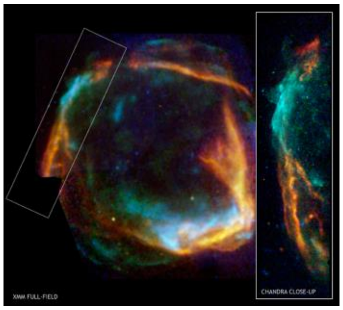
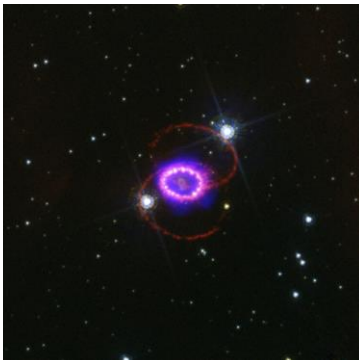
X-Ray Spectroscopy of Supernova Remnants

Introduction and Background:



RCW 86 (Chandra, XMM-Newton)

RCW 86 is a supernova remnant that was created by the destruction of a star approximately two thousand (2000) years ago. This age matches observations recorded by the Chinese and the Romans in 185 A.D. RCW 86 is 8200 light years away in the direction of the constellation Circinus and is considered to be the earliest recorded observation of a supernova event. Supernova events are relatively rare in the Milky Way Galaxy (MWG), occurring about twice every one hundred (100) years. The last known supernova event in the MWG occurred ~146 years ago. Because supernovas are rare within any galaxy, obtaining a good sample of supernovas to study requires regular monitoring of many galaxies. In the Large Magellanic Cloud galaxy, one hundred and sixty thousand (160,000) light years away, a supernova event took place in 1987. Astronomers and spacecraft have been monitoring this event (SN 1987A) continuously as it changes over time. The movie clip on the right is a composite image showing the effects of the powerful shock wave moving away from the collapse. Bright spots of X-ray and optical emission arise where the shock collides with structures in the surrounding gas. These structures were carved out by the wind from the progenitor star. Hot-spots in the Hubble image (pink-white) now encircle Supernova 1987A and the Chandra data (blue-purple) reveals multimillion-degree gas at the location of the optical hot-spots. These data greatly increase our understanding of the processes involved as a supernova remnant expands into the surrounding interstellar medium.



Chandra Time-lapse Movie of SN1987A

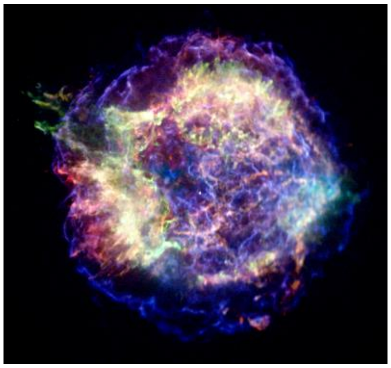
Type II Supernovas

SNR G292.0+1.8 (Chandra) Type II

There are several scenarios that can result in a supernova event; however, supernovas are classified by the type of triggering mechanism that initiates the destruction. Type II supernovas are produced by the core collapse of a massive star – RCW 86 and SN 1987A mentioned above are Type II events. Thermonuclear fusion in stars with masses between ~0.8 and 8 solar masses produces the outward radiation pressure to counterbalance gravitational forces for approximately ten billion years. When the core hydrogen has been converted to helium and fusion stops, gravity takes over and the core begins to collapse. The layers outside the core collapse also - the layers closer to the center collapse more quickly than the ones near the stellar surface. As the layers collapse, the gas compresses and heats up. The core temperature becomes high enough for helium to fuse into carbon and oxygen, with hydrogen to helium fusion continuing in a thin layer surrounding the core. The outer layers expand to an enormous size and the star is now called a red giant. The star brightens by a factor of 1,000 to 10,000, and the surface temperature of the extended envelope drops to about 3,000K to 4,000K, giving the star its reddish appearance. A strong wind begins to blow from the star's surface, carrying away most of the hydrogen envelope surrounding the star's central core. During the final shedding of its envelope, when the mass loss is greatest, the star pulsates - the surface layers expand and then contract in repeating cycles with periods ranging from several months to more than a year. The material ejected by the star forms a planetary nebula which expands into the surrounding interstellar medium at ~17to35 km/s. The core of the star left in the center of the planetary nebula is called a white dwarf. The planetary nebula is very tenuous, and becomes so thin that after ~50,000 years it is no longer visible. A white dwarf cannot create internal pressure and its complete collapse is only prevented by quantum mechanics. Two electrons with the same “spin” are not allowed to occupy the same energy state. Since there are only two ways an electron can spin, only two electrons can occupy any single energy state; this is called the Pauli Exclusion Principle. In a normal gas, this is not a problem – there are not enough electrons floating around to completely fill up all the energy states. In a white dwarf, all of the electrons are forced close together, and all the energy states in its atoms are filled with electrons. If all the energy states are filled, and it is impossible to put more than two electrons in each state, then the white dwarf has now become degenerate. This means the white dwarf is now degenerate matter; gravity cannot compress it any more because quantum mechanics tells us there is no more available space. The complete collapse of the white dwarf is prevented because it is held in equilibrium with gravity by electron degeneracy pressure. The white dwarf is extremely dense, ~200,000 times more dense than the Earth. The mass limit for a white dwarf to remain in equilibrium between gravity and electron degeneracy pressure is 1.4 solar masses - the Chandrasekhar limit. Over hundreds of billions to a trillion years the white dwarf will radiate its remaining heat away and become a black dwarf - a cold, dark mass of electron degenerate matter.

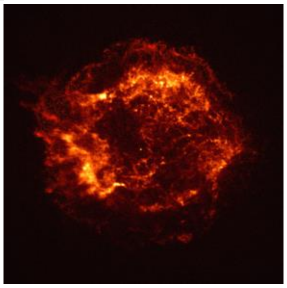
NGC 6543 Planetary Nebula (Chandra, Hubble)

Stars with masses greater than eight solar masses continue nuclear fusion beyond that of core helium. The carbon-oxygen core more massive stars acquired during the core helium fusion contracts and heats. After all of the helium in the core is gone, carbon and oxygen begin to fuse. Their fusion yields neon, magnesium, silicon, and sulfur. Eventually, silicon and sulfur fuse in the star's core to form iron, nickel, and other elements of similar atomic weight. The star's structure now resembles an onion. The central core of the onion consists of iron. Surrounding it is a shell in which silicon and sulfur fuse, adding more iron to the iron core. In additional levels further out, lighter elements fuse - oxygen, carbon, helium, and hydrogen. The iron core is very compact and cannot induce further nuclear fusion. Nuclear fusion is possible only if the reactions release energy. The fusion of iron with other nuclei to make still heavier nuclei requires an input of energy - it is an endothermic nuclear reaction. The energy required to produce elements heavier than iron becomes available only during the imminent catastrophic collapse of the star's core and the violent explosion of the star's outer envelope.



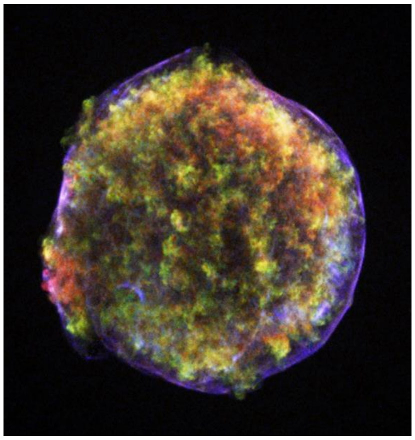
Cas A Type II Supernova Remnant (Chandra)

The mass of the star’s iron core approaches 1.4 solar masses due to the continued silicon and sulfur fusion in the thin layer adjacent to the iron core, and the continued fusion of iron requires more energy than is available. Radiation pressure is no longer able to support the core against gravity and the iron core collapses. In less than a second, the core collapses from a diameter of ~8000 kilometers to ~19 kilometers - the collapse happens so rapidly that the outer layers have no time to react or collapse along with the core. The energy released during core collapse is unimaginable - more energy than is produced by 100 stars like the Sun during their entire lifetimes of more than 10 billion years. Most of the energy released during collapse is carried off into space by neutrinos; a small fraction of the energy triggers the accompanying supernova explosion. The core collapses so fast that it momentarily goes past its equilibrium point at nuclear density and instantaneously rebounds. The innermost layers of the star are still in-falling and meet the rebounding core, creating a super strong shock wave that runs outward through the layers towards to the star's surface. The shock wave heats the outer layers, inducing explosive nuclear fusion, and ejects the outermost layers at speeds in excess of ~16 million kilometers per hour. The energy released by the shockwave produces elements heavier than iron. When the shock wave reaches the star's surface, it heats the surface layers and brightens them - within a day or two the exploding star becomes brighter than a billion Suns. The expanding gaseous shell, referred to as a supernova remnant, plows into the surrounding interstellar medium (ISM), and pushes, compresses, and intermingles with it. A forward and a reverse shock are created when the supernova shock wave interacts with the ISM. The forward shock continues to expand into the ISM, and the reverse shock travels back into the freely expanding supernova ejecta – heating the material to millions of degrees Kelvin and producing thermal X-ray emissions. This is a Type II supernova event - the core collapse of a massive star. The end product within the remnant depends upon the initial mass of the star, and is a neutron star, pulsar, magnetar, or black hole.



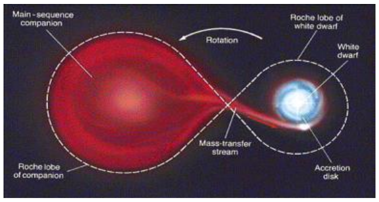
Cas A Type II Supernova Event Movie

Type Ia Supernovas



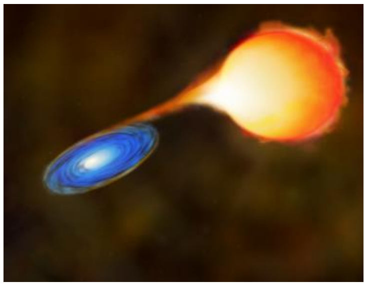
Tycho Type Ia Supernova Remnant (Chandra)

A white dwarf is not always the end product in the collapse of a mid-sized (~.8 to 8 solar masses) star if it is in a contact binary system. Suppose two stars, one with one solar mass and the other with five solar masses are in a binary system. The five solar mass star runs out of hydrogen faster than its less massive companion, becomes a red giant, shrugs off a planetary nebula, and collapses into a white dwarf. Eventually the companion star runs out of hydrogen and enters the red giant stage. The outer layers of the red giant are loosely held by the star, and the extreme gravitational field of the white dwarf starts pulling the material from the red giant into an accretion disk around the white dwarf. The mass transfer continues, with the material orbiting the white dwarf in the accretion disk. Magnetic friction slows the matter's orbital motion, which causes the matter to spiral through the disk down onto the surface of the white



dwarf. The falling and spiraling of the matter towards the white dwarf releases large amounts of gravitational energy and heats the accretion disk. The white dwarf accretes matter from its companion relatively rapidly at the Langarian point – the point where the Roche lobe of the white dwarf and red giant make contact. The Roche lobe is the region of space around a star in a binary system within which orbiting material is gravitationally bound to that star; the red giant's outer atmospheric layers are easily transferred by the strong gravity of the white dwarf.

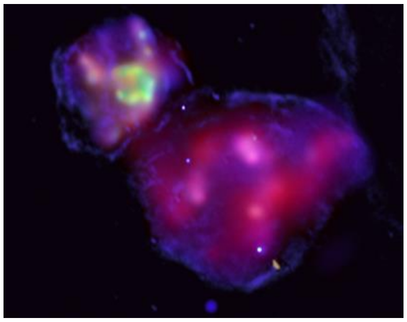
Consequently, the white dwarf accretes mass. As the mass of the white dwarf starts to approach Chandrasekhar's limit (1.4 solar masses), the density and temperature in the center of the white dwarf become so severe that carbon starts fusing explosively. Within one second the fusion moves from the center to the surface and the white dwarf undergoes a thermonuclear explosion and is completely destroyed. Only the remnant remains. All of the core's matter – the products of nuclear fusion (iron, nickel, silicon, magnesium and other heavy elements) plus unfused carbon and oxygen – are ejected into the ISM at speeds upwards of ~48,000,000 km/hr. This type of event is called a Type Ia supernova.



Mira Red Giant & White Dwarf Companion (Chandra Illustration)

Type II and Type Ia Supernovas

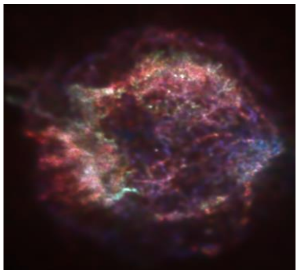
Type II supernova events – core collapses of massive stars – are more common than Type Ia events – the thermonuclear explosion of white dwarfs. The progenitor stars for Type II supernovas exist for a much shorter length of time. The initial mass of a star determines its evolutionary history; the more massive the star the more rapidly the core hydrogen is fused into helium – and when all the core hydrogen is fused the stage is set for the eventual collapse of the star. The entire process takes from ~70 million years for a six solar mass star to ~500 million for a two solar mass star. Type Ia supernovas occur when a white dwarf exceeds Chandrasekhar's Limit. A white dwarf is the end product of a mid-sized star such as the sun, and from protostar to white dwarf takes ~10 billion years. The universe is ~13.7 billions years old; therefore fewer mid-sized stars have had time to evolve into white dwarfs than massive stars have had to collapse into neutron stars, pulsars, magnetars or black holes.



DEM L316 (Chandra/NOAO)

The composite X-ray (red and green)/optical (blue) image of DEM L316 reveals an image produced by the remnants of two exploded stars in the Large Magellanic Cloud galaxy. The upper remnant is a Type Ia event and the lower remnant is a Type II event. It takes billions of years to form a white dwarf star, whereas a massive young star will collapse in a few million years. The disparity of ages for the progenitor stars for these two remnants means that it is very unlikely that the two events happened in close proximity. The apparent closeness of the two remnants is most likely the result of a chance alignment.

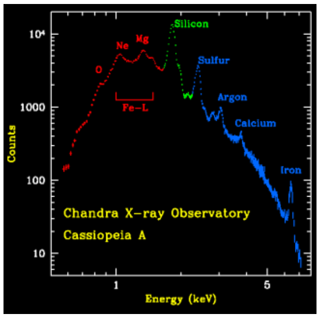
How do scientists determine if a supernova remnant is the result of a core collapse of a massive star or the thermonuclear destruction of a white dwarf? In DEM L316 one indicator is the large amount of iron in the upper Type Ia remnant compared to the amount of iron in the lower Type II remnant. The composition of supernova remnants is determined by analyzing their spectra. The elements and their relative abundances are different for Type Ia and Type II remnants because the progenitor stars are different. Type Ia remnants – from white dwarfs – usually show relatively strong Si, S, Ar, Ca, and Fe, and weak O, Ne, and Mg lines; Type II remnants – from massive stars – generally have the reverse pattern. In addition to the composition of the ejecta, spectroscopy can show how much of the stellar material was convectively mixed during the supernova event by calculating the density and temperature of the ionizing gas that generates the spectral lines. However, spectroscopy of supernova remnants is not clear cut and drawing conclusions is complicated; it is sometimes difficult to determine if a remnant is Type II or Type Ia. The Chandra and XMM-Newton missions have inaugurated the era of true spatially resolved X-ray spectroscopy. For supernova remnants, this means the capability to measure, for the first time, the detailed distribution of the ejecta and the spectra of ejecta at different positions in the remnant. This capability is greatly increasing our knowledge of the dynamics and processes involved in stellar catastrophic events. Chandra has detected numerous pulsars and their associated pulsar nebulas. These discoveries are proving to be one of the best ways to identify supernova remnants produced by the core collapse of a massive star, and distinguish them from Type Ia supernova remnants.



Cas A Distribution of Elements

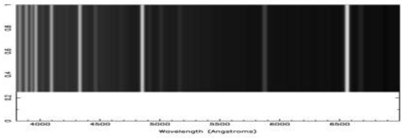
Animation

X-Ray Radiation and Spectroscopy

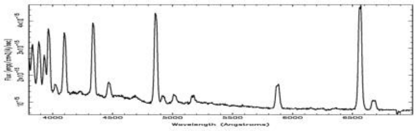


Cas A X-Ray Spectra (Chandra)

The animation above shows the distribution of elements in the Cas A supernova remnant. The X-ray spectrum to the left shows the abundances of those elements. The Cas A spectrum is typical of X-ray spectra, and differs from optical spectra – which is what is we are most familiar with. The cataclysmic spectral image below is an emission spectrum – showing the composition of a star in the optical part of the spectrum. To accurately measure the wavelengths of the emission lines, a spectral plot is constructed. On a spectral plot, the emission lines appear as sharp peaks.

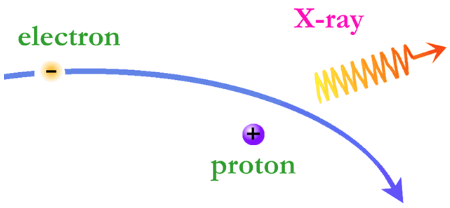


Cataclysmic Spectral Image - Optical



Cataclysmic Spectral Plot - Optical

On the X-ray spectra above, the emission lines produced by the elements also show as peaks; the higher the peak, the stronger the emission line. However on the X-ray spectra the emission lines are superimposed on top of a large curve. This curve is produced by the acceleration of electrons as they are deflected by positively charged atomic nuclei and is called Bremsstrahlung (breaking) radiation. Bremsstrahlung is also referred to as free-free radiation. This refers to radiation that arises as a result of a charged particle that is free both before and after the deflection (acceleration) that caused the emission. When a free-ranging electron is accelerated by the electric field of a proton, the photons emitted can have a wide range of energies that depends on how fast the electrons are moving and how much they are accelerated. The distribution of photon energies due to this process is called a continuous spectrum, and is graphed as a smooth curve as in the Cas A spectrum above. In addition, emission lines can appear superimposed on the Bremsstrahlung radiation curve corresponding to the ejection of K and L shell electrons knocked out of atoms in collisions with the high-energy electrons. Higher energy electrons then fall into the vacated energy states emitting X-ray photons and producing the emission lines. The energies of these emission lines can be used to identify the elements in plasmas such as supernova remnants. A hot gas or plasma will produce a spectrum composed of many emission lines due to the various elements that are present.



Bremsstrahlung Radiation