Gamma-Ray Bursts

PRIMER:
THE COLLAPSAR - FIREBALL MODEL

Gamma-ray bursts — shining hundreds of times brighter than a supernova and as bright as a million trillion suns — are quick bursts of gamma-ray photons that satellites detect almost daily in wholly random directions of the sky. The bursts last from a few milliseconds to roughly 100 seconds. The short-duration bursts are defined as those lasting less than 2 seconds, while long-duration bursts last more than 2 seconds. These bursts are often followed by an afterglow, a secondary burst of light in the form of X rays, visible light, and radio waves. The afterglow can persist for hours, days, or even weeks.

What causes these bursts? The burst detected on October 4, 2002, called GRB 021004, was a particularly long burst, lasting nearly 100 seconds. GRB 021004 has become the best-studied burst to date. Observations strongly suggested that this burst was created by a collapsar — a massive Wolf-Rayet star that collapses onto itself during an especially powerful supernova, dubbed a hypernova.

Theorists have proposed that long-duration gamma-ray bursts result from a collapsar. When such a star, with the mass at least 20 to 30 times the sun, depletes its nuclear fuel, it has no outward radiation pressure to support its bulk. The core of the star — containing the mass of several suns — implodes (collapses) into a black hole, while most of the star's bulk explodes into the surrounding interstellar medium. We recognize the explosion as the supernova event. The gamma-ray burst, however, begins to evolve before the star breaks apart, set in motion by the newly formed black hole.

Theorists suggest that the black hole immediately begins to pull in more stellar material; and very quickly a disk of material called an accretion disk forms, with the inner portion of the disk spinning around the black hole at near light speed. Rotating, conducting fluids create a magnetic field, and this accretion disk is no exception. Yet because the inner portion of the accretion disk is rotating more quickly than the outer portion, the magnetic field lines twist violently. This causes a jet of material to blast outward at almost the speed of light perpendicularly to the accretion disk. The jet contains matter and antimatter in the form of electrons, positrons and protons.

This is the collapsar model of gamma-ray bursts: the collapse of the stellar core into a black hole. But it is only the first step in making a gamma-ray burst. Step two is the relativistic fireball shock model.

Because this jet of material moves at nearly the speed of light, relativistic effects (referring to Einstein's theory of special relativity) take over. The jet is the "fireball," although it really is more like a fire hose. The fireball behaves as a shock wave as it races outward, plowing into and sweeping up matter in its way. Inside the fireball, pressure, density and temperature vary, resulting in a series of internal shock waves moving back and forth within the fireball as faster moving blobs of material overtake slower moving blobs. (From the frame of reference of the faster blobs, though, the slower blobs appear to be moving at relativistic speeds backwards through the plasma.)

Gamma rays are produced as a result of the collisions of blobs of matter. But the fireball medium does not allow the light to escape until it has cooled just enough to become transparent — at which point the light particles race outward in the direction of motion of the jet, just ahead of the lead shock front. From our perspective on Earth, the photons first detected have been accelerated toward us, resulting in a "blueshift" to the shortest frequencies and highest energies possible (i.e. gamma rays). This is the gamma ray burst.

The afterglow results when material in the fireball plows into the material in the interstellar medium to create a wide array of less energetic light. Initially X rays result, but as the blobs of matter bump into each other, they lose their kinetic energy and the resulting energies decrease — through visible light and eventually into radio waves. In theory, the afterglow can persist for months as the energies gradually shift to lower frequencies.

Gamma-Ray Bursts

A BRIEF HISTORY

October 1963: The U.S. Air Force launches the first in a series of "Vela" satellites carrying X-ray, gamma-ray and neutron detectors in order to monitor any nuclear testing by the Soviet Union or other nations in violation of the just-signed nuclear test ban treaty.

July 2, 1967: The Vela 4a,b satellite makes first-ever observation of a gamma-ray burst. The actual determination would come two years later in 1969. The results would not be declassified and published until 1973.

March 14, 1971: NASA launches the IMP 6 satellite. Aboard the satellite is a gamma-ray detector. Although the main purpose of the instruments was not to detect for gamma-ray bursts (GRB), it nevertheless inadvertently observes them while monitoring solar flares.

September 1971: The Seventh Orbiting Solar Observatory (OSO-7) is launched. It carries an X-ray telescope designed to measure hard (very energetic) X-rays from sources across the sky. OSO-7 also includes a gamma-ray monitor.

1972-1973: Los Alamos scientists analyze various Vela gamma-ray events. They conclude that gamma-ray bursts are indeed "of cosmic origin." They publish their findings concerning 16 bursts as observed by Vela 5a,b and Vela 6a,b between July 1969 and July 1972 in the Astrophysical Journal in 1973.

1974: Data from Soviet Konus satellites is published, confirming the detection of these bursts of gamma rays.

1976: The start of the Interplanetary Network (IPN), a set of gamma-ray detectors placed on spacecraft studying the Sun and planets. These detectors work in unison to located gamma-ray bursts through a process of triangulation. By localizing the sources of GRBs to a few arc minutes, the IPN shows that these sources are not known sources of interest, such as X-ray emitters. The IPN continues today.

March 5, 1979: An unusual gamma-ray transient is found, later localized to the N49 supernova remnant in the LMC. This causes a controversy that lasts for over a decade: One side maintains accidental coincidence (the thought was that GRBs could not come from anything as distant as the LMC galaxy), while the other maintains two classes of sources exist, and that this is a separate one from GRBs. Later study of Soft Gamma Repeaters by ASCA proves the latter to be correct. (And, GRBs do come from very distant sources.)

April 5, 1991: NASA launches the Compton Gamma Ray Observatory. Among its payload is the Burst And Transient Source Experiment (BATSE) instrument, which detects over 2,700 gamma-ray bursts in nine years. BATSE data proves that gamma-ray bursts are uniformly distributed across the sky, not concentrated along the plane of the Milky Way. This means that gamma-ray bursts originate far outside of the Milky Way galaxy. This disproves the galactic neutron theory. It also suggests that gamma-ray bursts have mind-boggling energies associated with them in order to be detectable across the entire observable universe. This marks a pardigm shift; gamma-ray bursts are now viewed as cosmological.

December 30, 1995: NASA launches the Rossi X-ray Timing Explorer, designed to study how the emission lines of X-ray emitting sources change with time. This will be used subsequently to study the X-ray afterglow of gamma-ray bursts.

April 30, 1996: The BeppoSAX satellite, a joint collaboration of the Italian Space Agency and the Netherlands Space Agency, is launched.

February 28, 1997: Using BeppoSAX, astronomers looking at GRB979228 detect an X-ray afterglow associated with a gamma-ray burst for the first time. This begins the era of studying GRB afterglows.

January 23, 1999: The afterglow of GRB990123 is detected within seconds of the initial burst. Based on careful analysis, astronomers determined that the energy is channeled (beamed) in narrow jets and that we detect GRBs only if the jet is aimed along our line of sight. The energy output of GRB990123 is put at 10^{43} watts — 1,000 times more luminous than quasars and one hundred quadrillion times more luminous than the Sun.

July 5, 1999: GRB990705 is detected. Analysis of the emission lines from the afterglow shows an iron-absorption feature that is characteristic of a supernova.

December 12, 1999: Observations of emission lines from GRB991216 afterglow from the Japanese X-ray satellite ASCA and NASA's Chandra X-ray Observatory detect iron lines. This helped pinpoint a distance to the burst.

January 21, 2000: Peter Meszaros, Bohdan Paczynski and Martin Rees are each awarded the Bruno Rossi Prize by the High Energy Astrophysics Division of the American Astronomical Society for their work on gamma-ray bursts.

March 26, 2000: BATSE detects its final burst, number 2,704.

October 9, 2000: NASA's High Energy Transient Explorer (HETE) is launched. The international, MIT-built HETE was designed to detect and rapidly pinpoint the location of gamma-ray bursts.

December 11, 2001: GRB 011211 is detected. The European Space Agency's X-ray Multi-Mirror satellite finds evidence of silicon, sulfur, argon, and other elements in the shell of gas surrounding the burst. Such elements are typically associated with supernovae.

October 4, 2002: HETE detects a burst observed so quickly by other telescopes that scientists find evidence of the death of a massive star and the birth of what appears to be a black hole in its place.

October 17, 2002: The European Space Agency launches INTEGRAL, a gamma-ray observatory containing a burst detector. INTEGRAL detects several bursts during its first months of operation.

December 23, 2002: HETE detects the first "dark" gamma-ray burst with an afterglow. Such bursts, accounting for roughly half of all GRBs, were thought to be devoid of optical afterglows. This afterglow disappears within 2 hours -- meaning that if the afterglow hadn't been detected as quickly as it had, this GRB would've been labeled "dark". Perhaps no burst is truly dark if observed fast enough.

March 19, 2003: NASA announces compelling evidence that long-duration gamma-ray bursts (lasting over 10 seconds) form from the death of massive stars and simultaneous creation of black holes.

December 2003: NASA's Swift satellite is due to be launched. Swift will carry instruments designed to measure both GRBs and their afterglow in X-ray, ultraviolet and optical light wavelengths.

September 2006: The Gamma Ray Large Area Space Telescope (GLAST) will carry an instrument to detect gamma-ray bursts with photons thousands of times more energetic than what Swift detects.

Gamma-Ray Bursts
GLOSSARY

Afterglow: The less-energetic forms of electromagnetic radiation, including X rays, optical light and radio waves, that often follow the initial burst of gamma rays in a gamma-ray burst. The afterglow can persist for days to weeks, gradually dissipating with time. The BeppoSAX satellite discovered the afterglow phenomenon in 1997.

BeppoSAX: An Italian-Dutch X-ray satellite mission launched on April 30, 1996, and active for six years. BeppoSAX observed a wide range of celestial X-ray sources and also discovered the afterglow phenomenon from a burst on February 28, 1997. BeppoSAX also helped find more precise locations of many gamma-ray bursts.

Binary merger theory: A theory on the origin of gamma-ray bursts, in which two compact stellar objects merge. The objects could be neutron stars or stellar black holes, and the merger would result in a new, single black hole.

Black hole: An object so dense that its escape velocity exceeds the speed of light. Theoretically, the object collapses to a single point of infinite density, called a singularity. Light or matter that crosses the theoretical border of the black hole, called the event horizon, cannot return.

There are two main classes of black holes. A stellar black hole is the core remains of an imploded massive star. The Milky Way Galaxy is likely home to thousands of stellar black holes, with masses ranging from 3 to 20 solar masses. A supermassive black hole has a mass of millions to billions of solar masses confined to a region no larger than our Solar System. These likely exist is the center of most galaxies and are thought to power quasars. A new class of intermediate-mass black holes is now emerging.

BATSE: The Burst and Transient Source Experiment aboard the Compton Gamma Ray Observatory. This instrument detected over 2,700 gamma-ray bursts and helped astronomers determine that these bursts appear from all directions and originate billions of light years away.

Compact object: An extremely dense stellar object, namely a black hole, neutron star, or white dwarf. An observer sees such an object as a point, too small to resolve.

Compton Gamma Ray Observatory: The second of NASA's four Great Observatories, launched in April 1991. The satellite, no longer in orbit, lasted nine years, and its four main instruments discovered hundreds of exotic objects radiating in gamma rays. Compton's BATSE instrument detected over 2,700 gamma-ray bursts.

Dark gamma-ray burst: Long-duration gamma-ray bursts that leave little or no afterglow, comprising about 30 percent of all bursts. Such bursts are thought to be dark because (a) there is a lack of sufficient gas and dust in the interstellar medium to create the afterglow; or (b) the burst is so enshrouded in dust that only gamma rays can escape.

Fireball shock model: A model describing the behavior of an expanding fireball associated with a gamma-ray burst. The model explains how the fireball creates external and internal shock waves that propagate both in the forward and reverse directions. It also predicts the existence of the gamma-ray burst afterglow.

Gamma rays: The most energetic form of electromagnetic radiation, with extremely short wavelengths and high frequencies. The Earth's atmosphere blocks most celestial gamma rays from reaching the Earth's surface. The most energetic gamma rays create secondary particles in the Earth's atmosphere, which can be detected from the ground. Other gamma rays are detected from space.

Gamma-ray burst (GRB): A short-lived, extremely intense burst of gamma rays likely signaling the birth of a black hole. GRBs are common yet enigmatic and random, lasting from only a few milliseconds to about 100 seconds. GRBs are considered "short" if under two seconds and "long" if over two seconds. Most GRBs likely originate billions of light years away. GRBs are named by date; GRB 021004, for example, was detected on October 4, 2002.

Hard X ray: Also called soft gamma rays, referring to gamma rays of lower energy.

Hypernova: A theorized supernova, or star explosion, involving a star approximately 100 solar masses. This could be one possible cause of a gamma-ray burst, providing 100 times the energy of a "regular" supernova.

Long-duration burst: Gamma-ray bursts lasting longer than 2 seconds. Most long-duration bursts last about 10 seconds, though some as long as 100 seconds. These are believed to be produced by the explosion of a massive star.

Magnetar: A neutron star with an incredibly strong magnetic field, thousands of times stronger than that of an ordinary neutron star and over a hundred trillion times stronger than that of the Earth or Sun. Magnetars were first theorized in 1992 and detected in 1998.

Neutron star: The collapsed, core remains of a massive star that exploded in a supernova event. Neutron stars are ultra-dense spheres, only 10 to 15 miles across yet containing the mass of several suns. Neutron stars have a thin metallic crust, beneath which lies a superfluid of neutrons. Merging neutron stars might produce gamma-ray bursts.

Photon: A particle of light. As the carrier of electromagnetic radiation, this particle has zero mass and always moves, by definition, at the speed of light. Electromagnetic radiation with a certain wavelength (frequency) appears as visible light. The most energetic photons are called gamma rays.

Pulsar: A rapidly spinning neutron star. Such objects can spin thousands of times a second. The name derives from the fact that they appear to pulse regularly as they emit a range of electromagnetic radiation with a precision that rivals many of the best human-made clocks.

Redshift: An apparent shift toward longer wavelengths of the electromagnetic radiation (or, lower energies) emitted by an object moving away from the observer. Because the Universe is expanding, distant objects are rapidly moving away from the Earth and have large redshifts. Redshifts are used to measure distance and speed, analogous to Doppler radar.

Shock wave: A strong compression wave moving through a material medium where there is a sudden change in velocity, density, pressure, or temperature of the material. In the gamma-ray burst fireball model, the forward motion of the fireball creates a forward shock, while the bunching up of matter along the shock front creates a reverse shock that appears to propagate back through the fireball. The forward shock sweeps up material in the vicinity of a gamma-ray burst and slams it into material already in the interstellar medium. This collision forms the burst afterglow.

Short-duration burst: Gamma-ray bursts lasting less than 2 seconds. Such bursts are thought to result from the merger of two compact objects, such as a binary system containing neutron stars or black holes.

Soft X rays: Lower-energy X rays, also called extreme ultraviolet.

Supernova: The violent explosion of a massive star (at least 8 solar masses) that occurs when the star has exhausted its internal fuel supply. Without radiation pressure from nuclear fusion to support the mass of the star, the stellar core collapses while the outer shells explode outward. The core collapses into a neutron star or black hole. A supernova can outshine its host galaxy for several days.

Transitional burst: A rare category of gamma-ray bursts that have duration of about 2 to 3 seconds, placing them in between the short and long varieties.

X-ray rich gamma-ray burst: A type of gamma-ray burst in which more X rays are emitted than gamma rays. These account for 20 to 30 percent of the observed gamma-ray bursts. Some X-ray rich bursts produce no detectable gamma rays at all, just X rays. These are called X-ray bursts, and they are quite rare, perhaps originating as gamma-ray bursts so distant that their gamma-ray photons have redshifted to X-ray energies.