STELLAR EVOLUTION & THE CHANDRA X-RAY OBSERVATORY

The Milky Way galaxy contains several hundred billion stars of various ages, sizes and masses. A star forms when a dense cloud of gas collapses until nuclear reactions begin deep in the interior of the cloud and provide enough energy to halt the collapse.

Many factors influence the rate of evolution, the evolutionary path and the nature of the final remnant. By far the most important of these is the initial mass of the star. This handout illustrates in a general way how stars of different masses evolve and whether the final remnant will be a white dwarf, neutron star, or black hole.

Stellar evolution gets even more complicated when the star has a nearby companion. For example, excessive mass transfer from a companion star to a white dwarf may cause the white dwarf to explode as a Type Ia supernova.

The terms found in the image boxes on the following pages can be matched to those in the main illustration (page 2). These give a few examples of stars at various evolutionary stages, and what Chandra has learned about them. X-ray data reveal extreme or violent conditions where gas has been heated to very high temperatures or particles have been accelerated to extremely high energies. These conditions can exist near collapsed objects such as white dwarfs, neutron stars, and black holes; in giant bubbles of hot gas produced by supernovas; in stellar winds; or in the hot, rarified outer layers, or coronas, of normal stars.

STELLAR EVOLUTION

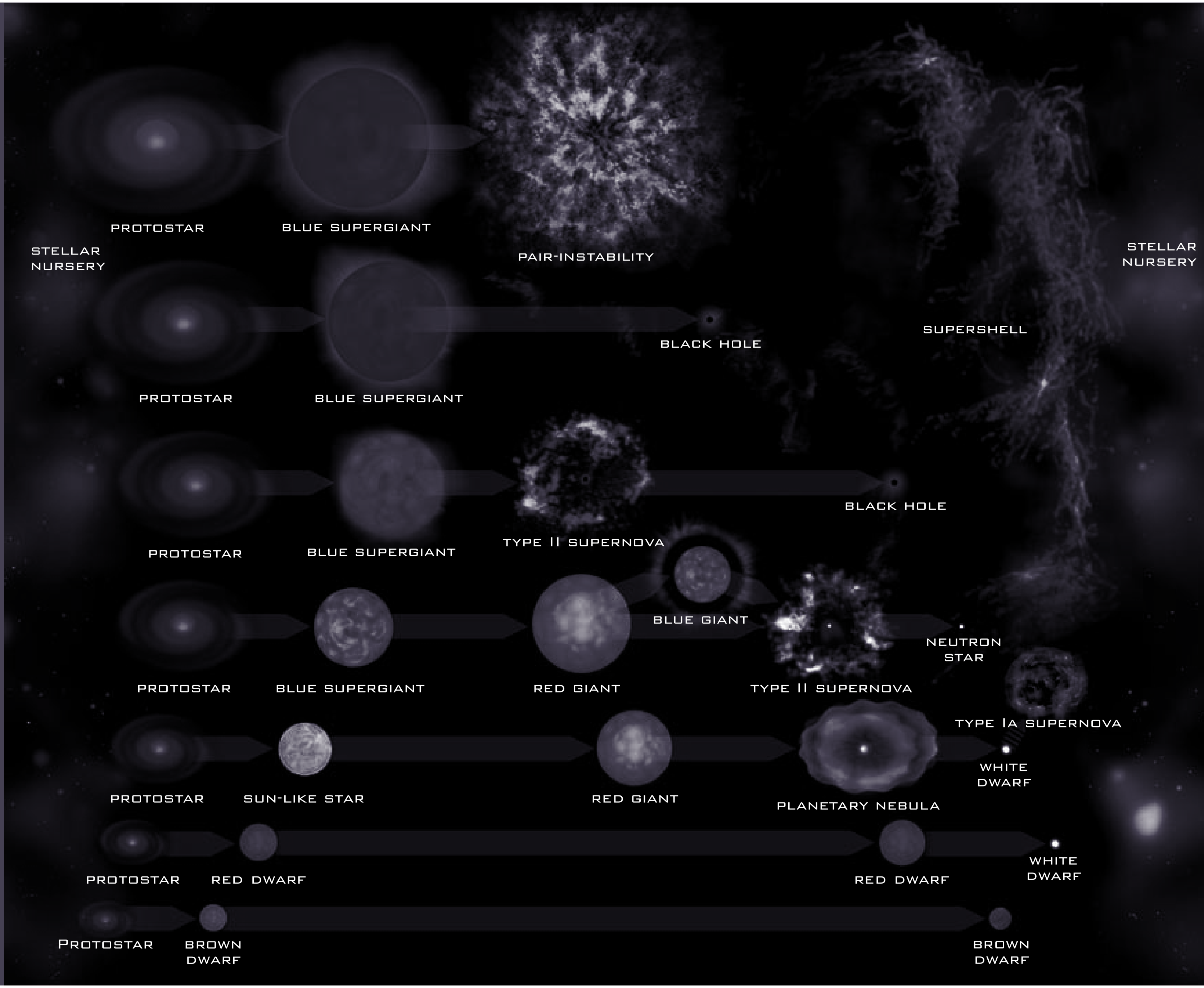
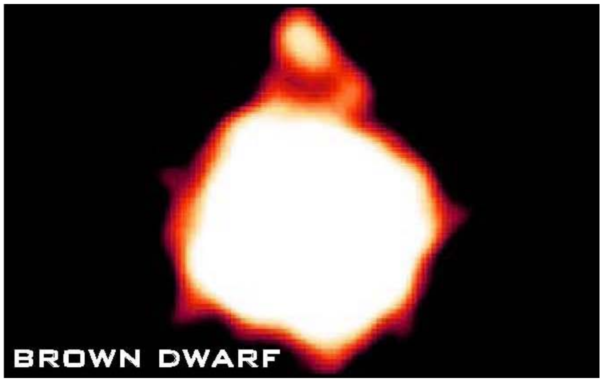


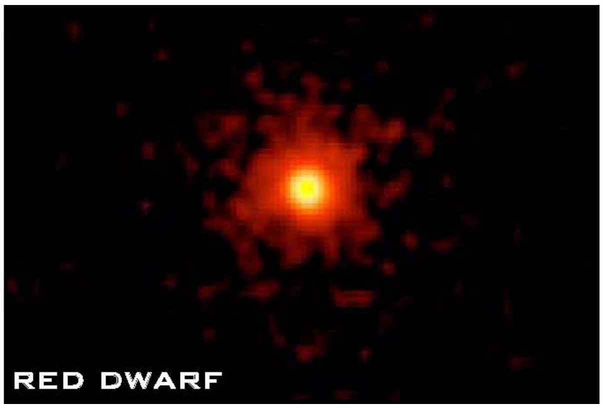
Illustration: NASA/CXC/M. Weiss

TWA 5B



An object that has a mass of less than about 8% of the mass of the Sun cannot sustain significant nuclear fusion reac-tions in its core. This marks the dividing line between red dwarf stars and brown dwarfs. The brown dwarf TWA 5B has a mass estimated at about 3% that of the Sun. The turbu-lent interiors of young brown dwarfs can combine with rapid rotation to produce a tangled magnetic field that can heat their upper atmospheres, or coronas, to a few million de-grees Celsius. The X-rays from TWA 5B are likely due to this process.

PROXIMA CENTAURI



The nearest star to the Sun, Proxima Centauri, is the most common type of star in the Galaxy—a red dwarf star. Red dwarfs have a mass between approximately 8% and 50% of the mass of the Sun. Because of their low mass, nuclear fusion reactions that consume all of the hydrogen in the core of red dwarfs can take 20 billion years or more—longer than the estimated 14 billion-year age of the Universe. A red dwarf has a turbulent interior that tangles the magnetic field and heats the star's corona, sometimes explosively. For this reason, red dwarfs are observed to be strongly variable X-ray sources.

SUN

The Sun and other stars are balls of gas that shine as a result of nuclear fusion reactions that release energy deep in their interiors. The Sun is now in a long-lived phase of its evolution wherein nuclear reactions are converting hydrogen to helium in the central core. In a thick outer shell of the Sun, the gas is in a state of rolling, boiling turmoil called convection. This up and down motion, coupled with the Sun’s rotation, twists the magnetic field and increases its strength. Twisted, magnetized loops of hot gas rise high above the surface of the Sun, where they make up the corona – the outermost layers of the Sun’s atmosphere. The Sun's X-rays (too intense for Chandra to observe) are produced in these loops, which can also be the site of solar flares.

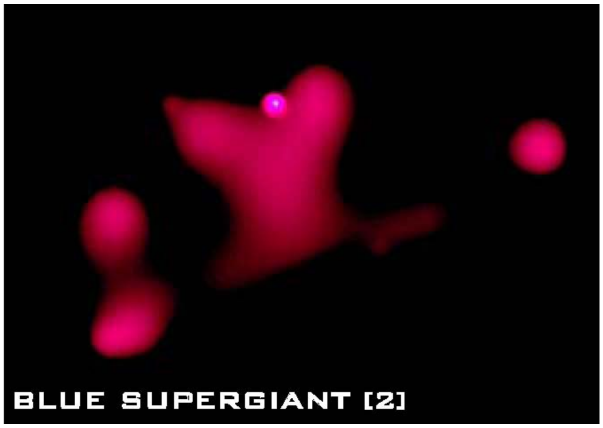
SN 2006GY

For an extremely massive star, with a mass between 140 and 260 suns, the temperature in the central regions of the star would rise to several billion degrees. At these high temperatures, thermal energy is converted into mass in the form of pairs of electrons and antielectrons, or positrons. The production of electron-positron pairs saps energy from the core of the star and triggers an extraordinarily powerful thermonuclear explosion that blows the star completely apart, leaving no compact remnant. SN 2006gy, the most luminous supernova ever observed, may be an example of a so-called “pair instability” supernova.

ETA CARINAE

A massive star exists in a delicate balance between the outward push of intense radiation and the enormous crush of gravity. There is no clear consensus as to the maximum mass of a star—the best estimate is about 150 times the mass of the Sun. Candidates for the heavyweight champion among stars in the Galaxy include Eta Carinae or one of the stars in the Arches cluster. The X-rays in the center of the Chandra image may be caused by the collision of stellar winds rushing away from Eta Carinae and a suspected companion.

NGC 346

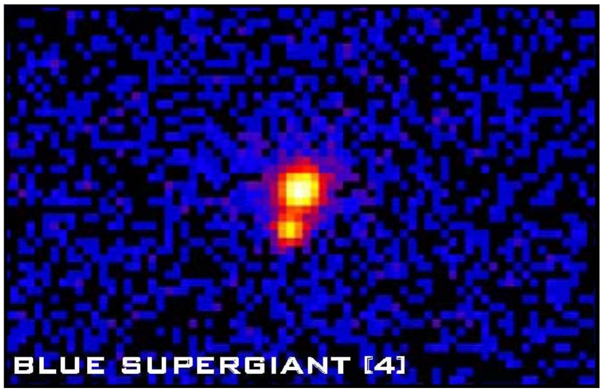


The most massive known stars have masses of about 150 times the mass of the Sun. These stars, of which HD 5980 (see comparison from Chandra) is an example, are violently unstable, probably because of the intense amounts of radiation they produce, and are called luminous blue variables. HD 5980 (the bright star in the center of the Chandra image) has been observed to undergo dramatic eruptions during the last decade. The fate of such massive stars is not known, but it is likely that, a few million years after their formation, they will explode either as a supernova or hypernova, or collapse directly to form a black hole.

ARCHES AND QUINTUPLET

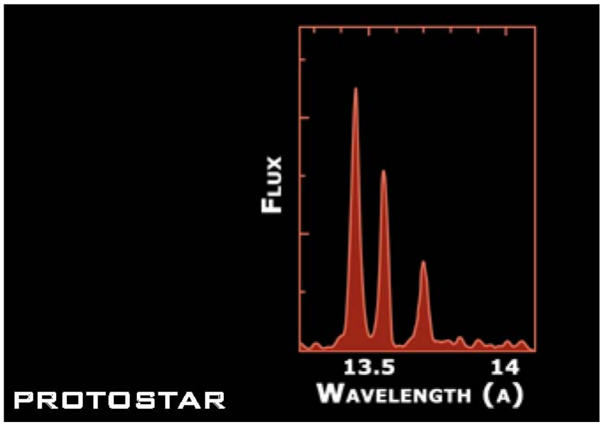
Some of the most luminous and massive stars observed are located near the center of the Galaxy in the Arches and Quintuplet star clusters. Some of these stars are 50 times as massive as the Sun and live short, furious lives that last only a few million years. During this period, gas is ejected from these stars in the form of intense stellar winds. Such stars are likely to explode as supernovas and leave behind black holes. The X-rays observed by Chandra (see comparison) are thought to be due to collisions of the winds from numerous stars and their companions.

ZETA ORIONIS



When compared to the Sun, the blue supergiant Zeta Orionis has 20 times the diameter, 30 times the mass, and 100,000 the total power output. The enormous power output of this star is driving the outer layers of its atmosphere away at speeds in excess of 4 million miles per hour. This wind speed is not steady, so rapidly moving groups of particles slam into slower ones, producing shock waves. These shock waves are the likely source of most of the X-rays from Zeta Orionis, though hot gas trapped in magnetic fields near the surface of the star may also produce X-rays.

TW HYDRAE

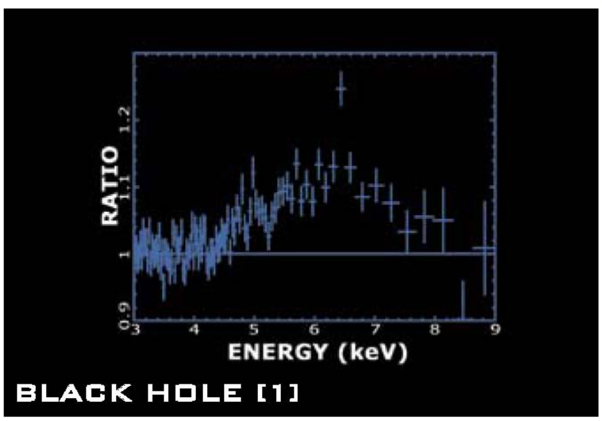


Protostars and very young stars are usually surrounded by disks of dust and gas. Some of this matter will fall onto the young star, some may form into planets, and the remainder will be blown away by intense radiation from the star. In TW Hydrae, the X-ray spectrum provides strong evidence that this very young star is pulling in matter from a circumstel lar disk. X-rays are produced as the infalling matter collides with the surface of the star.

ORION NEBULA

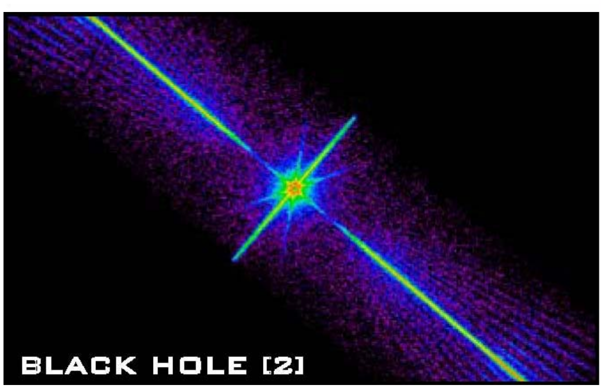
Most stars form as members of star clusters created by the collapse of cold (10 degrees above absolute zero), dense clumps of gas and dust embedded in much larger clouds of cold gas and dust. At a distance of about 1,800 light years, the Orion Nebula cluster is the closest large star-forming region to Earth. Chandra's image shows about a thousand X-ray emitting young stars in the Orion Nebula star cluster. The X-rays are produced in the hot, multimillion-degree upper atmospheres of these stars. (The dark diagonal lines and the streaks from the brightest stars in the Chandra image are instrumental effects.)

CYGNUS X-1



If the core of a collapsing star has a mass that is greater than three Suns, no known force can prevent it from forming a black hole. If a black hole has a nearby companion star, gas pulled away from the companion will be heated to tens of millions of degrees and produce X-rays as it falls toward the black hole. Radiation from the hot gas can be detected until the gas passes beyond the event horizon of the black hole. The Chandra spectrum of Cygnus X-1 shows the effect of gravity on radiation from atoms about 70 miles from the event horizon.

XTE J1118+480

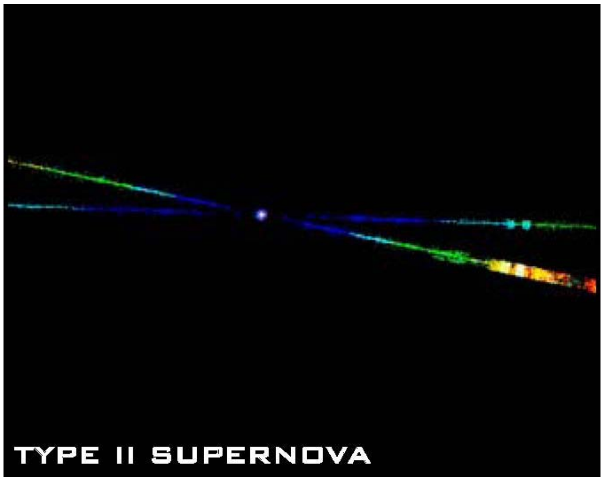


XTE J1118+40, like Cygnus X-1, is a black hole with a nearby companion star. About 20 confirmed cases of these binary systems have been identified in our Galaxy. This Chandra image was made by an instrument which sorts the X-rays according to their energy, and produces a spectrum which appears as the bright line extending from the upper left to the lower right. The central bright dot of X-radiation marks the location of the black hole. The other lines and spokes in the image are instrumental artifacts. An analysis of the X-ray spectrum revealed that the disk of matter around this black hole stops about 600 miles from the black hole.

TARANTULA NEBULA (30 DORADUS)

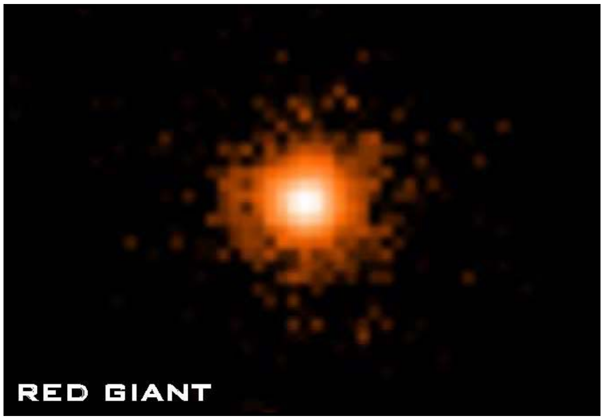
The Tarantula Nebula is in one of the most active star-forming regions in the Local Group of galaxies to which the Milky Way belongs. Some massive stars in the Nebula are producing intense radiation and searing winds that carve out gigantic bubbles in the surrounding gas. Other massive stars have exploded as supernovas. The combined activity of many stellar winds and supernovas create expanding supershells that can trigger the collapse of clouds of dust and gas to form new generationsof stars.

GRB 020813



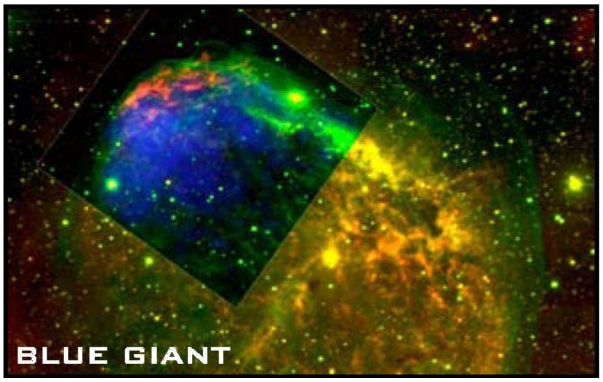
Very massive stars are thought to explode as supernovas, or perhaps an even more energetic explosion called a hyper-nova, and leave behind a black hole. Hypernovas have been proposed to explain the mysterious gamma-ray bursts —a black hole formed in the explosion could produce a jet of high-energy particles responsible for a bright burst of X- rays and gamma-rays. Interaction of the jet with the eject ed shell produces the X-ray afterglow, which can last for days or even months. Chandra's observation of the X-ray afterglow from the gamma-ray burst GRB 020813 revealed an overabundance of silicon and sulfur ions in the expand ing shell. Two gratings spread out X-rays to produce the crossed bands shown—the narrow bright regions represent X-rays from various elements.

BETA CETI



A solar-type star becomes a red giant after nuclear fusion reactions that convert hydrogen to helium have consumed all the hydrogen in the core of the star. The core collapses until hydrogen fusion begins in a hot, gaseous shell around the core. Energy generated by hydrogen fusion in the shell causes the star's diameter to expand about a hundredfold. As the gas expands, it cools, and the star becomes a red giant. During this period, the star emits X-rays weakly. Eventually the core contracts and heats until fusion reactions begin to convert helium to carbon, and the star becomes a core-helium-burning giant. Beta Ceti is an example of such a giant star, which can be X-ray active.

CRESCENT NEBULA (NGC 6888)



When a massive star uses up the hydrogen fuel in its central core, it expands enormously to become a red giant. In this phase the outer layers of the star are ejected, and the star becomes a blue giant, or Wolf-Rayet star. Intense radiation from the blue giant pushes gas away at speeds in excess of 3 million miles per hour. The collision between the high speed "stellar wind" and the previously ejected red giant material creates a spectacular nebula, such as the Crescent Nebula. The massive star that has produced the nebula appears as the bright yellow dot near the center of this image, just outside the composite X-ray (blue)/optical (red & green) image.

G292.0+1.8

TYPE II SUPERNOVA

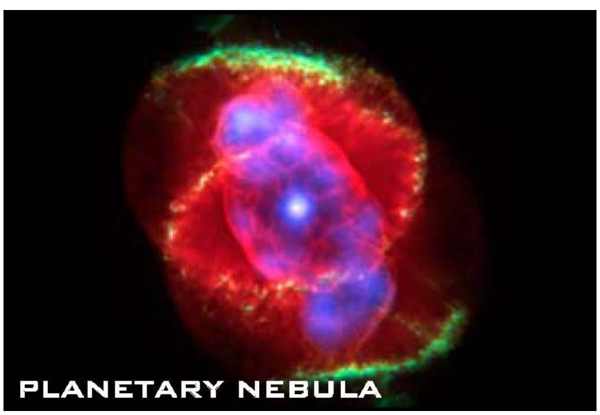
A Type II supernova occurs when a massive star has used up its nuclear fuel and its core collapses to form either a neutron star or a black hole. Gravitational energy released by this process blows the rest of the star apart. The expanding stellar material produces shock waves that heat a multimillion-degree shell of gas that glows in X-rays for thousands of years. The supernova remnant G292.0+1.8 shown here has an estimated age of 1,600 years. The neutron star is the white dot below and to the left of center.

CRAB NEBULA PULSAR

NEUTRON STAR

During a supernova, the core of a massive star can be compressed to form a rapidly rotating ball composed mostly of neutrons that is only twelve miles in diameter. A teaspoonful of such neutron-star matter would weigh more than one billion tons! Young, rapidly rotating neutron stars can produce beams of radiation from radio through gamma-ray energies. Like a rotating lighthouse beam, the radiation can be observed as a powerful, pulsing source of radiation, or pulsar, as in the case of the Crab Nebula pulsar shown here. The jets and rings are caused by high-energy particles flowing away from the pulsar.

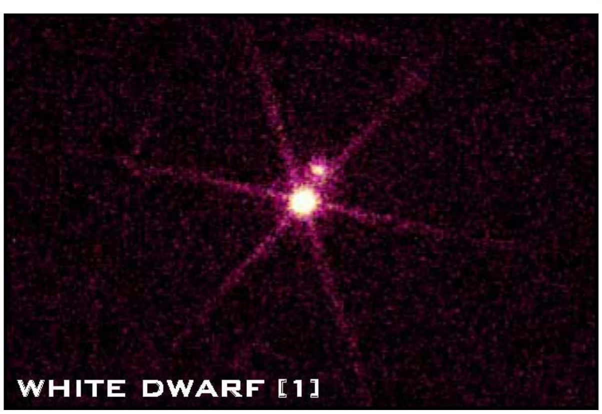
CAT'S EYE (NGC 6543)



PLANETARY NEBULA

After the core-helium-burning giant phase, all of a Sun-like star's available energy resources will be used up. The exhausted giant star will puff off its outer layer leaving behind a smaller, hot star with a surface temperature of about 50,000 degrees Celsius. When the high speed "stellar wind" from the hot star rams into the slowly moving material ejected ear lier, the collision creates a complex and graceful filamentary shell called a planetary nebula. A composite image of the Cat's Eye from Chandra (purple) and Hubble (red & green) shows where the hot, X-ray emitting gas appears in relation to the cooler material seen in optical wavelengths.

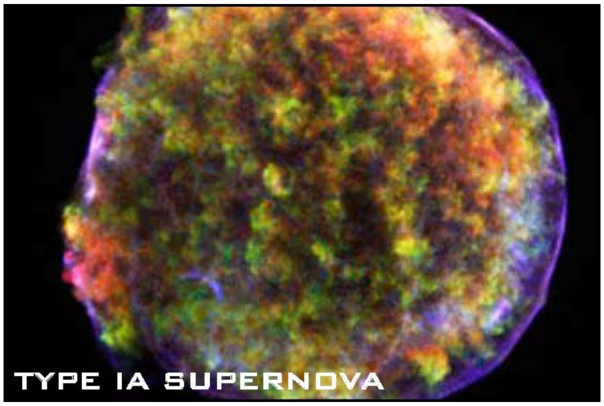
SIRIUS B



WHITE DWARF [1]

The central star of a planetary nebula will eventually collapse to form a white dwarf star. In the white dwarf state, all the material contained in the star, minus the amount blown off in the red giant phase, will be packed into a volume one millionth the size of the original star. An object the size of an olive made of this material would have the same mass as an automobile! For a billion or so years after a star collapses to form a white dwarf, it is white-hot with surface temperatures of about 20,000 degrees Celsius. After that it slowly cools to become an undetectable "black dwarf". The bright source in this image is the white dwarf Sirius B. (The spikelike pattern is an instrumental artifact.)

TYCHO'S SUPERNOVA REMNANT



Subrahmanyan Chandrasekhar, the Chandra X-ray Observatory's namesake, used relativity theory and quantum mechanics to show that if the mass of a white dwarf becomes greater than about 1.4 times the mass of the Sun—called the Chandrasekhar limit—it will collapse. If a white dwarf is a member of a binary star system, a nearby companion star could dump enough material onto the white dwarf to push it over the Chandrasekhar limit. The resulting collapse and explosion of the white dwarf are believed to be responsible for a Type Ia supernova—the type that produced Tycho's supernova remnant.

RED DWARF TO WHITE DWARF STAGE

As a red dwarf star with a mass less than about a third that of the Sun runs lower on hydrogen, the rate at which it generates energy gradually declines. Gravity pulls the outer layers inward to compress the core of the star, but unlike a more massive star, the temperatures never rise high enough for any other nuclear reactions to occur. For this reason, low-mass red dwarfs do not go through a red giant phase, but very slowly, over many billions of years, shrink to become white dwarf stars about the size of the Earth. Chandra does not have an image of such a star, because it takes longer than the age of the Universe to form one! Put another way, the discovery of such a star would indicate that either the theory of red dwarf evolution or the Big Bang theory is wrong.

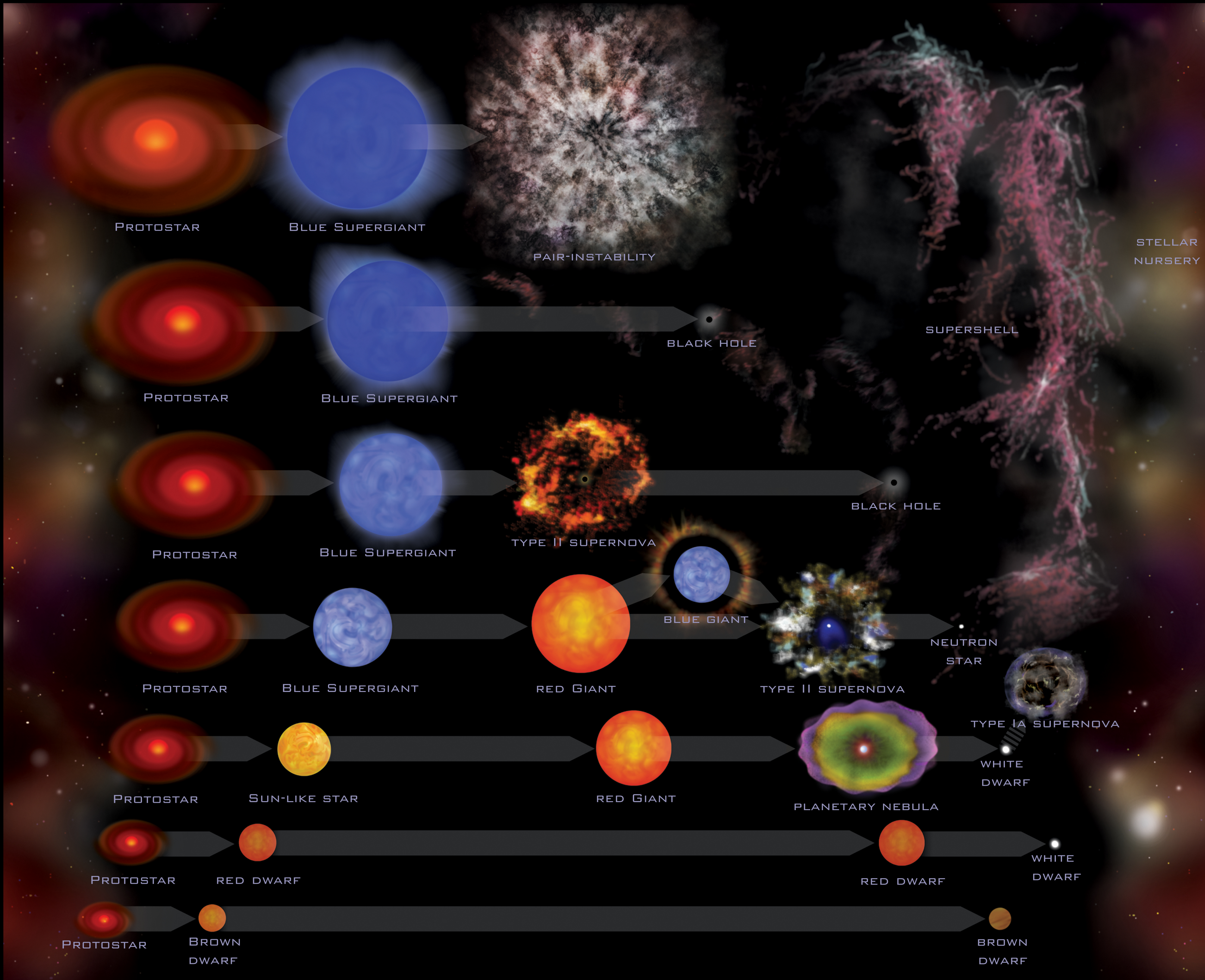


Illustration: NASA/CXC/M. Weiss