Exploring the Extreme:
20 Years of Chandra

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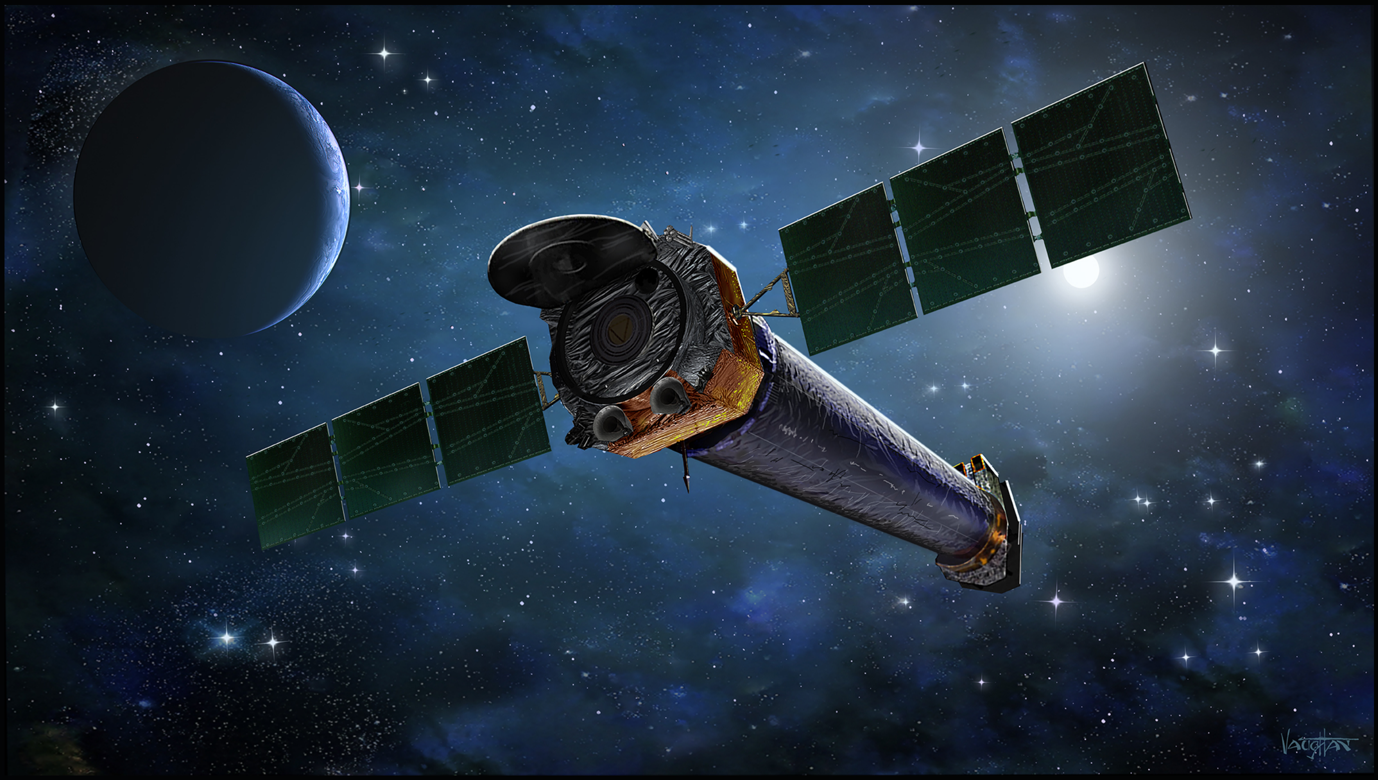
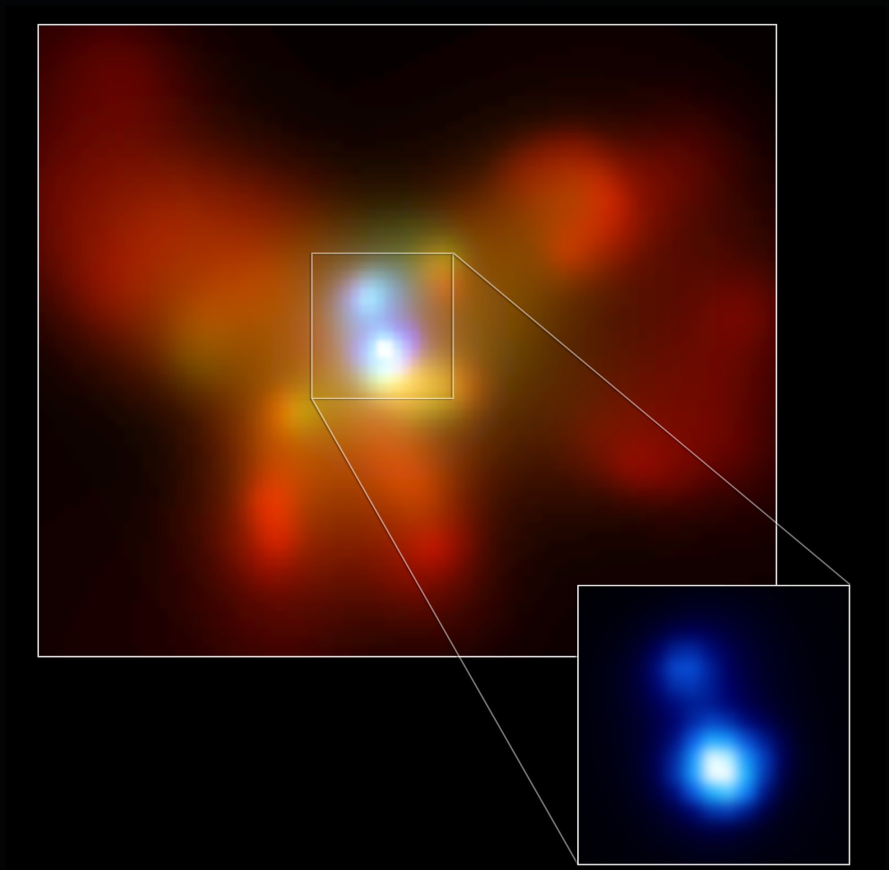


The Chandra X-ray Observatory was launched on the Space Shuttle Columbia (STS 93) on 23 July 1999, as the third of four observatories in NASA's Great Observatory series. With the highest precision X-ray mirrors ever built, Chandra produces images with a resolution comparable to that of ground-based optical observatories, allowing scientists to reveal details about the sites of high energy emission from celestial objects as diverse as planets and black holes.

Over the first twenty years of operation, Chandra has produced major scientific discoveries across a stunning range of topics in astrophysics. The following selection is a decidedly incomplete sample of highlights, aimed at illustrating the breadth and excitement of Chandra science carried out in its first two decades.

Merging Supermassive Black Holes

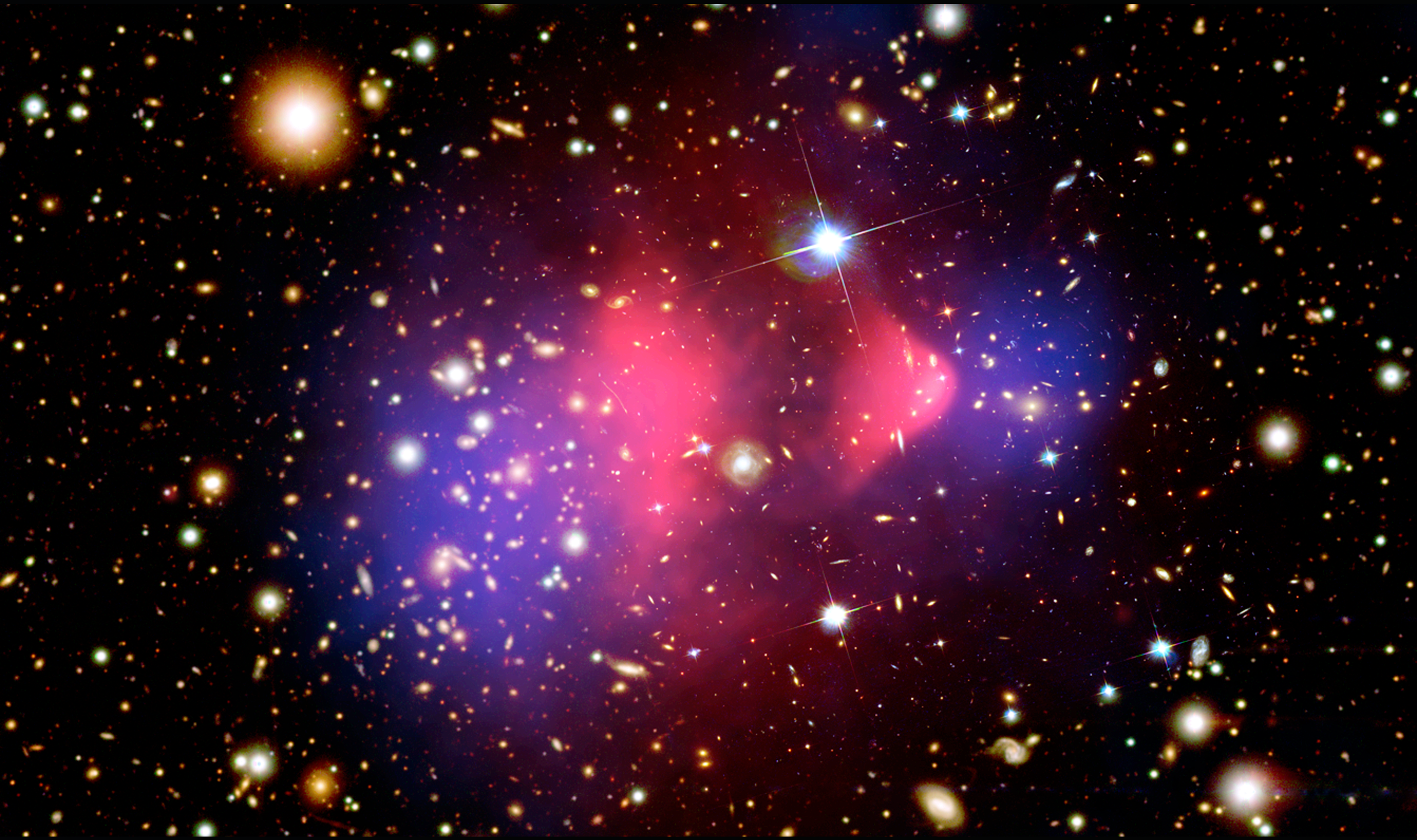


Throughout their evolution, galaxies undergo a series of mergers with other galaxies. During these mergers, every component of the galaxies will coalesce, including the supermassive black holes (SMBHs) that reside at the heart of massive galaxies. Galaxies with multiple supermassive BHs should thus be common in the Universe. Galaxies with pairs of SMBHs are particularly interesting, as these sources may explain the distortion and bending seen in the powerful jets they produce. In addition, the process of merging is expected to be the most powerful sources of gravitational waves in the Universe.

NGC 6240, a galaxy at a distance of about 400 million light years, is a prime example of a system with a pair of SMBHs. The superb angular resolution of Chandra played a key role in identifying two BHs at the heart of NGC 6240. While previous X-ray observatories had shown that the central region was an X-ray source, its origin remained mysterious. Radio, infrared, and optical observations had detected two bright nuclei in the center of the galaxy, but based on these data it was not possible to constrain the nature of these sources.

Chandra was able to show that the X-rays were coming from two spatially distinct sources. In addition, Chandra measured the X-ray spectra of both sources, which revealed the characteristic high-energy photons from gas swirling around a SMBH, and X-rays from fluorescing iron atoms in gas near BHs. Thus, Chandra played a key role in identifying a pair of SMBHs, which are about 3000 light years apart, in a galaxy that recently experienced a merger. Over the course of the next few hundred million years, the two SMBHs will drift toward one another and merge to form one larger SMBH.

Probing Dark Matter: The Bullet Cluster

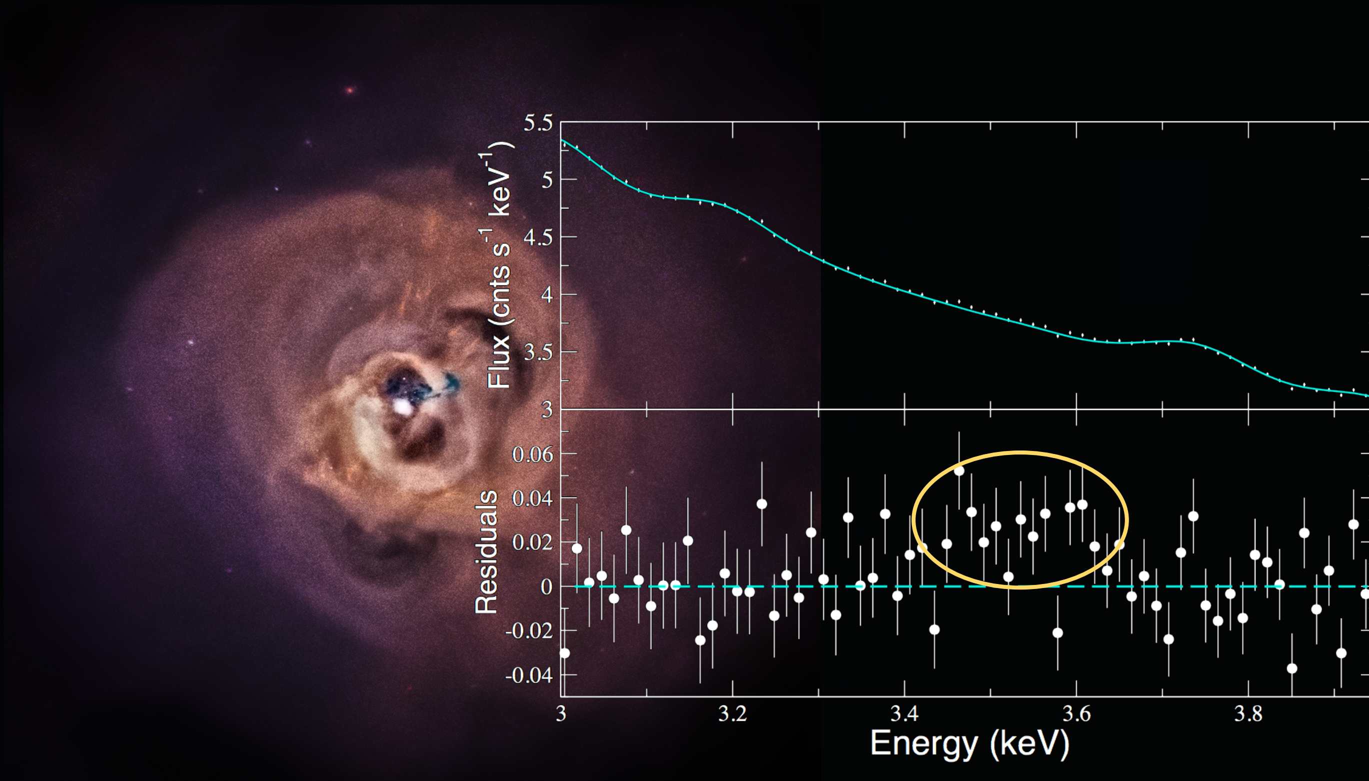


Until about 15 years ago the existence of dark matter, which accounts for about 85% of the matter in the Universe, was based on a collection of indirect observational evidence. Although the exact nature of dark matter is still debated, astrophysicists have established that it does not emit electromagnetic emission and it only interacts with normal baryonic matter gravitationally. However, the direct observational evidence of dark matter was lacking until groundbreaking Chandra observations of the so-called Bullet cluster.

The Bullet Cluster, located at a distance of 3.7 billion light-years, actually contains two massive galaxy clusters that are colliding at a speed of 10 million miles per hour. During this collision, interactions between the luminous matter in each cluster result in deceleration of the material. However, the dark matter component of the clusters does not interact and passes through unobstructed. Due to this difference in the collision speed, the dark matter and the luminous matter become separated, with the luminous matter lagging behind. This observational evidence provided the first direct detection of dark matter.

To achieve this outstanding conclusion, Chandra observations played a key role. Specifically, these data were used to map the morphology of the luminous matter - hot X-ray emitting gas residing in the galaxy clusters (shown in red). In addition, data from the Hubble Space Telescope, the European Southern Observatory's Very Large Telescope and the Magellan optical telescopes were used to determine the total mass distribution of the clusters (shown blue) by using a technique called gravitational lensing. The clear spatial separation between the two different components demonstrates the presence of the two types of matter that builds up the Universe: the well-known baryonic matter and the exotic dark matter.

Getting a Line on Dark Matter



Early in its mission, the Chandra X-ray Observatory played a key role in providing direct observational evidence for the existence of the mysterious dark matter though studies of the Bullet Cluster. About a decade later, X-ray data from Chandra and XMM-Newton were used to potentially determine the nature of dark matter. By analyzing the X-ray energy spectrum of the nearby Perseus galaxy cluster, along with a set of 73 other galaxy clusters, a team of astronomers detected a previously unknown emission line at an energy of 3.55 keV. Given our current knowledge of spectral lines produced by hot X-ray gas, the presence of an emission line at this energy cannot be explained. An alternative suggestion was thus put forth, that this previously undetected line originates from the decay of dark matter.

The 3.55 keV emission line could be a telltale sign that dark matter particles are sterile neutrinos, which have been popular candidates for explaining dark matter. In this picture, the observed emission line originates from the decay of sterile neutrinos with a mass of 7.1 keV, during which process the sterile neutrino decays into a 3.55 keV X-ray photon and an active neutrino. This discovery produced considerable interest and excitement: "*We know that the dark matter explanation is a long shot, but the pay-off would be huge if we're right.*" said Esra Bulbul of the Center for Astrophysics | Harvard & Smithsonian (CfA) in Cambridge, MA, who led the study.

There are two major uncertainties associated with this discovery. First, the emission line signal is at the edge of detectability with Chandra. Second, there may be other explanations that could explain this mysterious emission line. Given the vast importance of this detection, a number of additional studies probed the existence of this mysterious emission lines. Some confirmed its presence, while others did not. The debate is still not settled, and additional studies are underway to establish whether or not the 3.55 keV emission line truly originates from dark matter.

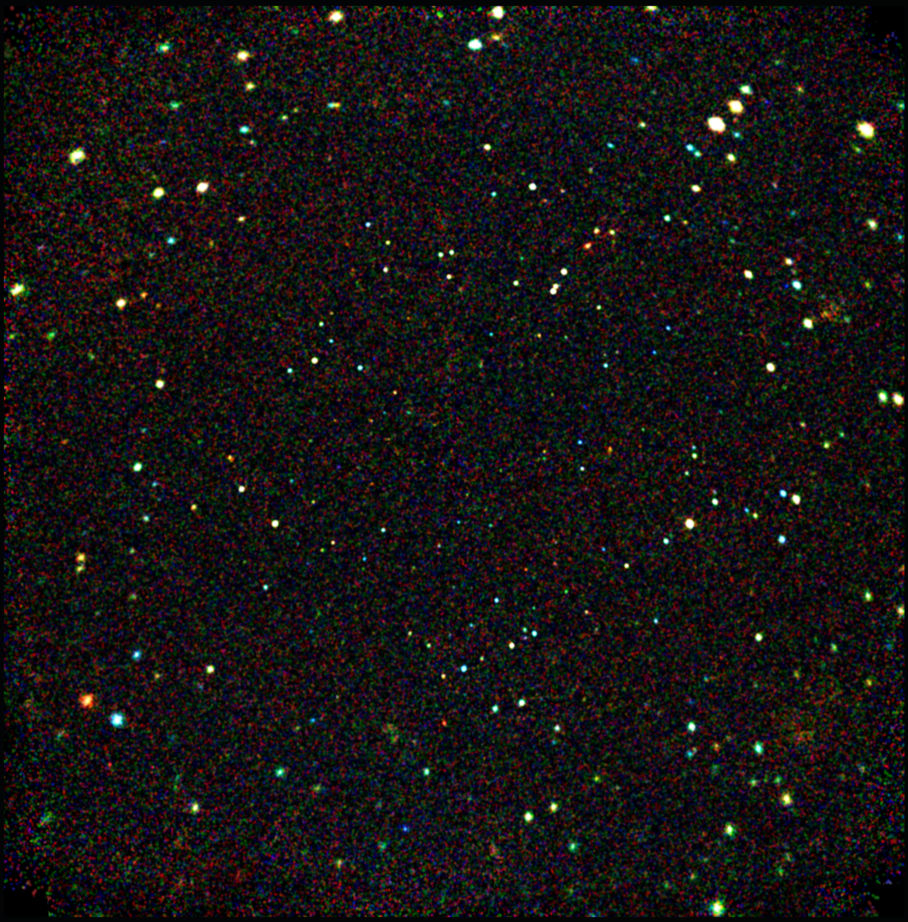
Progenitors of Type Ia Supernovae

The characteristics of Type Ia supernova explosions are very similar to one another. Type Ia supernovae are so-called standardizable candles, which - thanks to a set of empirical relations - can be used as cosmic distance markers. Thanks to their near-uniform brightness, Type Ia supernovae played a key role in establishing the accelerating expansion of the Universe, which has been attributed to the effects of dark energy.

It is well established that a Type Ia supernova originates from the thermonuclear explosion of a carbon-oxygen white dwarf. However, it is debated whether the explosion is triggered when a white dwarf accumulates matter from a companion star until it reaches the critical mass, the so-called Chandrasekhar limit, or when two sufficiently massive white dwarfs merge in a compact binary system. For the 10th supernova explosion in 2014 (SN 2014J), in the nearby galaxy M82, Chandra X-ray observations played an essential role in constraining the formation scenarios of Type Ia supernovae.

If a white dwarf exploded because it had been accreting matter from a companion star, a cloud of gas would have surrounded the white dwarf star. Then the blast wave originating from the supernova explosion would have hit the gas cloud, producing bright X-ray emission that should have been visible at the time of the follow-up Chandra observations. However, no such X-ray emission was detected in the Chandra observations of M82 (shown above) either before or after the explosion. The absence of the detection promotes the formation scenario in which two white dwarfs merge in a relatively clean environment where no significant mass transfer is occurring before the Type Ia supernova explosion.

Peering Deep into the Universe with X-rays

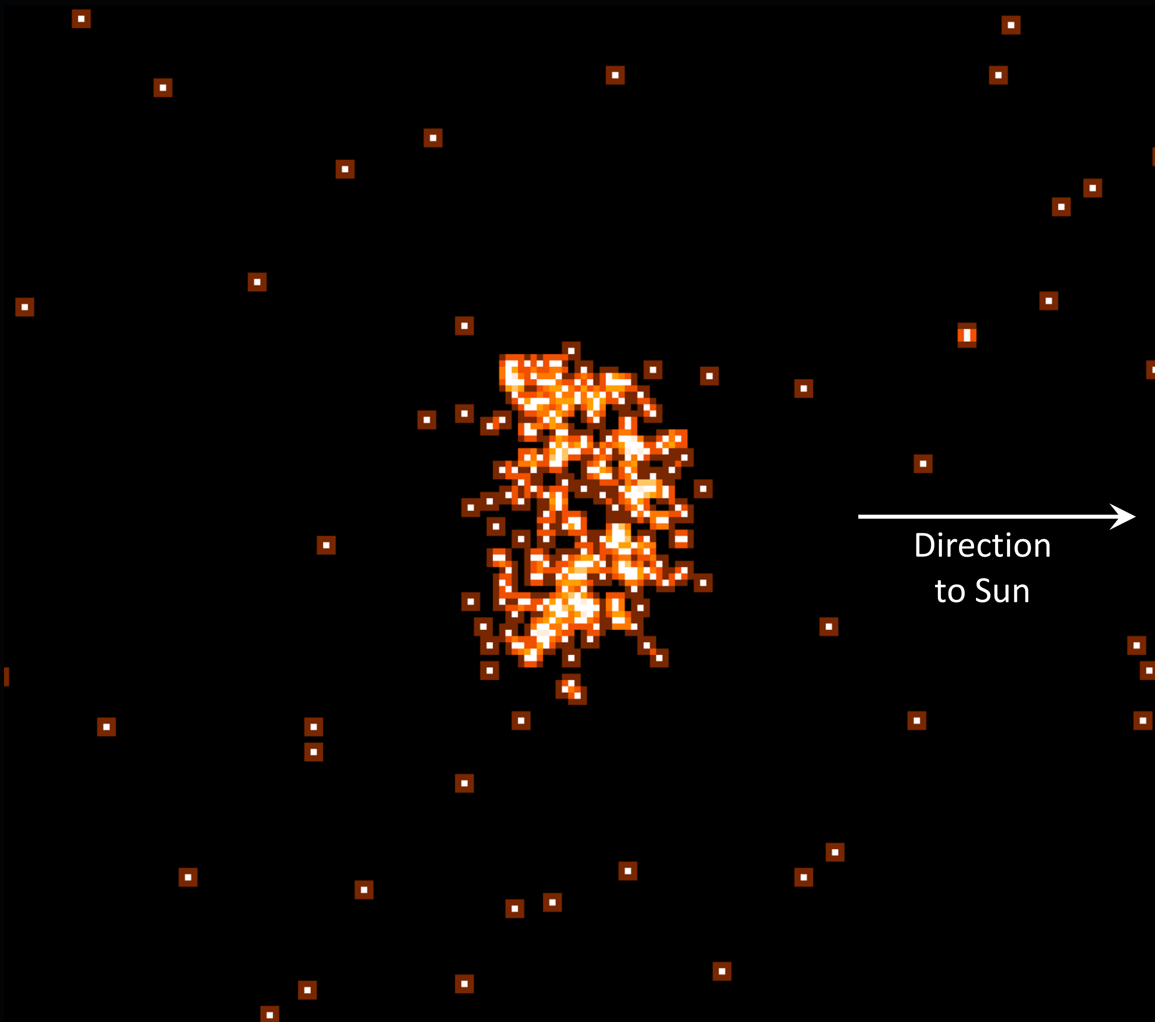


Supermassive black holes (SMBHs) are possibly the most enigmatic objects of the Universe. Luckily, the Chandra X-ray Observatory is uniquely suited to probe the growth and evolution of SMBHs both in the present-day and in the infant Universe. To probe the earliest days of black holes in the Universe, deep observations are needed. To this end, Chandra - in concert with the Hubble Space Telescope - observed a small patch of the sky to an extreme depth. This field, the so-called Chandra Deep Field South (CDF-S), has been exposed for 7 million seconds - equivalent to nearly 3 months.

CDF-S reveals a large number of bright X-ray sources, most of which are SMBHs in the center of galaxies that are rapidly growing by accreting material. As SMBHs accrete matter from their surroundings, they grow at a fast pace and shine bright in X-rays. Many of these BHs are surprisingly massive and are located in distant galaxies that formed when the Universe was only 1-2 billion years old. The detection of such massive BHs in the early Universe poses one of the major mysteries about their formation and evolution: how did SMBHs grow to 10^9 solar masses in less than 1 billion years after the Big Bang?

The Chandra data suggest that the first “seed” SMBHs were heavy, with masses of 10^4 - 10^5 solar masses. By starting with a more massive seed, SMBHs can accrete material at a much faster pace, allowing them to grow to large masses in the early phases of the Universe. "*By detecting X-rays from such distant galaxies, we're learning more about the formation and evolution of stellar-mass and supermassive black holes in the early Universe.*" said team member Fabio Vito of Pennsylvania State University.

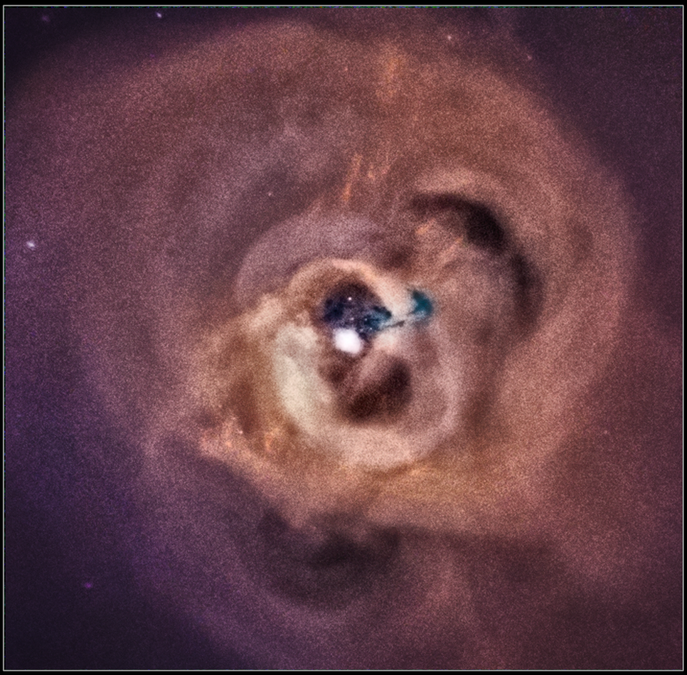
Studying the Inner Solar System: X-rays from Venus



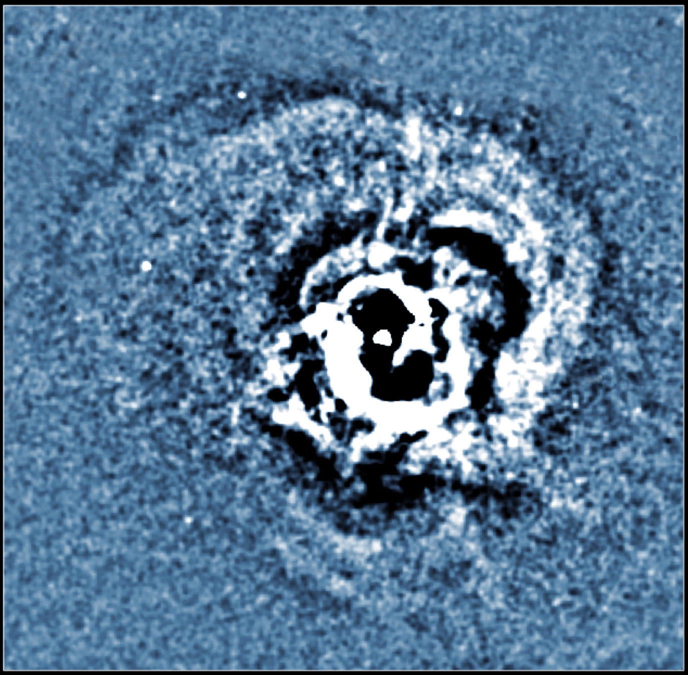
When astrophysicists think about X-ray emitting sources, they will likely first consider objects like accreting supermassive black holes or massive galaxy clusters. Interestingly though, our neighboring planet, Venus, is also a source of X-ray emission. Detection of the X-rays is challenging, however, because Venus is never separated by more than about 47° from the Solar limb. Chandra is the first imaging X-ray telescope with both the sensitivity to detect Venus and the capability to observe this close to the Solar limb. Chandra observed Venus early in the mission and revealed that the X-ray and optical appearance of the planet is surprisingly similar. However, the source of photons in visible and X-ray wavelengths are quite different.

The optical emission from Venus is produced by the scattering of incident sunlight by clouds located at altitudes of 50 to 70 kilometers. In X-rays, the photons are produced primarily by fluorescence. When Solar X-rays hit the atmosphere of Venus, atoms are excited to a higher energy levels. As the atoms return to their lower energy state they emit fluorescent X-rays, detectable by Chandra. The fluorescent X-rays mostly originate from oxygen and carbon atoms that reside in the upper atmosphere of Venus, at altitudes between 120 and 140 kilometers. The Sun-lit hemisphere of Venus is surrounded by an optically-thin, luminous shell in X-rays with enhanced emission toward the outer edges, characteristic of limb-brightening associated with longer path lengths through the shell near the edges of the planet.

Perseus Sound Waves and Cavities



Chandra X-ray [3-Color]



Chandra X-ray [Sound Waves]

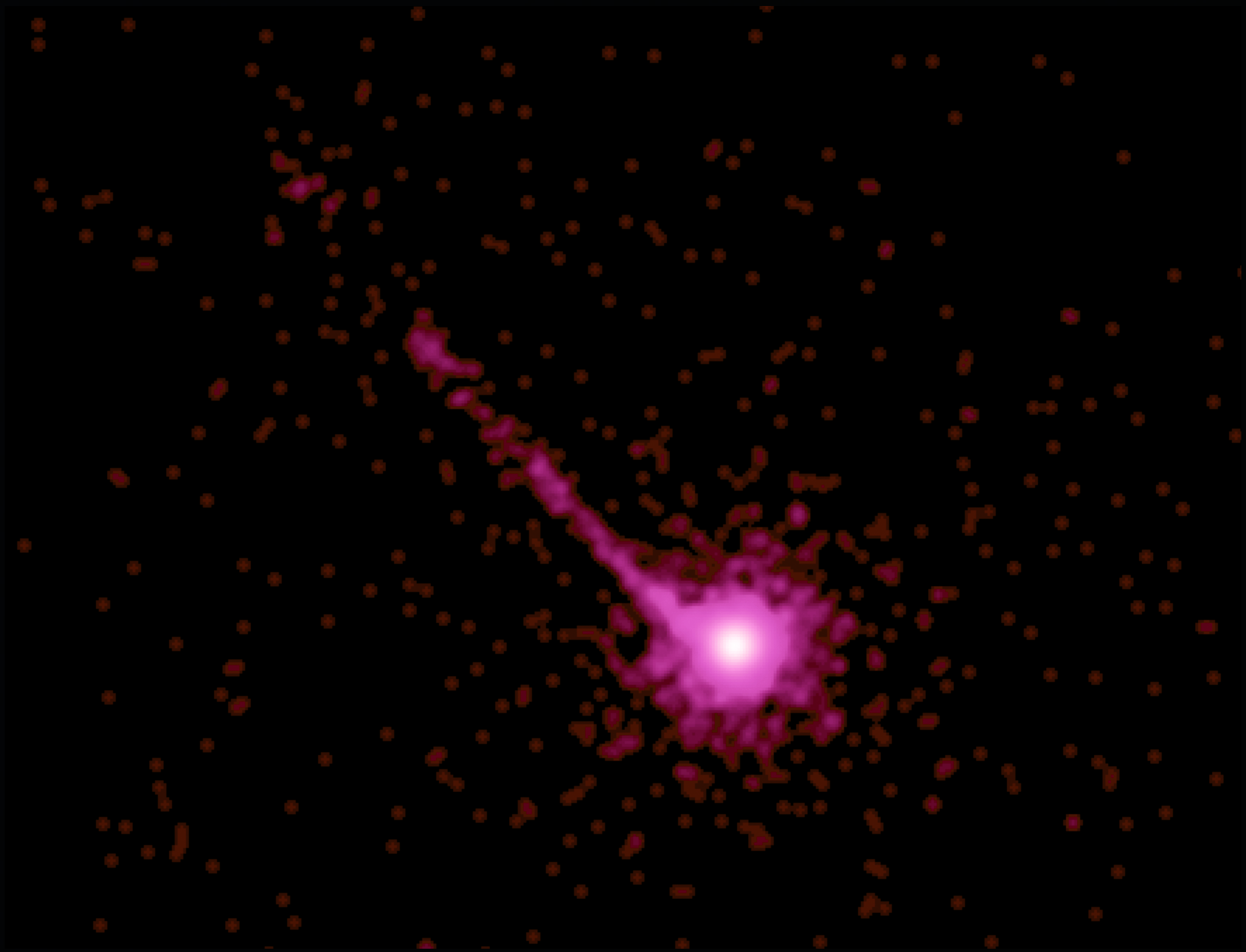
Galaxy clusters are the largest gravitationally bound structures of the Universe, with typical total masses of 10^{14}-10^{15} $M_{\odot}$. They are also well-known sources of X-ray emission, associated with a large amount of highly ionized hot gas, the so-called intracluster medium (ICM) between the galaxies. The peak temperature of the hot gas ranges from 20-150 million degrees Kelvin. The main sources of the X-ray emission from the ICM are the bremsstrahlung process and the X-ray emission lines from heavy elements such as silicon and iron.

The Perseus cluster is a massive galaxy cluster at a distance of about 250 million light-years. When Chandra observed the cluster, the resulting X-ray image (left) showed large-scale diffuse emission along with two bubble-shaped central cavities and numerous faint ripples in the gas filling the cluster. These features originate from energy that has been released by a supermassive black hole (SMBH) residing in the heart of a massive galaxy at the center of the Perseus cluster, and are particularly evident in an image for which unsharp-masking techniques have been applied to highlight the underlying features (right). The large cavities are from recent energy injection from the central SMBH, while the outer ripples correspond to pressure waves from previous episodes of injection. The disruptions propagate as sound waves through the ICM, with the rough periodicity corresponding approximately to a pitch of B flat – but 57 octaves below middle-C.

"*We have observed the prodigious amounts of light and heat created by black holes, now we have detected the sound*," said Andrew Fabian of the Institute of Astronomy (IoA) in Cambridge, England, and leader of the study.

At a frequency over a million, billion times deeper than the limits of human hearing, this is the deepest note ever detected from an object in the Universe.

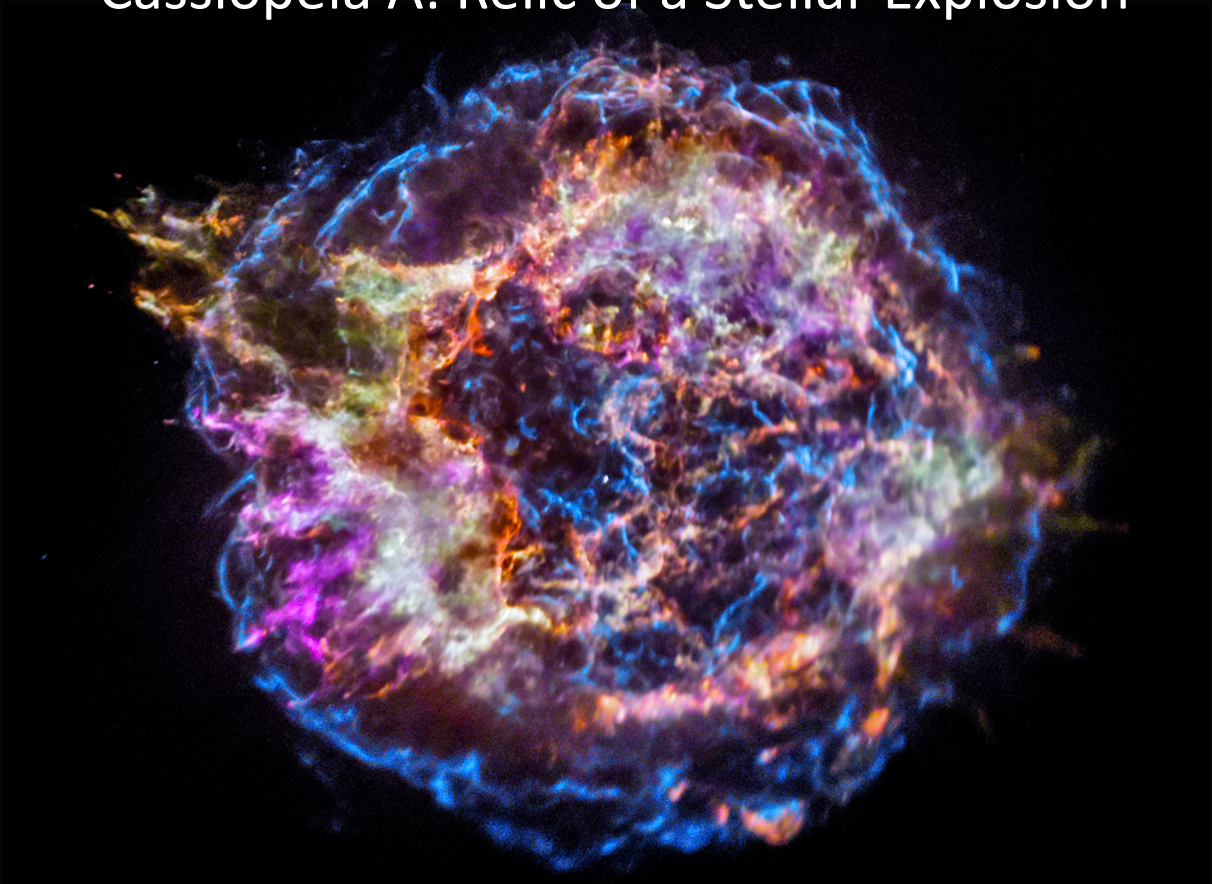
Quasar Jets



The unparalleled, sub-arcsecond, angular resolution of the Chandra X-ray Observatory allows us to explore a wide range of phenomena that remained hidden from the previous generations of X-ray telescopes. Of particular interest are the X-ray structures associated with distant quasars. Before the launch of Chandra, X-ray emission associated with radio jets was detected only in a handful of systems. Chandra has completely revolutionized our understanding as it has revealed a large sample of X-ray jets on arcsecond scales.

PKS 1127-145 is an extremely luminous quasar at a distance of about 10 billion light-years. The quasar is detected in many wavelengths across the electromagnetic spectrum: visible, radio, and X-rays. Curiously, the Chandra X-ray image revealed an enormous jet that extends to about 1 million light-years. The X-ray jet is powered by the explosive activity of the supermassive black hole residing in the center of the host galaxy. The origin of the detected X-ray emission is most likely inverse Compton scattering, which involves the upscattering of low energy photons from the cosmic microwave background to higher energies by ultra relativistic electrons. The observed characteristics of the jet, such as its length and the bright knots, suggest that the explosive activity of the central supermassive black hole is intermittent and long-lived.

Cassiopeia A: Relic of a Stellar Explosion

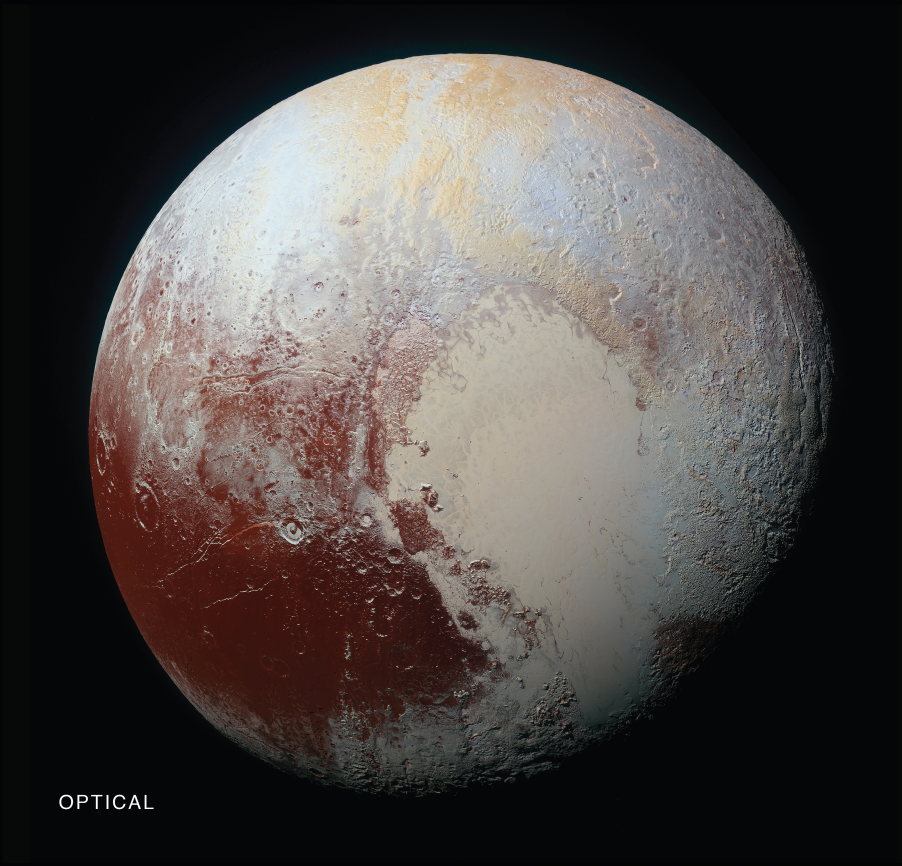


The supernova remnant (SNR) Cassiopeia A (Cas A) is one of the most iconic objects studied with the Chandra X-ray Observatory. This young SNR, located about 11,000 light-years from Earth, was showcased in Chandra's official "First Light" image that was released on August 26, 1999. The results immediately delivered a great surprise. Thanks to the sub-arcsecond spatial resolution of Chandra, the image revealed a point-like source close to the center of the SNR, which was quickly recognized as the compact neutron star created in the explosion that formed Cas A. Curiously, the object is far different from other young neutron stars known at the time, with much fainter emission and no evidence for pulsations typically associated with the rapidly-rotating, highly-magnetic objects.

Chandra also provided detailed insights into the stellar ejecta cast off in the supernova explosion. The Chandra image revealed a wide range of structures, including dense knots, complex filamentary structures, and a jet-like structure of material protruding out of the shell. Thanks to the high energy resolution of its detectors it became possible to map the chemical elements that were ejected during the explosion. The distribution of iron, silicon, and calcium (shown above in purple, red, and green), for example, provide important clues about the nature of the explosion and the state of the star before the blast.

Through Chandra observations at many epochs, it became possible to trace the expansion of the hot gas in Cas A. As the blast wave expands with a speed of about 11 million miles/hour, it accelerates particles to higher energies, producing X-ray synchrotron emission around the SNR rim. As it encounters the surrounding material, it is decelerated, and a second shock wave – a so-called reverse shock – propagates back into the ejecta, heating it to X-ray emitting temperatures.

Pluto: X-rays from a Former Major Planet

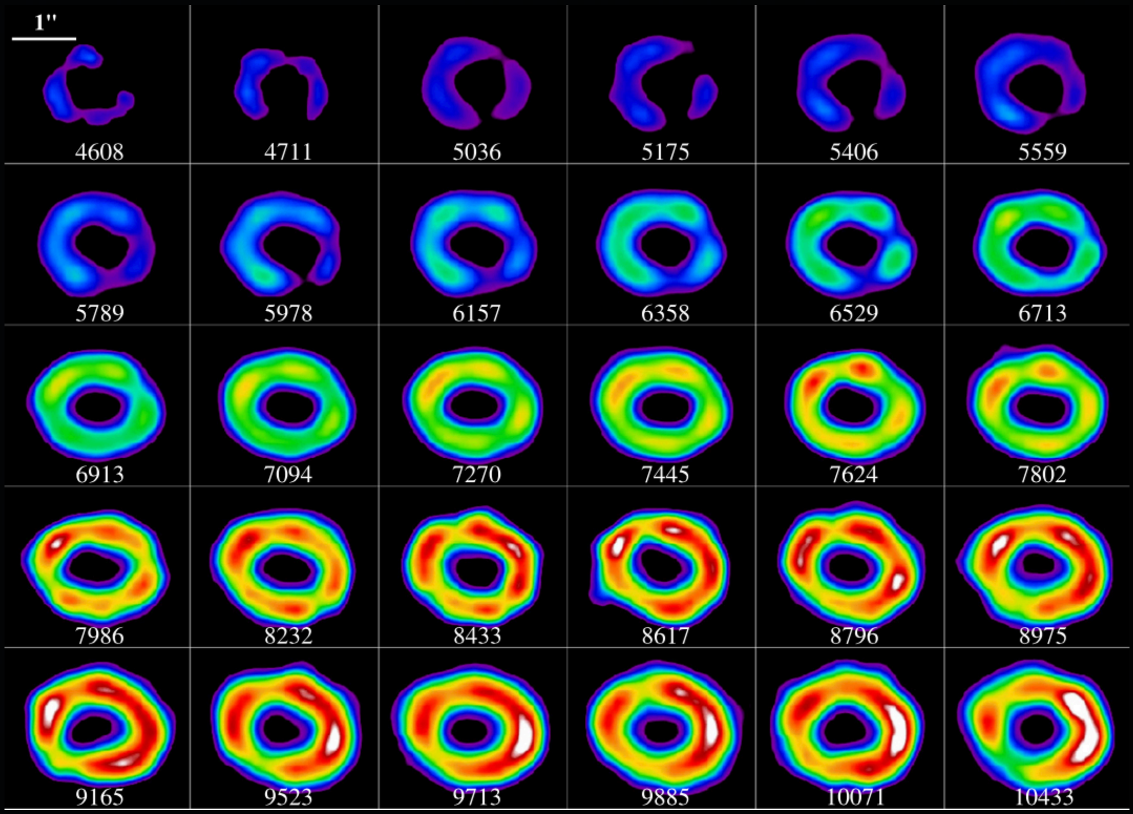


Over the course of 20 years, the Chandra X-ray Observatory has studied a wide variety of objects. However, one of the most surprising detections is associated with Pluto, a dwarf planet in the Kuiper belt. Chandra observed Pluto in concert with the New Horizons mission to probe its X-ray emitting properties.

"Before our observations, scientists thought it was highly unlikely that we'd detect X-rays from Pluto, causing a strong debate as to whether Chandra should observe it at all," said Scott Wolk, of the Center for Astrophysics | Harvard & Smithsonian. *"Prior to Pluto, the most distant solar system body with detected X-ray emission was Saturn's rings and disk*." Yet, Chandra detected soft X-rays from Pluto. The origin of the detected X-ray emission is charge exchange, during which process charged particles from the Sun excite the gases leaving Pluto's atmosphere.

Measurements from New Horizons provided estimates of the escape rate of gases from the surface of Pluto, which is believed to be sufficient to produce the observed X-ray emission. While Pluto may provide sufficient amounts of gas, results from one of the instruments aboard New Horizons suggest that the solar wind proton density is too low to explain the observed X-ray emission. To alleviate this issue, various scenarios were considered that result in an enhanced solar wind density around Pluto. However, given the currently available data, it is not possible to conclusively distinguish between various theoretical models, implying the need for further detailed studies with Chandra and next-generation X-ray telescopes.

Supernova 1987A

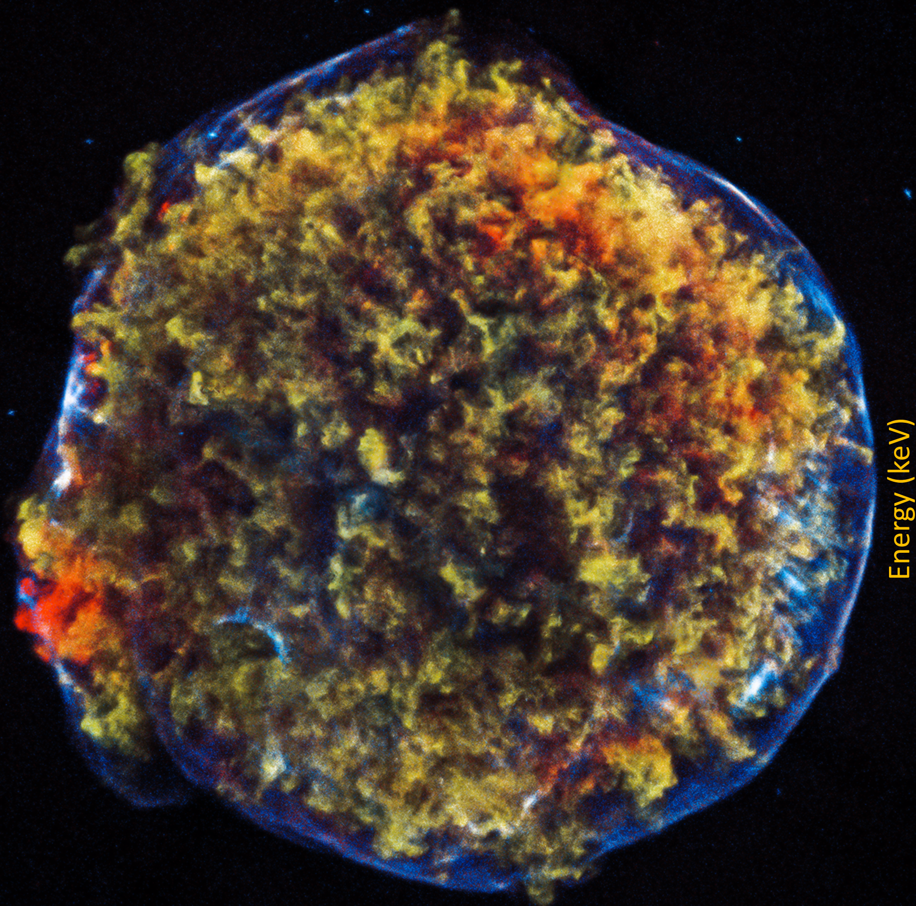


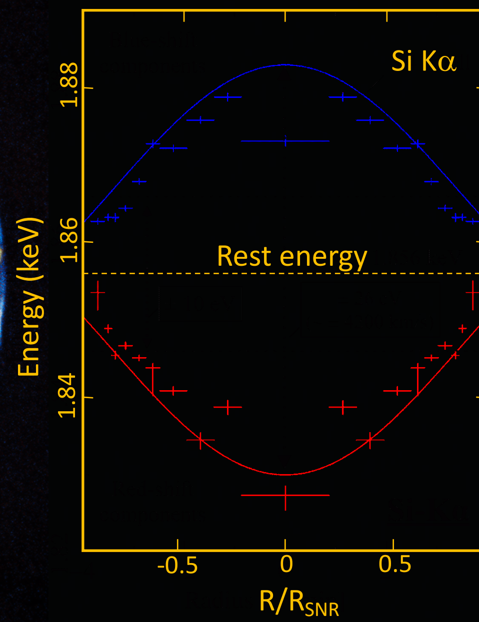
The supernova explosion SN 1987A was a truly spectacular event for modern astronomy. It was the brightest supernova explosion seen in more than 400 years, which allowed astronomers to study the physics of core-collapse supernovae in unprecedented detail. The supernova explosion occurred in the Large Magellanic Cloud, a nearby dwarf galaxy, and companion of our Milky Way galaxy. For the first time, scientists across the globe were able to track every phase of the death of a star, including archival optical observations of the progenitor star – a blue supergiant about five orders of magnitude more luminous than our Sun.

When a massive star, such as the progenitor of SN 1987A, exhausts its nuclear power source, nuclear fusion cannot support the core against its own gravity, and the core collapses and forms a neutron star or a black hole. During the collapse, the outer layers of the star are blown away at speeds in excess of 50 million kilometers per hour. The exploding matter creates a shock wave that sweeps up the surrounding gas and heats it to temperatures of millions of degrees, creating a shell that is observable in X-rays.

The Chandra X-ray Observatory has closely monitored SN 1987A since its launch. From 1999 until 2013, the observations showed that the X-ray emitting ring became brighter every year as the blast wave from the explosion was heating the ring of gas ejected by the star before its explosion. However, since 2013 the brightening of the ring stopped and part of the ring started to fade. These changes suggest that the blast wave from the explosion is exiting the ring and entering a region where the gas density is significantly lower. In the near future, the X-ray emission from SN 1987A will become dominated by the shock-heated ejecta instead of the circumstellar ring. Ongoing observations with Chandra will provide crucial spectroscopic measurements of the supernova ejecta in the upcoming years.

Tycho’s Supernova Remnant



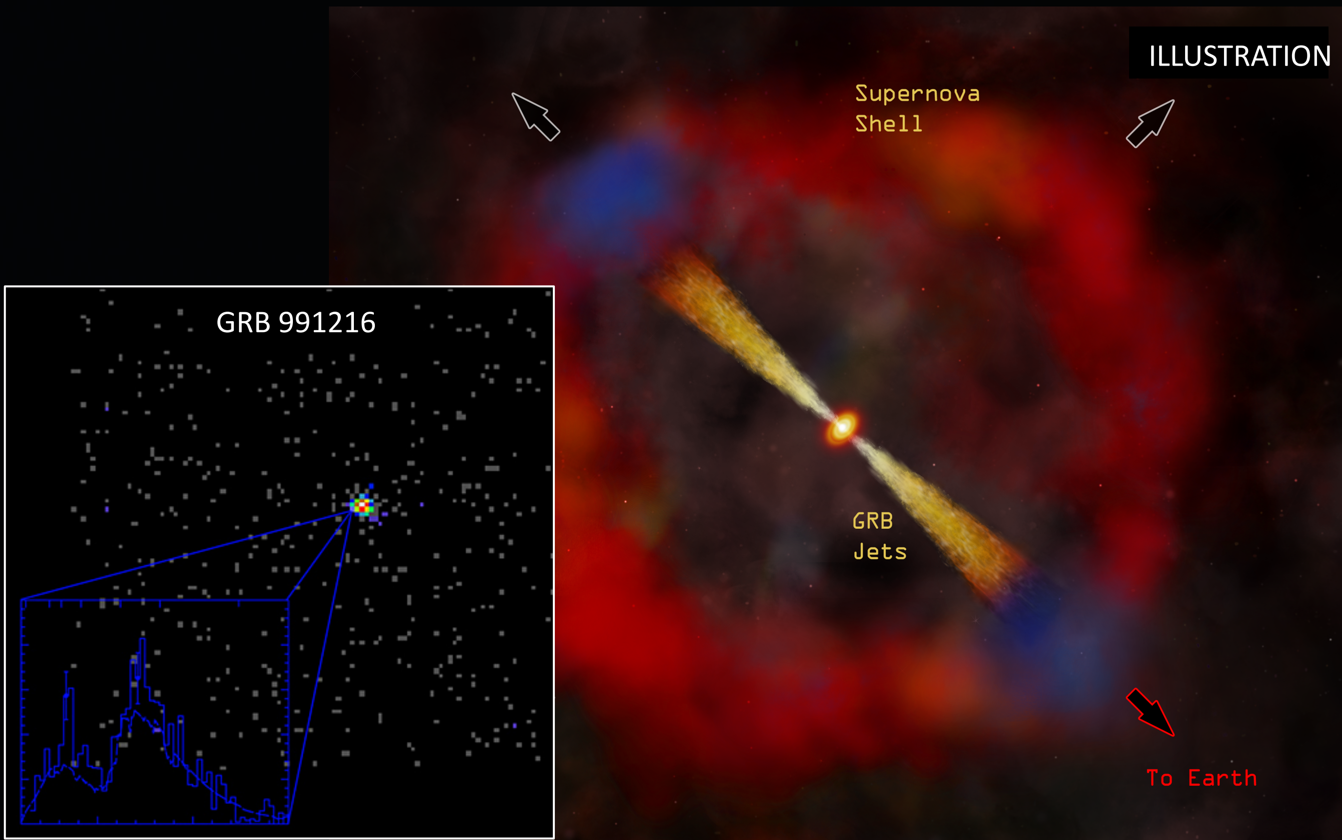


Tycho's supernova remnant (SNR) is the relic of SN 1572, a supernova in the Milky Way that exploded in 1572, and was observed extensively by the Danish astronomer Tycho Brahe. The supernova is classified as a Type Ia event, understood to have originated from the explosion of a carbon-oxygen white dwarf in a binary system.

The Chandra image of Tycho reveals the presence of hot X-ray emitting gas inside a supersonically expanding shell. The outermost regions of the shell form the blast wave, or so-called "forward shock,” of the system, which is being driven by the rapidly-expanding material ejected in the explosion. This shock sweeps up the surrounding interstellar material, heating it to X-ray emitting temperatures, and also accelerates particles to energies in excess of 50 TeV, acting as a source of Galactic cosmic rays. The thin blue rim around the SNR is synchrotron radiation from highly relativistic electrons spiraling in the compressed magnetic field at the shock front.

Shocked ejecta fill the center of the Chandra image, and are seen to be composed of a complex system of knots and clumps. The remnant expansion velocity is 4000 - 5000 km s^{-1}, sufficiently rapid for Chandra to have measured the increase of the blast wave radius over the course of 15 years. In addition, velocities of individual X-ray emitting knots have been measured through Doppler shifts in their spectral lines, providing a measurement of the 3D expansion of Tycho's SNR, as shown in the accompanying plot that shows both blue-shifted and red-shifted lines of the Si Kα emission, which show decreasing shifts toward SNR edge where the expansion along the line of sight is smallest.

Origin of Long Gamma-Ray Bursts

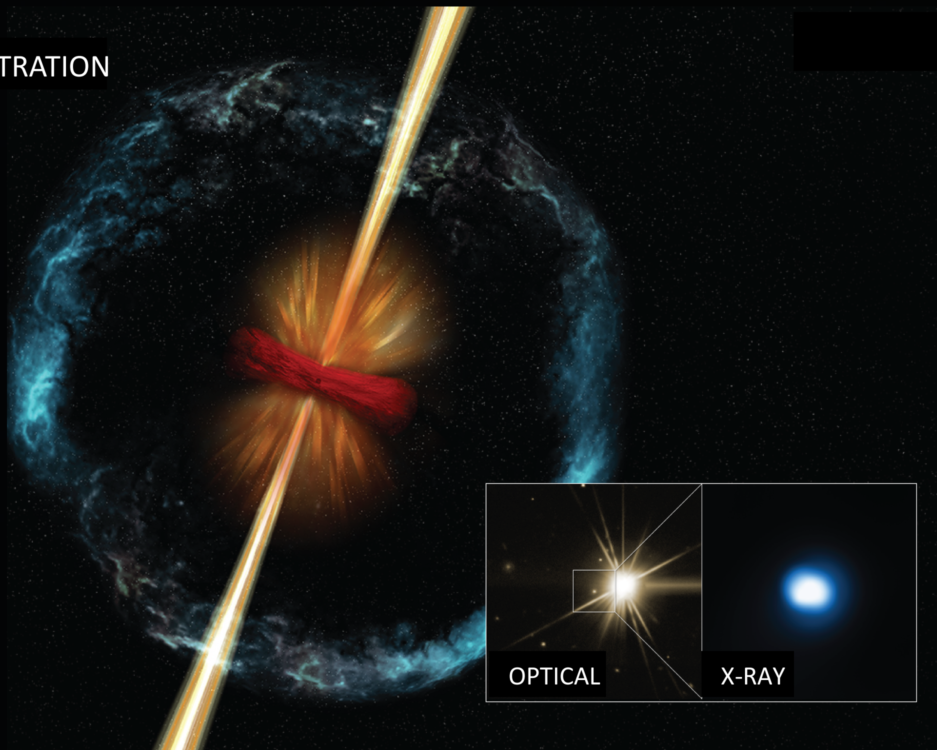


The first gamma-ray bursts (GRBs) were detected in the late 1960s by satellites designed to identify gamma radiation pulses originating from secret nuclear weapon tests in space. After studying several of these bursts, it became clear that their characteristics were dissimilar to any nuclear weapons. Furthermore, determination of the sky position of GRBs revealed that they did not have a terrestrial or solar origin.

The distribution of GRBs is isotropic, which means that they can be detected virtually everywhere in the sky. The duration of the GRBs lasts from ten milliseconds to hours. Based on their duration, they are divided into short and long GRBs. NASA's Chandra X-ray Observatory played an essential role in constraining the origin of both the short and long GRBs.

About 70% of all bursts last longer than 2 seconds, and these long GRBs tend to have bright afterglows, which helped to pin down their origin. Indeed, most of the long GRBs are detected in galaxies with active star formation, which suggests that they may originate from the explosions of extremely massive stars. High energy resolution Chandra spectra provided a major clue to understanding the origin of long gamma-ray bursts. Chandra observations of the afterglow of a bright GRB pointed out that ions were moving away from the burst at a tenth of the speed of light, as the matter was ejected in a supernova explosion. The observed spectral lines were sharply peaked, indicating that they were coming from a narrow region of the expanding shell. This suggests that gamma-ray burst illuminated only a fraction of the shell, as would be expected if the burst was beamed into a narrow cone.

Origin of Short Gamma-Ray Bursts

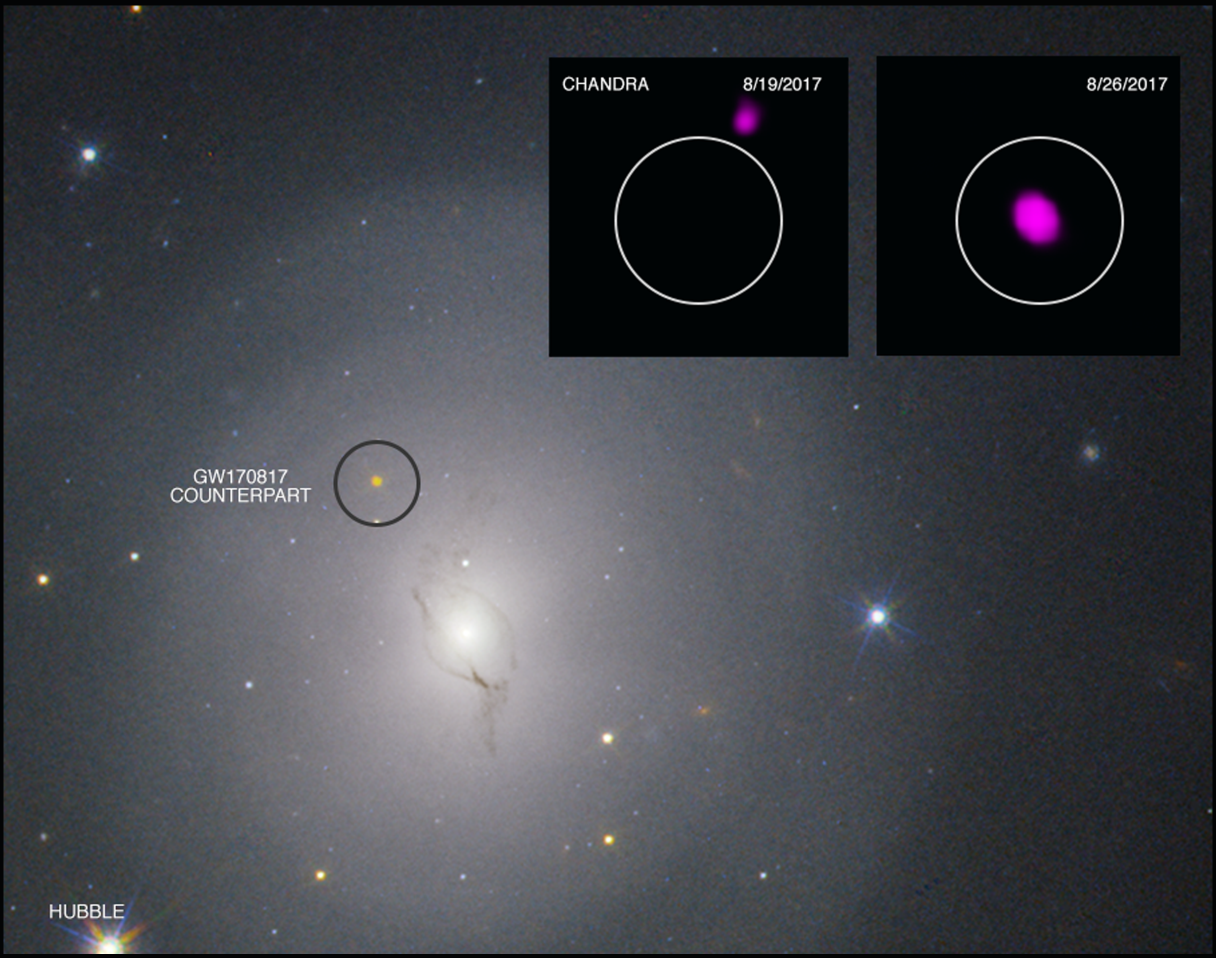


Gamma-ray bursts (GRBs) are the most energetic electromagnetic events of the Universe. Based on their duration, two different types of GRBs have been identified. Long GRBs last for more than two seconds, and they are believed to originate from the collapse of massive stars in distant galaxies. However, the origin of short GRBs remained mysterious until such events were observed by multiple observatories, including Chandra.

On May 9, 2005, the Swift satellite detected a short GRB that was followed by an X-ray afterglow. Before this event, no afterglow had been detected from any short event. The afterglow was also observed by Chandra and the Hubble Space Telescope. Thanks to these coordinated efforts, it was revealed that no supernova explosion had occurred at the position of the bursts, and that the burst was located in the outskirts of a galaxy where no massive stars reside. These observations disfavored the possibility that short GRBs originate from the death of a massive star. Since the detection of this event, many other short BRGs were observed to have afterglows. A significant fraction of these bursts were located in quiescent galaxies without star-formation, which further solidified the conclusion that short GRBs cannot originate from the explosion of massive stars.

The most likely origin of GRBs is the merger of a neutron star with another neutron star or black hole. A natural consequence of the merger of two neutron stars is the release of gravitational waves, which could potentially be observed by the Laser Interferometer Gravitational-Wave Observatory (LIGO). The detection of the gravitational wave event, GW170817, provided the final confirmation on the origin of short gamma-ray bursts. This gravitational wave marks the merger of two neutron stars, an event that was accompanied by the detection of a short GRB by the Fermi Gamma-ray Space Telescope. This detection resolved the decade-long mystery and proved that short GRBs indeed originate from the merger of two compact objects.

GW170817

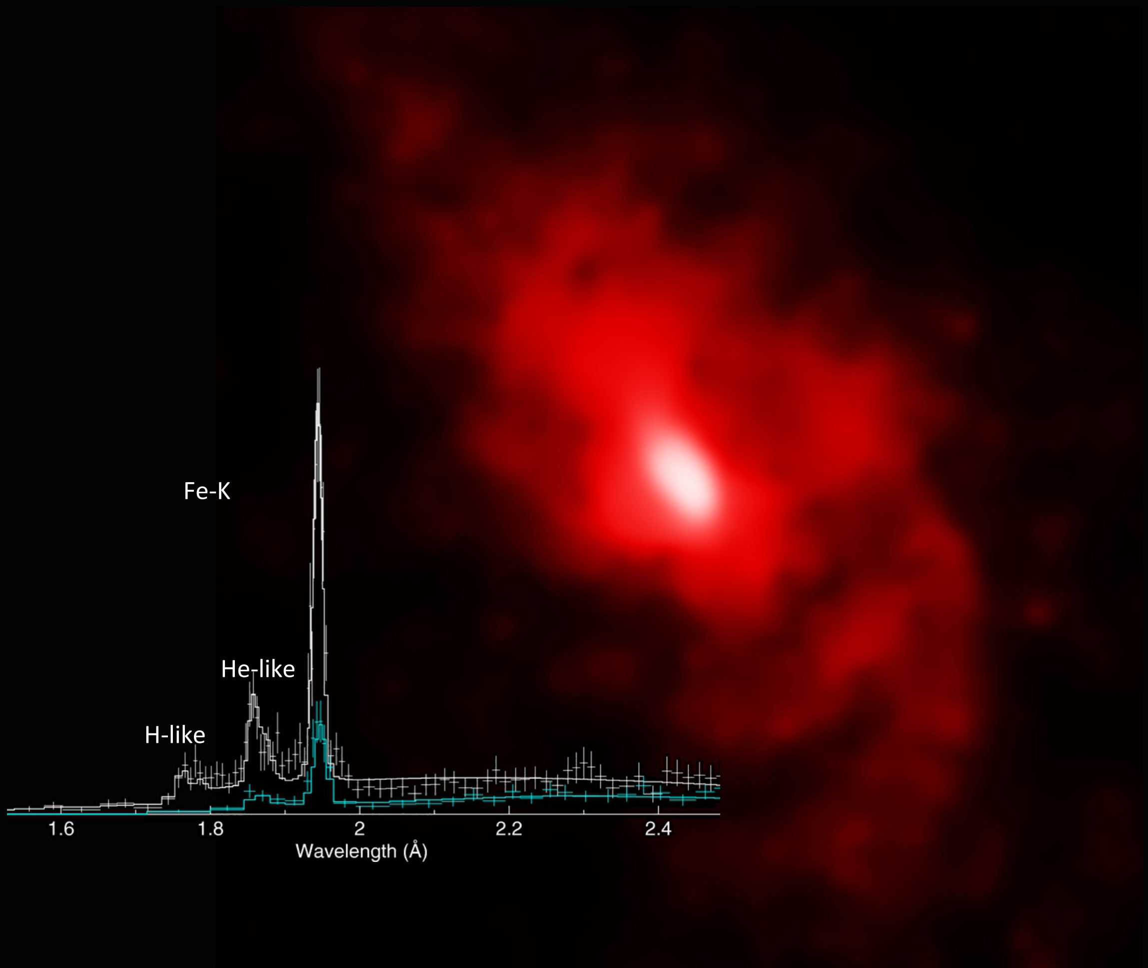


The existence of gravitational waves was predicted more than 100 years ago, but the first direct detection of gravitational waves took place only recently. The discovery of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) has opened a new window through which we can explore the Universe, allowing us to test predictions of general relativity and to study a wide range of physical phenomena associated with the merger of compact objects.

The gravitational wave event, GW170817, is one of the most exciting detections of LIGO. The merger of two neutron stars that generated gravitational waves resulted in the formation of a black hole. This black hole, which is estimated to have a mass of 2.7 times the mass of the Sun, is the lowest mass black hole ever detected. The Chandra X-ray Observatory played an essential role in determining that the object that formed after the merger of the neutron stars is a black hole.

Chandra observed GW170817 several times after the detection of the gravitational waves. The initial observation, two to three days after the event, failed to detect any X-ray emission. However, multiple follow-up observations detected the source from 9 days to 160 days after the merger. Had the merger of the neutron stars resulted in a heavier neutron star, bright X-ray emission would have been expected from the rapidly spinning object and from an associated expanding bubble of high-energy particles. The X-ray brightness of GW170817 is much lower than expected in this scenario, indicating that a black hole likely formed instead.

Winds from Supermassive Black Holes: NGC 1068

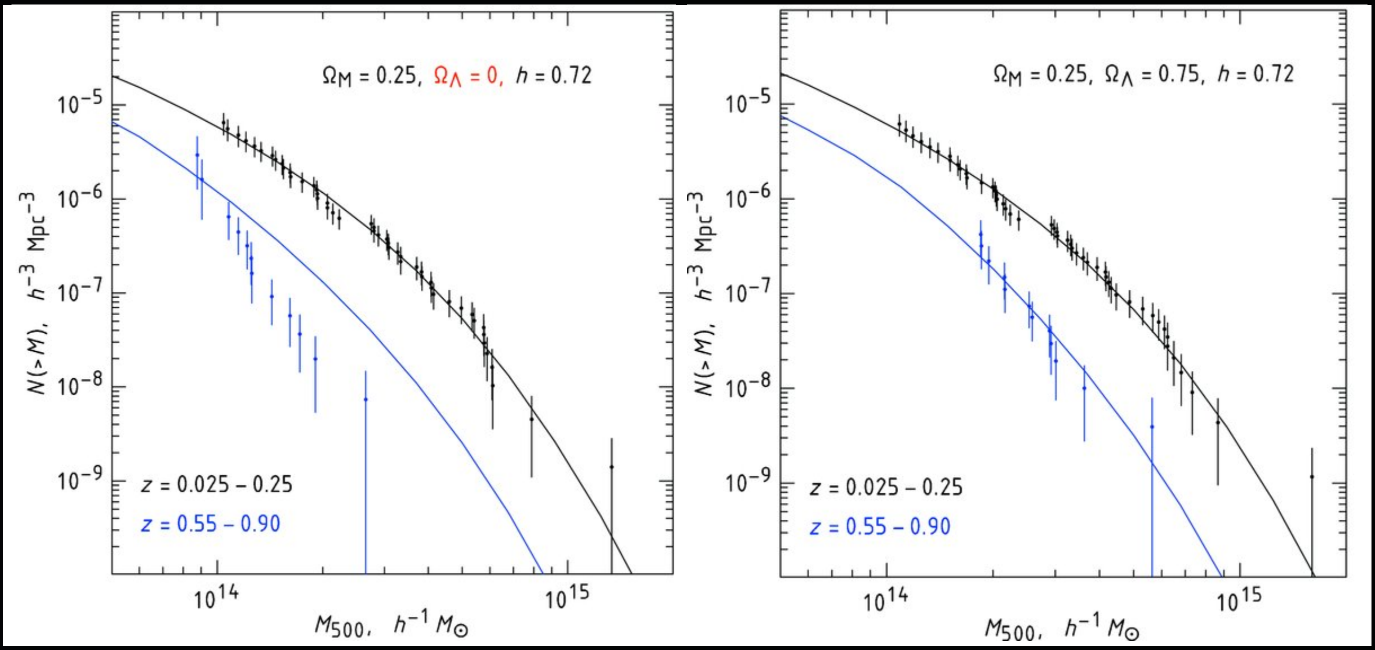


The barred spiral galaxy, NGC 1068, is one of the X-ray brightest galaxies residing at a distance of 47 million light-years. The galaxy hosts a supermassive black hole (SMBH) at its heart, with a mass only twice as large as the SMBH at the center of the Milky Way. However, the SMBH in NGC 1068 accretes gas through its accretion disk at an extremely rapid pace. As the gas swirls toward the SMBH, the gas gets superheated and becomes visible in X-ray wavelengths. A fraction of the gas is pulled into the SMBH, but some of it is thrown back out into space at high speeds.

Chandra has observed the SMBH and the outflowing wind using the high-resolution grating instrument, which can map the various emission lines with superb accuracy, such as the emission from H-like, He-like, and nearly neutral Fe shown above. Measuring Doppler line shifts allowed astronomers to explore how wind speed varies along the cone. It was estimated that each year a large amount of material, several times the mass of the Sun, is being blown out to large distances, about 3,000 light-years from the SMBH. The wind likely carries enough energy to heat the surrounding gas and suppress the star formation in the galaxy.

The detection of the wind from the SMBH can explain how the active central object alters the evolution of its host galaxy. Although it was suspected that material blown away from a central SMBH can affect its environment, it was not previously clear that such winds can provide sufficient amount of energy to stop the ongoing star formation.

Dark Energy



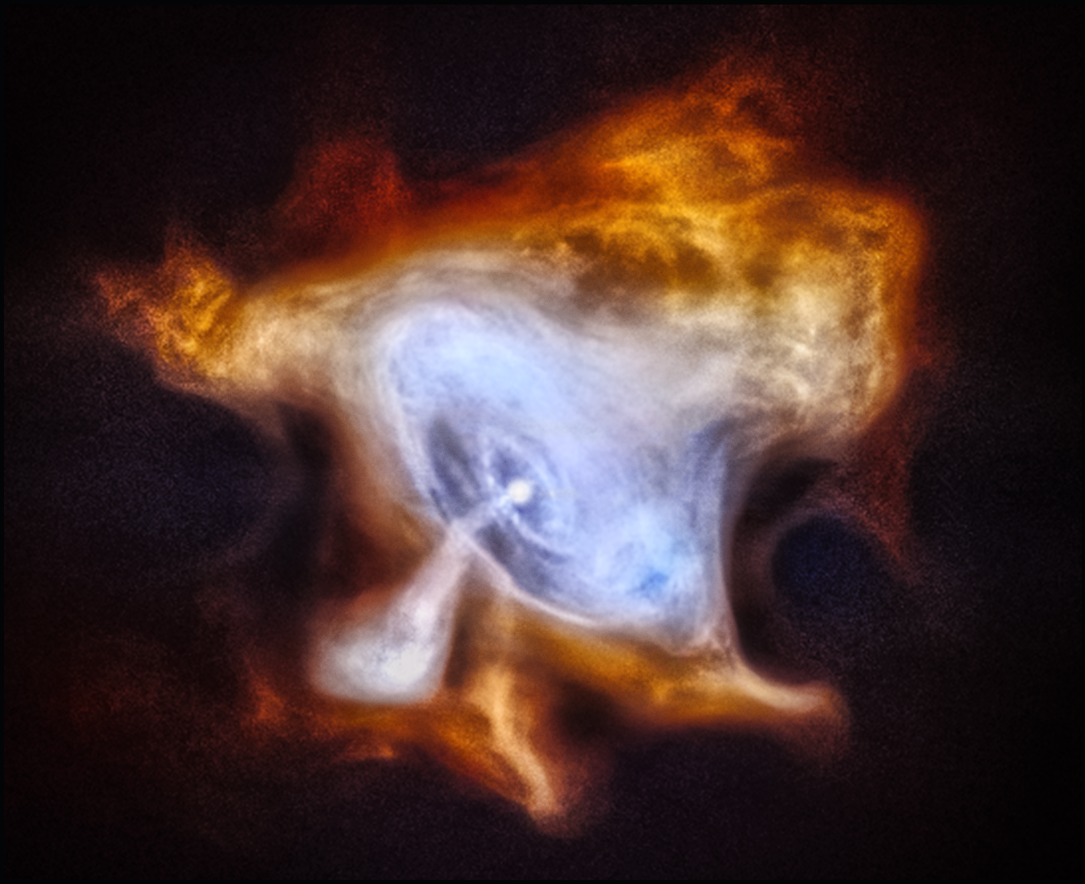
Dark energy is believed to be a form of repulsive gravity that makes the Universe larger. However, the nature of dark energy remains a mystery. Possible explanations of its nature include the cosmological constant, which is equivalent to the energy of empty space. Other possibilities include a modification in general relativity on the largest scales or a more general physical field. To differentiate between these possibilities, scientists utilized the Chandra X-ray Observatory to study the growth of galaxy clusters over time.

By studying the hot gas content of galaxy clusters, it was found that the increase in the mass of the galaxy clusters over time is consistent with a Universe dominated by dark energy. It is more difficult for objects like galaxy clusters to grow when space is stretched, as caused by dark energy. Thus, models without dark energy predict fewer large clusters at large distances (blue curve and points in left panel; here, larger values of z correspond to larger distances, and thus earlier stages of evolution). The cluster measurements are consistent with a dark energy comprising about 75% of the energy density of the Universe (right panel). The astronomers combined their results with those obtained from other studies, such as supernovas, the study of the cosmic microwave background, and the distribution of galaxies.

"*Putting all of these data together gives us the strongest evidence yet that dark energy is the cosmological constant, or in other words, that 'nothing weighs something'. A lot more testing is needed, but so far Einstein's theory is looking as good as ever,*" said Alexey Vikhlinin of the Center for Astrophysics | Harvard & Smithsonian, the lead author of the study.

If dark energy is explained by the cosmological constant, the expansion of the Universe will continue to accelerate. Due to the accelerated expansion of the Universe, in about a hundred billion years all other galaxies ultimately will disappear from the Milky Way's view and, eventually, the local superclusters of galaxies also would disintegrate.

Crab Nebula



The Crab Nebula is one of the most extensively studied objects in the night sky. The relic of a supernova reported in historical records from 1054, the nebula is the result of the collapse and subsequent explosion of a massive star upon depletion of the nuclear fuel supply in its core. The stellar core is compressed to supranuclear densities, creating a neutron star with a mass of about 1.5 times that of the Sun. Such neutron stars typically have magnetic fields of a trillion Gauss or higher, and rotation periods of only tens to hundreds of milliseconds.

The rapidly-rotating, highly magnetic neutron star generates extremely high electric potentials capable of accelerating particles to high energies, and producing beams of radiation that produces pulses of emission as they sweep past a distant observer. These so-called pulsars drive a wind of energetic particles and magnetic flux, creating an extended pulsar wind nebula that produces bright synchrotron radiation from relativistic electrons and positrons.

The Chandra image of the Crab reveals an inner ring surrounding the pulsar, which defines the termination shock at which the rapid pulsar wind joins the more slowly-expanding nebula. Particles emerge from the shock and form a larger torus-like structure that defines the equatorial regions of the system, perpendicular to the rotation axis of the pulsar. Jets of material are funneled along the rotation axis. The Chandra image thus reveals the pulsar, its wind, and the actual orientation of the spin axis. The most energetic particles in the nebula lose energy most rapidly, resulting in spectrum with fewer high energy particles in the outer regions. This is seen in the Chandra image as a reddening of the emission toward the outside of the pulsar wind nebula.

Orion Nebula

The Orion Nebula is a rich cluster of young stars in the Milky Way, located at a distance of 4200 light-years from the Earth. It is the closest region of massive star formation to Earth, hosting about 700 young stars in various stages of formation. Due to its proximity and brightness, the Orion Nebula is visible with the naked eye, and it is an ideal target for astrophotography.

Thanks to its extremely sharp vision, the Chandra X-ray Observatory revealed an unprecedented view of the Orion Nebula. Deep Chandra observations allowed us to study the X-ray properties of young Sun-like stars with ages between 1 and 10 million years. In the image above, X-ray energies are represented by colors of the visible spectrum, running from low energy (red) to high energy (blue). The vast variety of colors reveal stars with a large range in temperatures, as well as the effects of absorption (reddening) for stars embedded in dense material.

Many of these stars were found to produce extremely violent X-ray outbursts and flares. These events are more frequent and energetic than those observed from the Sun. Theoretical models suggest that such flares could produce strong turbulence in a planet-forming disk around a young star. The turbulence might influence the position of rocky planets and prevent them from migrating towards the young star. This, in turn, might drastically increase the survival rate of Earth-like planets.

Toothbrush Cluster

Galaxy clusters are the most massive gravitationally bound objects of the Universe. According to our current understanding, structures grow in a bottom-up manner, meaning that smaller structures develop first, which assemble into larger structures, eventually building up galaxy clusters.

During their evolution, some galaxy clusters also violently merge with each other. The hot gas that fills up galaxy clusters plays an important role in the cluster's evolution. The hot intracluster gas contains rapidly moving charged particles that radiate strongly at radio wavelengths. Some of these mergers produce elongated radio structures, which are perpendicular to the symmetry axis of the cluster. These immense structures are believed to be shock fronts produced by the collisions between the sub-clusters.

The "Toothbrush" galaxy cluster, 1RXS J0603.3+4214, is a poster child of the merger between galaxy clusters. Pictured above on a background of stars and a map of the maximum gravitational lensing regions (blue) it exhibits prominent radio features (green) that extend over more than six million light-years and resemble the brush and handle of a toothbrush. Interestingly, the handle is not only large and very straight, but it is off-center from the axis of the cluster. The Chandra X-ray image (purple) exhibits two main peaks, which show the two merging sub-clusters. By combining Chandra X-ray and radio observations, astronomers concluded that the observed features are consistent with the merger of two galaxy clusters, and learned about the nature of cluster merger shocks.