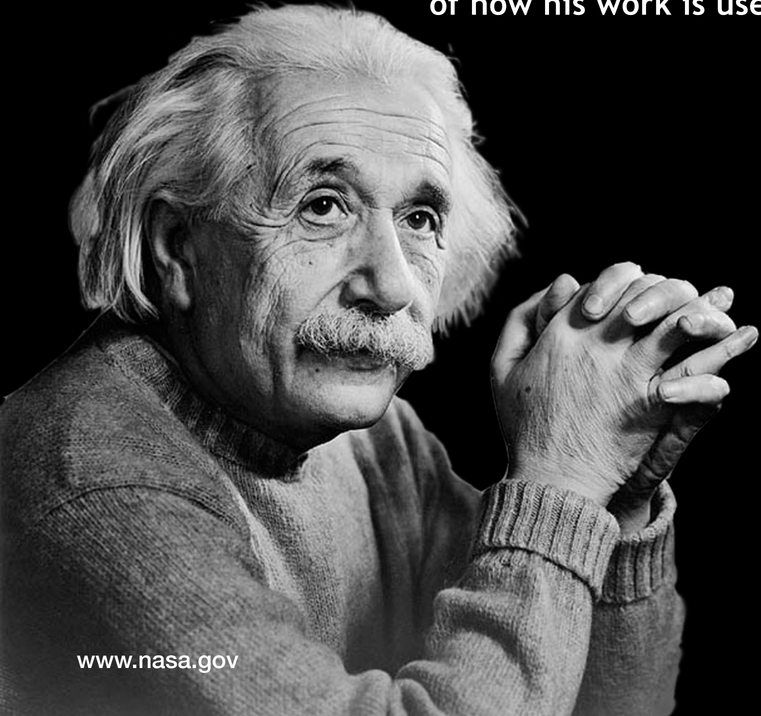
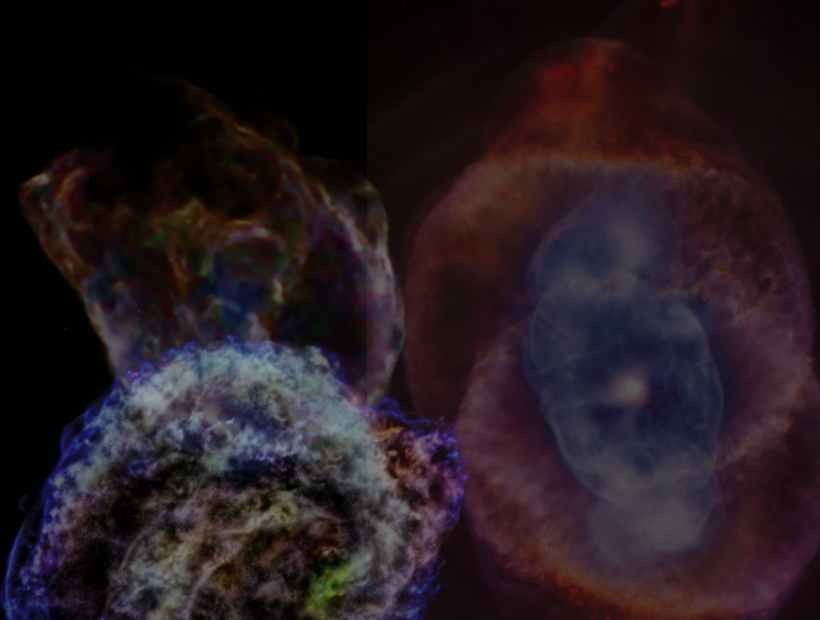
National Aeronautics and Space Administration

EINSTEIN
ALL THE TIME

More than a century has passed since Albert Einstein's "miraculous year" in which he published three papers, all within a few months, describing ideas that have since influenced all of modern physics. The first paper claimed that light must sometimes behave like a stream of particles with discrete energies, "quanta." The second paper offered an experimental test for the theory of heat. The third paper addressed a central puzzle for physicists of the day—the connection between electromagnetic theory and ordinary motion—and solved it using the "principle of relativity."

Einstein's fingerprints can be found on virtually every scientific result obtained with Chandra X-ray Observatory data. These results in turn have expanded our concept of the Universe far beyond what was imagined at the beginning of the 20th century. Three of Einstein's discoveries—the photoelectric effect, the theory of special relativity, and the theory of general relativity (published in 1915)—are described here, with examples of how his work is used extensively by X-ray astronomers.

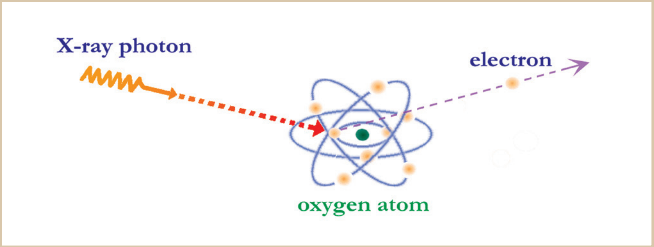




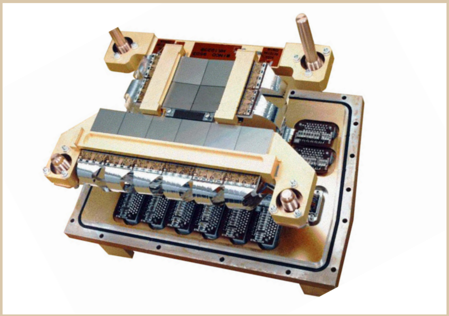
EINSTEIN ALL THE TIME

PHOTOELECTRIC EFFECT

It is well known that Einstein's work on relativity transformed the landscape of physics, but it is not generally appreciated that he received the Nobel prize for his work on the photoelectric effect. His prizewinning work showed that the emission of electrons from a substance when high-energy light strikes it can be explained if light is composed of photons that behave like particles.



The energy of the X-ray goes tearing into one of the electrons away from its orbit around the nucleus of a nitrogen or an oxygen atom.



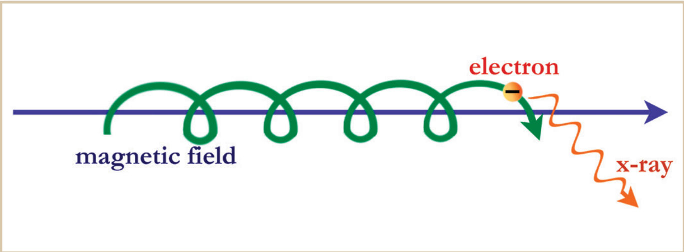
The Chandra Advanced CCD Imaging Spectrometer (ACIS) is one of two focal plane instruments. This instrument is an array of charged coupled devices (CCD's), which are sophisticated versions of the CCD's used in camcorders. This instrument is especially useful because it can make X-ray images, and at the same time, measure the energy of each incoming X-ray. It is the instrument of choice for studying temperature variations across X-ray sources such as vast clouds of hot gas in intergalactic space, or chemical variations across clouds left by supernova explosions.

The operation of Chandra and the interpretation of the data gathered by Chandra would be impossible without an understanding of the photoelectric effect. Chandra's two X-ray detectors make use of the ejection of electrons from atoms by X-rays via the photoelectric effect. This process is also responsible for the absorption of X-rays by the Earth's atmosphere, which is why Chandra has to be in space in the first place.

The role of the photoelectric effect in X-ray astronomy is crucial. Almost every spectrum of an X-ray source that Chandra makes shows evidence of the photoelectric absorption of X-rays either by atoms in interstellar space between the source and Chandra, or by atoms and ions clumped around a cosmic source, such as a cloud of cool gas around a young star, or an accreting black hole. This effect allows astrophysicists to determine the amount and composition of cool gas and dust in space, and to trace the motion of iron atoms orbiting very near black holes.

SPECIAL RELATIVITY

Among other things, the theory of special relativity implies that: time passes at different rates for reference frames in relative motion; that radiation from electrons moving at near the speed of light is highly beamed and boosted in energy; and that matter-antimatter pairs of electrons can be created from very high-energy photons.



Electrons moving near the speed of light can radiate photons by the synchrotron process as they spiral around a magnetic field.

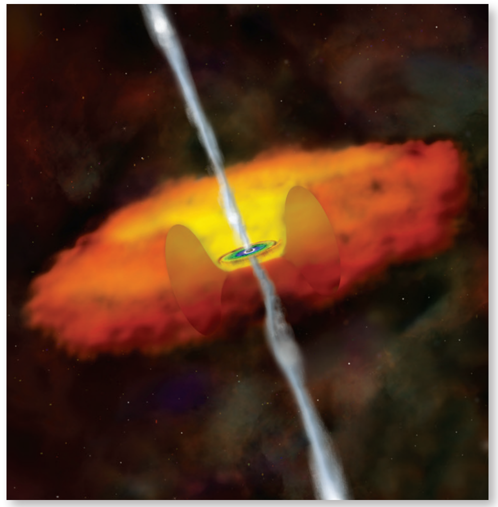
These effects are needed to interpret the light observed from pulsars, gamma ray bursts, and from X-ray jets that originate near supermassive black holes and extend over hundreds of thousands of light years.

GENERAL RELATIVITY

The theory of general relativity implies that mass curves space which in turn implies the existence of black holes.

Many of the powerful X-ray sources observed by Chandra are thought to be due to X-radiation from gas that is heated to millions of degrees as it swirls toward black holes. The theory of general relativity is used together with X-ray observations to determine how much gas is falling into these black holes, and to set limits on their masses.

A careful study of the X-rays from gas falling toward black holes may ultimately test the predictions of general relativity. Already, Chandra observations have provided evidence for the dragging of space around black holes, and for the existence of event horizons.



This artist's conception shows a black hole surrounded by a disk of hot gas, and a large doughnut or torus of cooler gas and dust. Jets of high energy particles are propelled away from the vicinity of the black hole by intense electric and magnetic fields.

Another consequence of the bending of space by matter is the bending of light, which causes massive galaxies and galaxy clusters to act like gravitational lenses. This phenomenon has enabled scientists using Chandra to study distant quasars, and, through comparison with optical observations, to probe the conditions in gas clouds around black holes with unprecedented accuracy.

Finally, general relativity is the fundamental theory needed to understand the evolution of the Universe. Chandra observations of distant clusters of galaxies enable astronomers to inventory the amount of dark matter and dark energy, the two dominant components of mass and energy in the Universe.

MIRRORS OF X-RAY TELESCOPES

X-ray telescopes in orbit above the Earth's atmosphere can collect X-rays from energetic sources billions of light years away. These cosmic X-rays are focused by barrel shaped mirrors onto an instrument especially designed to measure properties such as the incoming direction and energy of the X-ray photon. A gaseous or solid material in the instrument absorbs the X-rays by the photo-electric effect.

The building and operation of an X-ray observatory is a marvel of modern technology and ingenuity. Because the Earth's atmosphere absorbs X-rays, X-ray observatories must be placed high above the Earth's surface. This means that the ultra-precise mirrors and detectors, together with the sophisticated electronics that conveys the information back to Earth must be able to withstand the rigors of a rocket launch, and operate in the hostile environment of space.

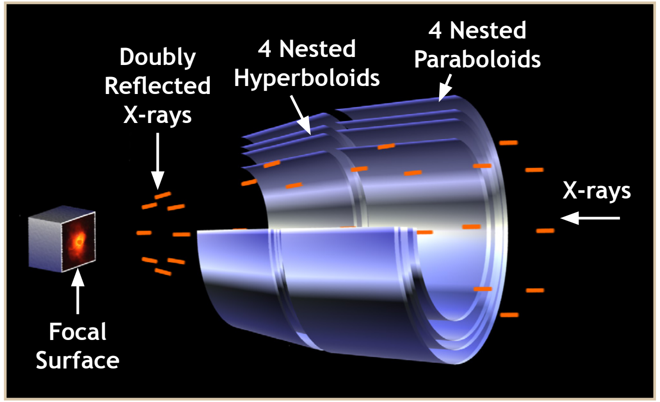
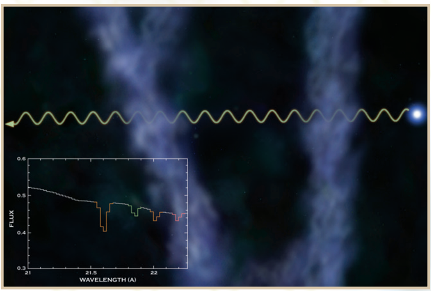


Illustration of the design and functioning of the High Resolution Mirror Assembly (HRMA) on Chandra. X-rays that strike a mirror head-on are absorbed, while X-rays that hit a mirror at grazing angles are reflected like a pebble skipping across a pond. Thus, X-ray telescope mirrors are shaped like barrels rather than dishes, where the X-rays reflect off the inner, polished surfaces and are focused onto a detector to produce an image.

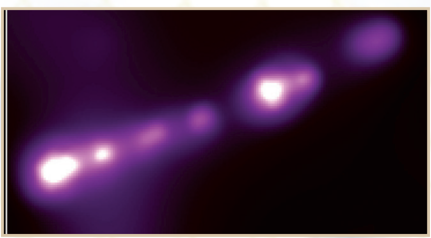
EINSTEIN & CHANDRA: ASTROPHYSICS OF THE HIGH-ENERGY UNIVERSE

CHANDRA X-RAY CENTER

A NEW BRANCH OF SCIENCE Within a decade after Einstein's death in 1955, the field of X-ray astrophysics was born. With the beginning of the Space Age, and humanity's ability to send instruments above the Earth's atmosphere, the Universe was opened for the study of high-energy phenomena and therefore for testing many of Einstein's predictions. Today, NASA's flagship mission of X-ray astronomy is the Chandra X-ray Observatory, named for another leading physicist of the 20th century and colleague of Einstein, Subrahmanyan Chandrasekhar. Using Chandra, scientists are now able to probe many of the ideas first introduced by Einstein in the "miraculous year" a century earlier.

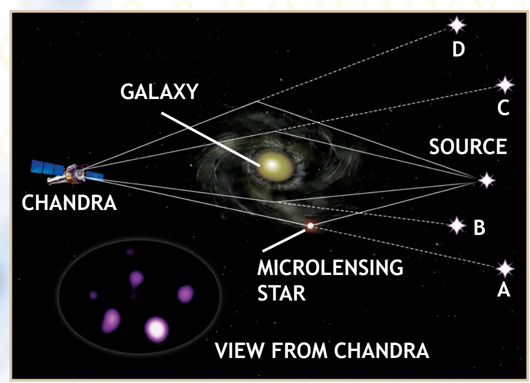


MKN 421 The photoelectric effect can probe the Universe, as shown by astronomers studying X-rays of distant objects. With a quasar acting as a lighthouse in a fog, scientists discovered two huge intergalactic clouds of diffuse hot gas that possibly constitute a large chunk of material in the Universe. X-rays from Chandra show the clouds of hot gas are filtering out, or absorbing, X-rays from a distant quasar known as Markarian 421 (see p.2). These clouds are the best evidence yet that a vast cosmic web of hot gas contains the long-sought missing matter—about half of the atoms and ions in the Universe.

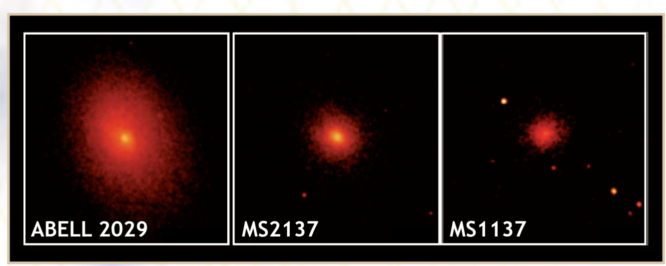


M87 Chandra observed an enormous jet blasting out the core of the giant elliptical galaxy known as M87. Not only impressive because it stretches out thousands of light years, this jet also represents an important testing ground of Einstein's Special Relativity theory. Astronomers must take the relativistic effects into account when studying the high-energy environment around black holes, like the one found at the center of M87 that produces this jet.

CLOVERLEAF QUASAR (A.K.A. H1413+117) One of the most dramatic examples in the cosmos of Einstein's theories is the so-called gravitational lens. When X-rays and other forms of light from a distant source pass by a large intervening mass, the light is bent. This bending can produce multiple images of that distant source. In the case of the Cloverleaf Quasar, Chandra detects what appears to be a cloverleaf-like pattern of sources. But, in fact, the gravitational field from some foreground object—likely one or more galaxies—has bent and magnified the light from this single quasar to produce multiple images.



ABELL 2029, MS2137.3-2353, AND MS1137.5+6624 Einstein's theories continue to provide the framework for understanding the evolution of the Universe—including the mysterious dark matter and dark energy that astronomers now believe to be its dominate components. Using Chandra, scientists can attempt to better understand dark matter and dark energy by studying clusters of galaxies. For instance, researchers used 26 Chandra images—three of which are shown here—to confirm that the expansion of the Universe is slowing down due to the effects of dark energy.



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