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ENCYCLOPEDIA ARTICLE

Astrophysics, high-energy

The study of the universe as revealed by high-energy, invisible forms of light: x-rays and gamma rays. These radiations are produced in the cosmos when gas is heated to millions of degrees Kelvin or electrons have been accelerated to near the speed of light by violent and extreme conditions. Exploding stars, neutron stars, black holes, and galaxy clusters, the most massive objects in the universe, are among the objects studied.

Instrumentation

The high energies of x-rays and gamma rays have two important consequences for astronomical research. First, these forms of light are absorbed by the atmosphere, so telescopes to detect them must be placed on spacecraft above the atmosphere. Second, the telescopes must be constructed differently. Gamma rays have such high energy that they cannot be focused by traditional techniques, although indirect methods can give a rough estimate of their direction.

X-rays will reflect off mirrors, but only if they strike at grazing angles, like a stone skipping across a pond. For this reason, x-ray mirrors have to be carefully shaped and aligned nearly parallel to the incoming x-rays. These barrel-shaped mirrors are nested one inside the other to increase the collection area, and therefore the sensitivity, of the telescope.

The *Chandra X-ray Observatory*, launched by the National Aeronautics and Space Administration (NASA) in July 1999, is the premier focusing x-ray telescope. It is an assembly of four pairs of mirrors. Chandra's mirrors are the smoothest mirrors ever constructed. The largest of the mirrors is almost 4 feet (1.2 m) in diameter and 3 ft (0.9 m) long. See also: X-ray telescope

The European Space Agency's *XMM*, a powerful telescope launched in December 1999, has 58 mirrors. These mirrors are not as smooth as *Chandra*'s mirrors, so *XMM* cannot make images of the same crispness, but it can detect fainter sources and measure the energies of x-rays very accurately.

NASA's *Rossi X-ray Timing Explorer (RXTE)*, launched in December 1995, has the ability to study changes in the intensity of x-rays produced in the violent environment around neutron stars and black holes on time scales ranging from microseconds to months. Two other NASA missions involving international cooperation, the *High Energy Transient Explorer (HETE-2)*, launched in 2001, and the *Swift* satellite, launched in 2004, are dedicated to the exploration of short-lived bursts of x-rays and gamma rays.

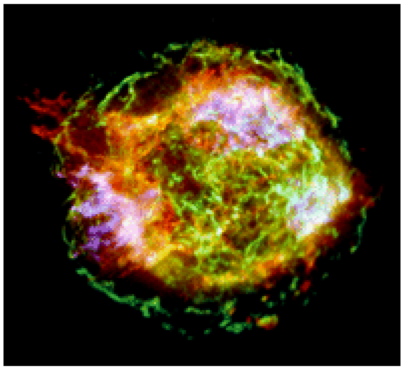
NASA's *Compton Gamma-Ray Observatory*, which inaugurated a new era in gamma-ray astronomy with its unprecedented sensitivity and coverage of a large range of gamma-ray energies, was deorbited and reentered the Earth's atmosphere on June 4, 2000. The *Compton Observatory* has been succeeded by the European Space Agency's *International Gamma-Ray Astrophysics Laboratory (INTEGRAL)*, launched in October 2002, an observatory with a complement of gamma-ray, x-ray, and optical telescopes. Several new telescopes are designed to observe flashes of visible light created high in Earth's atmosphere when extremely high energy (teraelectronvolt or TeV) gamma rays hit the upper atmosphere. For example, the *High Energy Spectroscopic System (HESS)*, an array of four 12-m (39-ft) mirrors on a mountain in central Namibia, has made a rough image of TeV gamma rays from the remnant of a supernova explosion. See also: Cerenkov radiation; Gamma-ray astronomy

Supernovae

When a massive star (ten or more times as massive as the Sun) has used up the nuclear fuel that makes it shine, the pressure drops in the central core of the star. Gravity crushes the matter in the core to higher and higher densities. Temperatures soar to billions of degrees Kelvin. The intense heat generated in the collapse produces a cataclysmic rebound that sends high-speed debris flying outward at speeds in excess of 5000 mi/s (8000 km/s). A thermonuclear shock wave races through the now expanding stellar debris, fusing lighter elements into heavier ones and producing a brilliant visual outburst with the brightness of several hundred million suns.

A massive star explodes about once every 50 years in the Milky Way Galaxy. The shell of matter thrown off by the supernova creates a magnetized bubble of multimillion-degree gas and high-energy particles called a supernova remnant. The hot gas expands and produces x-rays for thousands of years (**Fig. 1**). Gamma rays from radioactive elements have also been detected from supernova remnants by gamma-ray telescopes such as those that were on the *Compton Gamma-Ray Observatory*.

Chandra X-ray Observatory image of Cassiopeia A (Cas A), the 320-year-old remnant of a massive star that exploded. The image shows an expanding shell of hot gas produced by the explosion. This gaseous shell is about 10 light-years in diameter and has a temperature of about 5×10^7 Kelvin. (*NASA/Chandra X-ray Observatory Center/Goddard Space Flight Center/U. Hwang et al.*)



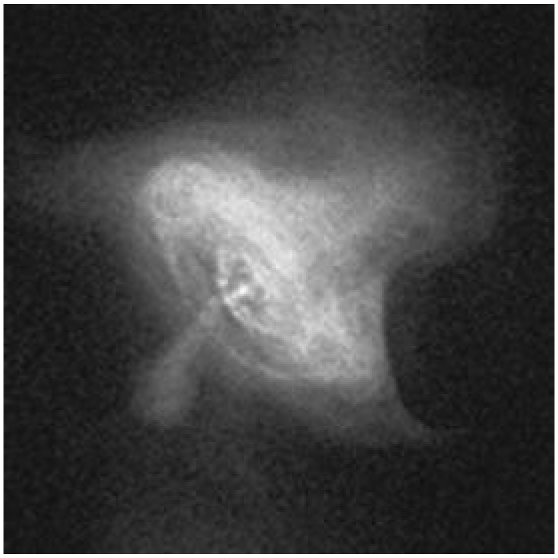
The study of remnants of exploded stars, or supernovae, is essential for understanding the origin of life on Earth. The cloud of gas and dust that collapsed to form the Sun, Earth, and other planets was composed mostly of hydrogen and helium, with a small amount of heavier elements such as carbon, nitrogen, oxygen, and iron. The only place where these and other heavy elements necessary for life are made is deep in the interior of a massive star. There they remain until a supernova explosion, spreads them throughout space. See also: Nucleosynthesis; Supernova

Neutron stars

When a massive star explodes, most of it is flung into space, but the core of the star is compressed to form a rapidly rotating dense ball of neutrons that is about 12 mi (20 km) in diameter. The collapse and rapid rotation of the neutron star cause it to become highly magnetized. A magnetized, rapidly rotating neutron star can produce electric voltages of 10^{16} V.

Neutron star gravity, which is more than 10^{11} times stronger than gravity on Earth, is overwhelmed by the electric field, and particles are pulled off the neutron star and accelerated to speeds near the speed of light. An intense shower of electrons and antimatter electrons, or positrons, is produced by these particles. The pulsed emission from the Crab Nebula, observed at all wavelengths from radio through gamma rays, is thought to be caused by this process (**Fig. 2**). See also: Crab Nebula; Pulsar

Chandra X-ray Observatory image of the Crab Nebula, a supernova remnant and pulsar in the constellation Taurus. The image shows the central pulsar, a rapidly spinning neutron star, or pulsar that emits pulses of radiation 30 times a second, surrounded by tilted rings of high-energy particles that appear to have been flung outward over a distance of more than a light-year from the pulsar. (*NASA*/*Chandra X-ray Observatory Center*/*Smithsonian Astrophysical Observatory*)



As particles stream out from the pulsar and spiral around magnetic field lines, they produce a distinctive kind of radiation known as synchrotron radiation. The Crab Nebula's bell-shaped appearance in the x-ray image is due to synchrotron radiation from a huge magnetized bubble of high-energy electrons that is several light-years in diameter. Dozens of these so-called pulsar wind nebulae have been discovered by the *Chandra X-ray Observatory*. See also: Synchrotron radiation

The rotation-powered activity of neutron stars such as the Crab pulsar can last only a few thousand years. However, if the neutron star has a nearby companion star, its x-ray intensity may increase again in a million years or so. When the companion star enters the red giant stage of its life, it will increase greatly in size and gas will flow from the giant star onto the neutron star. The gas will be heated to tens of millions of degrees Kelvin as it falls onto the surface of the neutron star, and will glow brightly in x-rays.

The Milky Way Galaxy contains several hundred of these neutron star x-ray binaries. Depending on the details of the rate at which the matter falls onto the neutron star, and how the magnetic field of the neutron star guides the inflow, the star will be observed to pulse, flicker, or flare up violently in x-rays. X-ray binaries provide a unique opportunity to study neutron stars. A similar process allows the study of even stranger objects, black holes. See also: Binary star; Neutron star

Black holes and quasars

When some very massive stars collapse, they will form black holes. A black hole does not have a surface in the usual sense of the word. There is simply a region in space around a black hole beyond which nothing can be seen, because nothing can escape from inside this region. This region is called the event horizon.

Anything that passes beyond the event horizon is doomed to be crushed as it descends ever deeper into the gravitational well of the black hole. Neither visible light, nor x-rays, nor any other form of electromagnetic radiation given off by the particle can escape.

A black hole cannot be seen directly. One way to find one is by observing the energy released by matter that is falling toward the black hole. As gas and dust particles swirl toward a black hole, they speed up and form a flattened disk. Friction caused by collisions between the particles heats them to extreme temperatures. Just before the particles pass beyond the event horizon, they produce x-rays and gamma rays as their temperatures approach 10^8 Kelvin.

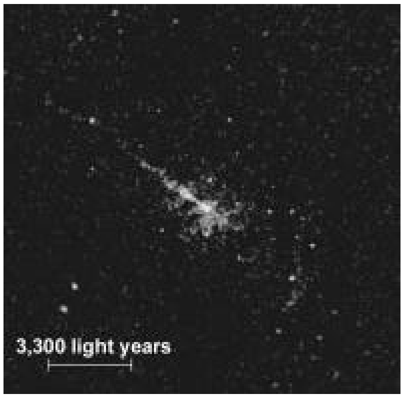
One of the best methods for finding a black hole has been to study x-ray binary systems. Although most of these systems consist of a normal star in a close orbit around a neutron star, there are about 20 cases in which the observations indicate that the mass of the invisible companion star is so great—more than three times the mass of the Sun—that it must be a black hole.

Neutron stars or black holes may be the explanation for one of the most important unsolved problems in astrophysics, gamma-ray bursts. As determined by the BATSE detector that was on the *Compton Gamma-Ray Observatory* and the Italian-Dutch satellite *Beppo-Sax*, these mysterious outbursts are observed to occur about once per day. In about a minute, gamma-ray bursts release as much energy as the Sun will give off at all wavelengths in its lifetime of 10^{10} years. There appear to be at least two types of gamma-ray bursts. Short bursts are likely produced by the merger of two neutron stars, or a neutron star and a black hole. Long bursts represent the explosions of extremely massive stars, greater than 50 times the mass of the Sun. According to the theory, a massive black hole forms in the center of the star just before the explosion. As matter in the center of the star pours into the black hole, a titanic explosion occurs, ejecting matter outward at nearly the speed of light. See also: Gamma-ray bursts

Black holes grow when matter falls into them. A black hole in the center of a galaxy where stars are densely packed may grow to the mass of 10^9 suns. Energy released from large clouds of gas as they fall into these supermassive black holes can be stupendous. This is the accepted explanation for quasars, sources in which the power output at the center of a galaxy can be a thousand times greater than an entire galaxy of 10^{11} stars. See also: Quasar

One of the most intriguing features of supermassive black holes is that they do not suck up all the matter that falls within their sphere of influence. Some of the matter falls inexorably toward the black hole, and some explodes away from the black hole in high-energy jets that move at near the speed of light (**Fig. 3**). These jets produce radio, optical, x-ray, and gamma radiation. The matter swirling around the black hole must somehow be producing enormous electric and magnetic fields that accelerate electrons to extremely high energies. Exactly how this happens is unknown and is a major focus of research. See also: Black hole

Chandra X-ray Observatory image of NGC 5128, a radio galaxy in the constellation Centaurus, 10^7 light-years from Earth. The image shows a bright source in the nucleus of the galaxy, which is thought to be due to a supermassive black hole. The jet extending to the upper left, far outside the galaxy, is caused by explosive activity around the black hole. (*NASA*/*Chandra X-ray Observatory Center*/*Smithsonian Astrophysical Observatory*)



Galaxy clusters and dark matter

More than half of all galaxies in the universe are members of groups of galaxies or larger collections of galaxies, called clusters. X-ray observations have shown that most clusters of galaxies are filled with vast clouds of multi-million-degree gas. The mass of this gas, which was heated when it collapsed from a much larger size, is greater than all the stars in all the galaxies in a cluster of a thousand galaxies. Galaxy clusters are the largest and most massive gravitationally bound objects in the universe.

The x-ray-producing hot gas found in a typical cluster of galaxies presents a great mystery. Over time this extremely hot gas should escape the cluster, since the galaxies and gas do not provide enough gravity to hold it in. Yet the gas remains in clusters of all ages. Scientists have concluded that some unobserved form of matter, called dark matter, is providing the gravity needed to hold the hot gas in the cluster. An enormous amount of dark matter is needed—about three to ten times as much matter as that observed in the gas and galaxies. This means that most of the matter in the universe may be dark matter.

The candidate that best reproduces the observations is called cold dark matter—hypothetical subatomic particles that produce no light and can at present be detected only through gravity. Detailed measurements of the size and temperature of the hot gas clouds in galaxy clusters with x-ray telescopes could help solve the dark matter mystery. See also: Dark matter; Galaxy, external

While an explanation for the source of dark matter is still lacking, an effect that is even more enigmatic has been discovered. Astronomers have observed that the visible light from type 1a supernovae, which act as standard candles, is fainter than expected in distant galaxies. The best explanation is that they are more distant than originally thought, which implies that the expansion of the universe must be accelerating. *Chandra*'s measurements of the dark-matter content of clusters of galaxies have verified this astounding result by an independent method.

Cosmic acceleration can be explained if the space between galaxies is filled with a mysterious dark energy that has the property that, as the universe expands, more dark energy is created. The existence of dark energy requires either a modification of Einstein's theory of general relativity or a major revision of some other area of fundamental physics. Assuming that dark energy is responsible for the acceleration, combining the *Chandra* results with observations of type 1a supernovae and the cosmic microwave background radiation indicates that dark energy makes up about 75% of the energy density of the universe, dark matter about 21%, and visible matter about 4%. See also: Cosmic background radiation; Cosmology; Dark energy; Relativity; Universe; X-ray astronomy

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Additional Readings

- Chandra X-ray Observatory Center

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