duration burst had been seen to occur. The afterglow originated from the halo of a giant elliptical galaxy 2.7 billion light-years away, with no signs of any young, massive stars in its spectrum. Furthermore, no supernova was ever detected after the burst, despite extensive searching.

What could produce a burst less than a second long, originating from a region with no star formation? The leading model involves the *merger* of two compact stellar corpses: two neutron stars, or perhaps a neutron star and a black hole. Since many stars come in binary or multiple systems, it's possible to have systems where two such star corpses orbit one another. According to general relativity (which will be discussed in Black Holes and Curved Spacetime), the orbits of a binary star system composed of such

objects should slowly decay with time, eventually (after millions or billions of years) causing the two objects to slam together in a violent but brief explosion. Because the decay of the binary orbit is so slow, we would expect more of these mergers to occur in old galaxies in which star formation has long since stopped.

To learn more about the merger of two neutron stars and how they can produce a burst that lasts less than a second, check out this [computer simulation](#) by NASA.

While it was impossible to be sure of this model based on only a single event (it is possible this burst actually came from a background galaxy and lined up with the giant elliptical only by chance), several dozen more short-duration gamma-ray bursts have since been located by *Swift*, many of which also originate from galaxies with very low star-formation rates. This has given astronomers greater confidence that this model is the correct one. Still, to be fully convinced, astronomers are searching for a “smoking gun” signature for the merger of two ultra-dense stellar remnants.

There are two examples we can think of that would provide more direct evidence. One is a very special kind of explosion, produced when neutrons stripped from the neutron stars during the violent final phase of the merger fuse together into heavy elements and then release heat due to radioactivity, producing a short-lived but red supernova sometimes called a *kilonova*. (The term is used because it is about a thousand times brighter than an ordinary nova, but not quite as “super” as a traditional supernova.) Hubble observations of one short-duration gamma-ray burst in 2013 show suggestive evidence of such a signature, but need to be confirmed by future observations.

The second “smoking gun” has been even more exciting to see: the detection of *gravitational waves*. As will be discussed in Black Holes and Curved Spacetime, gravitational waves are ripples in the fabric of spacetime that general relativity predicts should be produced by the acceleration of extremely massive and dense objects—such as two neutron stars or black holes spiraling toward each other and colliding. The first example of gravitational waves has been observed recently from the merger of two large black holes. If a gravitational wave is observed one day to be coincident in time and space with a gamma-ray burst, this will not only confirm our theories of the origin of short gamma-ray bursts but would also be among the most spectacular demonstrations yet of Einstein’s theory of general relativity.

Probing the Universe with Gamma-Ray Bursts

The story of how astronomers came to explain the origin of the different kinds of bursts is a good example of how the scientific process sometimes resembles good detective work. While the mystery of short-duration gamma-ray bursts is still being unraveled, the focus of studies for long-duration gamma-ray bursts has begun to change from understanding the origin of the bursts themselves (which is now fairly well-established) to using them as tools to understand the broader universe.

The reason that long-duration gamma-ray bursts are useful has to do with their extreme luminosities, if only for a short time. In fact, long-duration gamma-ray bursts are so bright that they could easily be seen at distances that correspond to a few hundred million years after the expansion of the universe began, which is when theorists think that the first generation of stars formed. Some theories predict that the first stars are likely to be massive and complete their evolution in only a million years or so. If this turns out to be the case, then gamma-ray bursts (which signal the death of some of these stars) may provide us with the best way of probing the universe when stars and galaxies first began to form.

So far, the most distant gamma-ray burst found (on April 29, 2009) originated a remarkable 13.2 billion light-years away—meaning it happened only 600 million years after the Big Bang itself. This is comparable to the earliest and most distant galaxies found by the Hubble Space Telescope. It is not quite old enough to expect that it formed from the first generation of stars, but its appearance at this distance still gives us useful information about the production of stars in the early universe. Astronomers continue to scan the skies, looking for even more distant events signaling the deaths of stars from even further back in time.

Key Concepts and Summary

Gamma-ray bursts last from a fraction of a second to a few minutes. They come from all directions and are now known to be associated with very distant objects. The energy is most likely beamed, and, for the ones we can detect, Earth lies in the direction of the beam. Long-duration bursts (lasting more than a few seconds) come from massive stars with their outer hydrogen layers missing that explode as supernovae. Short-duration bursts are believed to be mergers of stellar corpses (neutron stars or black holes).

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