Chapter 18

The Death of Stars Part II: High Mass Stars

Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University)

The fate of a star is ultimately determined by its mass. Low mass stars live unimpressive lives and die quietly. Alternatively, massive stars outshine hundreds of thousands of suns and die in a catastrophic explosion that rivals the brightness of an entire galaxy!

The remains of high mass stars are the most exotic compact objects, either a **neutron star** or a **black hole** (Figure 18.23). A black hole has such an extreme gravitational field that it traps light.

Moreover, massive stars are key to enriching the interstellar medium with the heavier elements, necessary to form rocky planets and enable life on Earth.

Supernovae

Heavy stars with eight or more solar masses live turbulent lives. These stars shed a significant amount of their mass through powerful stellar winds, particularly after leaving the Main Sequence. Their lives are short and intense, with their splendor lasting just a few million years.

A very massive star going through phases of instability is known as a **Luminous Blue Variable (LBV)**. These unstable supergiants can produce "burps" or huge eruptions of their stellar atmosphere. An example is Eta Carinae, which is surrounded by expanding lobes of material ejected by a great eruption that took place in the 1840's (Figure 18.12).

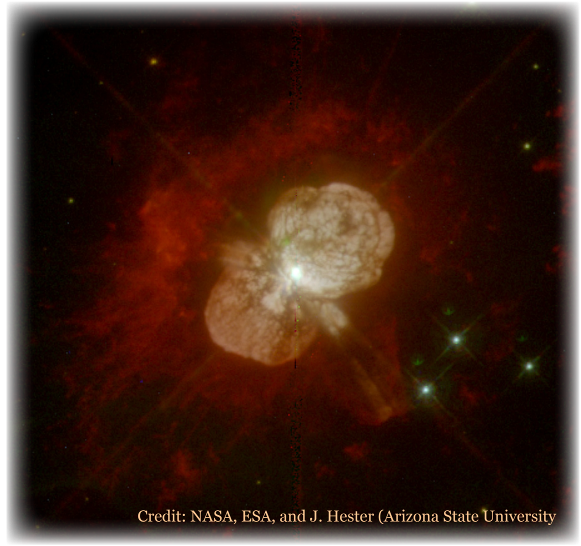


Figure 18.12 A Hubble Space Telescope image of the massive star Eta Carinae and the ejected material around it. Eta Carinae is about 4 million times brighter than our Sun and like other massive stars it is very unstable and can lose large amounts of material through violent outbursts.

In another phase of its life, a massive star may become a **Wolf Rayet** star, where the stellar wind becomes fierce and gaseous material is ejected at speeds as high as 11 million km/h (7 million mph).

Only a massive star is able to produce enough pressure and temperature in its core to fuse a sequence of heavy elements up to iron.

After fusing hydrogen, massive stars fuse helium in the core to produce carbon, and hydrogen ignites in a shell around the core. The stars swell and become giants and supergiants with sizes up to Jupiter's orbit! When the helium in the core is finally used up, gravity contracts the core until it becomes hot enough to initiate carbon fusion at about one billion K. Helium fusion then begins in a shell surrounding the core.

The ashes of a thermonuclear reaction become the fuel for the next thermonuclear fusion and the star develops a layered structure similar to an onion (Figure 18.13). Carbon fusion produces oxygen, neon, sodium, and magnesium. Successive reactions fuse neon, oxygen, and silicon to iron.

The fusion of heavier elements does not release as much energy as the fusion of lighter elements like hydrogen. As a result, the star fuses heavier elements much faster. A 25 solar mass star takes about 7 million years to fuse the hydrogen in its core, but it takes only 600 years for the carbon fusion, 6 months for oxygen fusion, and silicon fusion is completed in a single day!

Once iron is fused the star is at a dead end. An energy crisis occurs because reactions to build elements heavier than iron do not release, but rather consume, energy. Without a constant outward pressure from fusion reactions, the stellar core will collapse with tremendous force in a fraction of a second. A flood of neutrinos is released, removing a large amount of energy from the core. After the fast collapse the core rebounds, producing a **shock wave** that blasts the star's entire envelope out into space.

This explosion is so violent and energetic that many elements heavier than iron are formed as the envelope is blasted apart. Some of those elements like Nickel-56 are radioactive. Nickel-56 (28 protons and 28 neutrons) gradually decays to radioactive Cobalt-56 (27 protons and 29 neu-

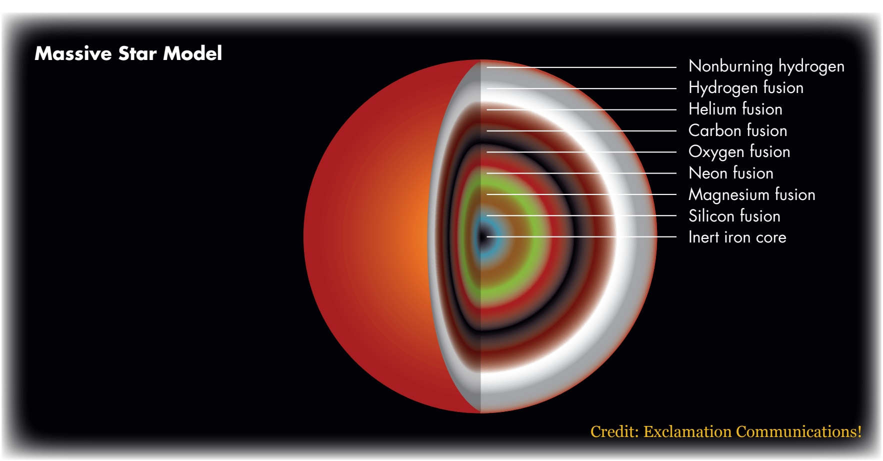


Figure 18.13 The layered structure of the central regions of a massive star close to the end of its life. This onion structure is surrounded by a much larger non-burning H layer.

trons), which decays to form stable Iron-56 (26 protons and 30 neutrons). After reaching a peak in luminosity, the bubble of expanding gas fades gradually according to the decay rate of the radioactive elements that were formed, and which cause it to shine.

What is left of the collapsed core is a compact object, either a neutron star or a black hole. The expanding cloud of gas is known as a **supernova remnant**, which disperses and mixes with the interstellar medium in just a few tens of thousands of years (Figure 18.14).

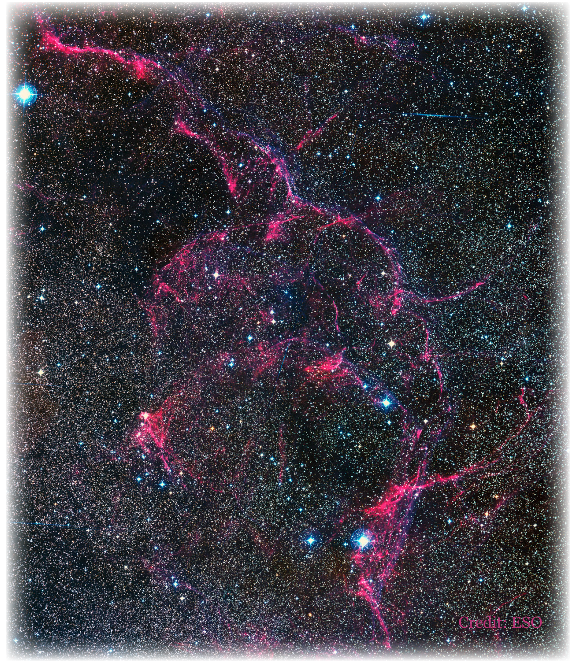


Figure 18.14 The Vela supernova remnant is the aftermath of a core collapse supernova type II explosion 11,000 years ago. The gases composed of many heavy elements mix with the interstellar medium enriching its composition.

Supernovae play an important role in enriching the interstellar medium with the heavier elements necessary for life. Some of the materials that make up our planet and our bodies were synthesized in massive stars and later spread and were even produced by catastrophic supernova explosions before the formation of the Solar System. Very heavy elements, such as gold and platinum are mainly produced by **kilonovae —** neutron star collisions (see frame The "Goldmine" of Neutron Star Mergers).

Supernovae produced by the rapid collapse of the core of massive stars are called Type II. Their spectra contain hydrogen lines because the star's gas envelope has hydrogen.

There are other types of supernovae produced by different mechanisms. Type Ib are also core collapse supernovae but their spectra lack hydrogen lines. This is probably because the star lost its hydrogen atmosphere due to the gravitational attraction of a close companion in a binary system.

Type Ia also lack hydrogen lines in their spectra, but for a different reason. The progenitor in this case is not a massive star, but it is thought to be a white dwarf in a binary system where mass transfer occurs. If the white dwarf gains mass from the donor star in excess of the Chandrasekhar limit it collapses and the resulting higher temperature ignites carbon and oxygen fusion in the core. These nuclear reactions occur in an explosive way because the matter is degenerate. When this happens, the star is entirely destroyed; there is no left over compact object after the explosion.

For a few weeks a supernova explosion can be as bright as an entire galaxy! This makes it possible for astronomers to observe supernovae inside galaxies billions of light-years away. In fact, Type Ia supernovae can be used to determine distances to remote galaxies. Because they explode as the white dwarf reaches a critical mass, they have about the same known luminosity and can therefore be used as standard candles.

Type Ia are more luminous at maximum brightness than Type II supernovae. Each type of supernova ejects a different mixture of elements in different proportions into space, and their light curve decays in different ways resulting in different light curve shapes that can help to distinguish them.

These scenarios account for most supernovae. However, astronomers have observed some super luminous supernovae, known as **hypernovae**, that shine 10 to 100 times brighter than typical supernovae. The mechanism that produces these powerful supernovae are not very well understood, but are thought to be related to the formation of rotating black holes or ultramagnetized neutron stars — **magnetars**, which have magnetic fields hundreds of trillions of times that of Earth. Hypernovae are also associated with gamma ray bursts powered by bipolar jets.

Supernovae are rare events and are thought to occur once or twice each century in a galaxy like the Milky Way. However, none has been observed within our galaxy in the last four hundred years. The last known occurrence was Kepler's supernova in 1604, which was before the invention of the telescope. Armed with modern telescopes and advanced detectors, astronomers eagerly await the next detonation.

In 1987 a supernova explosion became visible in the Large Magellanic Cloud, a neighbor galaxy of the Milky Way. This provided a great opportunity for astronomers to study a supernova remnant at unprecedented detail using modern telescopes and other equipment. Using previous images of the same region of the sky, the progenitor was identified as a blue supergiant of about 20 solar masses. Even though the supernova was not in our galaxy, it was observed with the naked eye in the southern hemisphere for a few weeks.

A few hours before the light of the explosion was first seen, two deep underground detectors sensed neutrinos over several seconds coming from that region of the sky. Given that neutrinos are "ghost" particles that do not interact easily with matter, the small number detected indicated that hundreds of thousands of trillions of neutrinos must have passed through the detectors. This confirmed theoretical models which predicted a burst of neutrinos after the collapse of a stellar core. The neutrinos travel through the star's material much faster than the shock wave that blasts the outer envelope, and thus they are detected a few hours before the supernova itself is seen.

Neutron Stars

While the envelope of a supernova is blown into space, the core collapses to form either a neutron star or a black hole. Whether the object left behind is a neutron star or a black hole depends on the initial mass and how much mass the star sheds during its lifetime. Theoretical calculations suggest that stars with an initial mass between roughly 8 to 20 solar masses will leave behind a neutron star. Stars more massive than 20 solar masses will not shed enough mass to become neutron stars and will ultimately form a black hole.

A neutron star is a highly magnetized body, a little more than one solar mass squeezed into a sphere of just about a 10 km (6 miles) radius, the size of a city (Figure 18.16). It has an extremely high density of almost 10^{15} g/cm^3. One teaspoon of the matter of a neutron star would weight about a billion tons! Matter is so densely packed that the atomic structure is broken. Protons combine with electrons to form neutrons.

Normal matter as we know it is made of atoms. The atom's mass is concentrated in the nucleus, which is very small compared to the size of the atom. If the size of an atom was a football field, the nucleus would be about the size of a grain of sand! Achieving the high densities inside a neutron star is like squeezing out all the empty space in the atoms. The densities of these compact objects are similar to the densities of atomic nuclei. A neutron star is like a gigantic atomic nucleus glued together by grav-

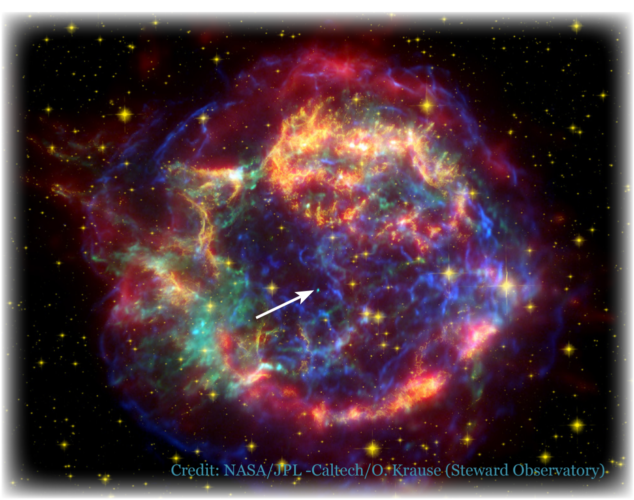


Figure 18.15 Image of the Cassiopeia A supernova remnant taken by three of NASA's Great Observatories. Infrared data by Spitzer Space Telescope is colored in red, visible data from the Hubble Space Telescope is colored in yellow, and X-ray data from the Chandra X-ray Observatory is colored in green and blue. Chandra also detected the neutron star (turquoise dot at the center of the shell).

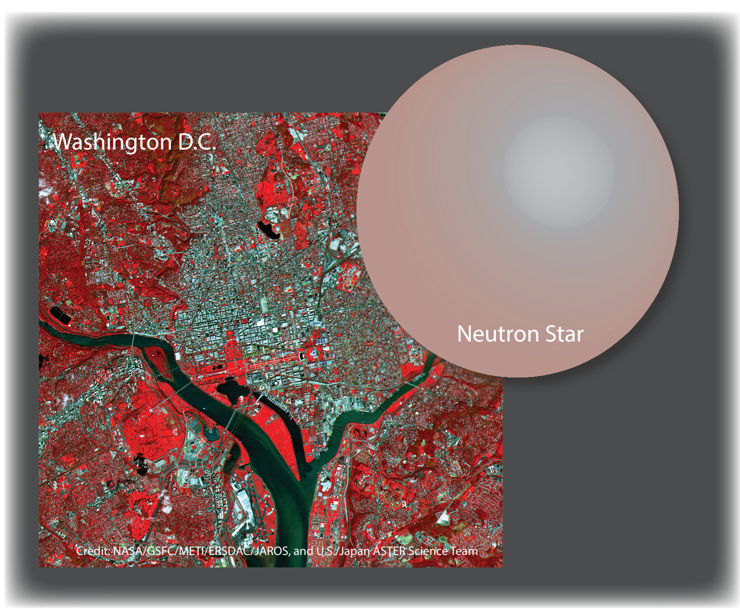


Figure 18.16 Neutron stars are the densest and smallest stars known in the universe. They are about the size of a typical metropolitan area in the US.

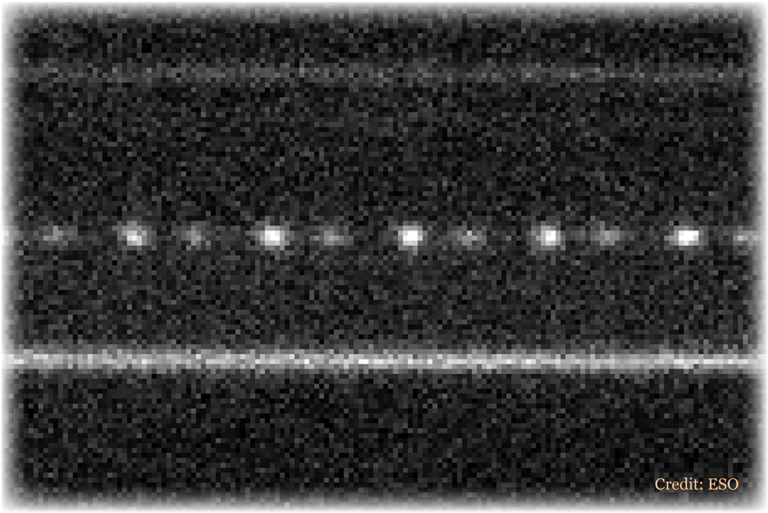


Figure 18.17 A series of images of the center of the Crab Nebula with time increasing to the right. The continuous line in the bottom is produced by a normal star, while the series of dots represents the pulses of the Crab pulsar, one pulse every 33 milliseconds. Because it is still very energetic, its pulses are observed at visible wavelengths.

Figure 18.18 A composite image of the center of the Crab Nebula showing the X-ray (blue), and optical (red) images superimposed. It is a young pulsar about 960 years old. Chinese astronomers recorded the observation of this supernova in AD 1054. Bright wisps move outward at half the speed of light to form an expanding ring around the pulsar.

ity and the strong nuclear force!

Inside these exotic stars neutrons are so densely packed that they become degenerate. Just like white dwarfs are supported against their weight by the pressure of degenerate electrons, neutron stars are supported by the pressure of degenerate neutrons. The gravity at its surface is so strong that an object would need to reach speeds about half the speed of light to escape its gravitational field.

While the upper limit for the mass of a white dwarf is well known, the upper limit for the mass of neutron stars is more uncertain, between two to three solar masses. This uncertainty exists because the extreme conditions of density, gravity, and magnetism found inside neutron stars cannot be reproduced in a laboratory on Earth, so they can only be studied theoretically.

These exotic objects are natural laboratories to study the behavior of matter at extreme conditions. It is thought that in the interior of neutron stars matter assumes special characteristics of **superfluidity** – matter can flow without any friction – and **superconductivity** – matter can flow without electrical resistance.

Neutron stars spin very fast as they are the result of the collapse of a rotating star. Just like an ice skater spins much faster when she pulls her arms close to her body, a star spins much faster as it shrinks in size due to conservation of **angular momentum**. Neutron stars are also very hot objects, with surface temperatures close to one million degrees. An object at this high temperature emits radiation in the X-ray portion of the electromagnetic spectrum. Because of their small surface areas neutron stars cool even slower than white dwarfs.

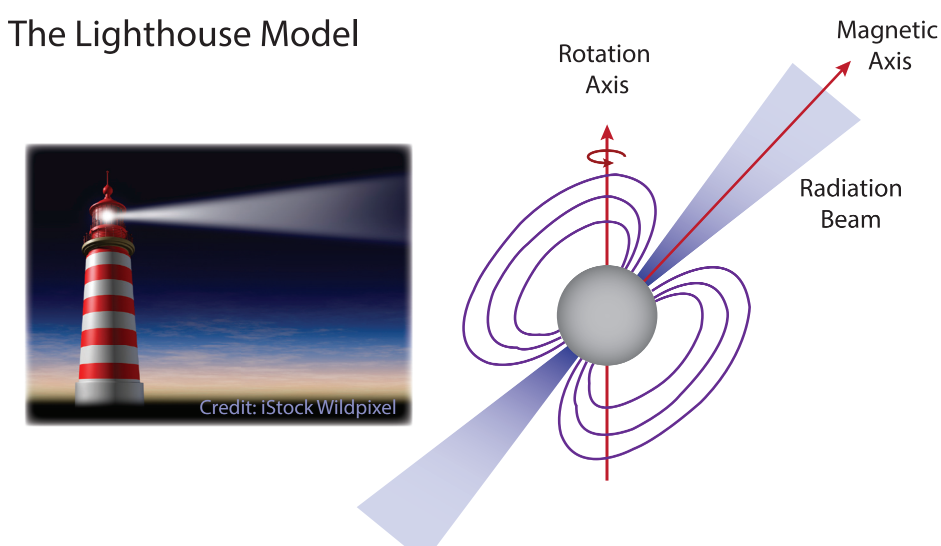


Figure 18.19 As a star rotates, a high energy beam emitted along the magnetic axis sweeps across the sky and if the beam points toward Earth a radio pulse is observed. The pulsar is analogous to a lighthouse beacon.

Although the existence of

First Detection of Gravitational Waves by Colliding Black Holes

In 2016 the LIGO scientific collaboration announced the first ever direct detection of gravitational waves — ripples in the fabric of space-time that propagate at the speed of light and are produced when a pair of massive objects orbit each other.

The existence of such waves was predicted by Einstein about 100 years ago and their detection is a remarkable confirmation of his general theory of relativity.

Analysis of the signal indicated that an extremely violent event happened 1.3 billion light-years away — the merger of two black holes, each with about 30 solar masses.

The amount of energy released in this collision in the form of gravitational waves was for a fraction of a second, greater than the energy emitted by all the stars in the observable universe!

This discovery opened a new window to explore the universe and to probe black holes. Gravitational waves carry information about cataclysmic events and when this gravitational signal is decoded, it reveals the masses of the black holes spiraling toward each other at speeds close to the speed of light, to merge and form a larger black hole.

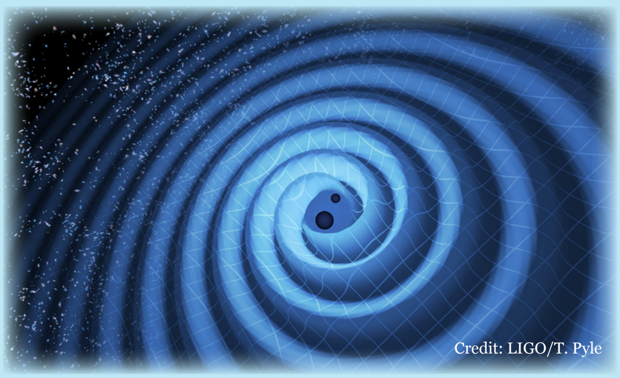


Figure 18.20 Illustration showing gravitational waves generated as the black holes spiral toward each other. Gravitational waves squeeze and stretch space-time as they pass by, travelling at the speed of light. By the time the signals reach Earth the wobbling is very tiny, even smaller than a proton!

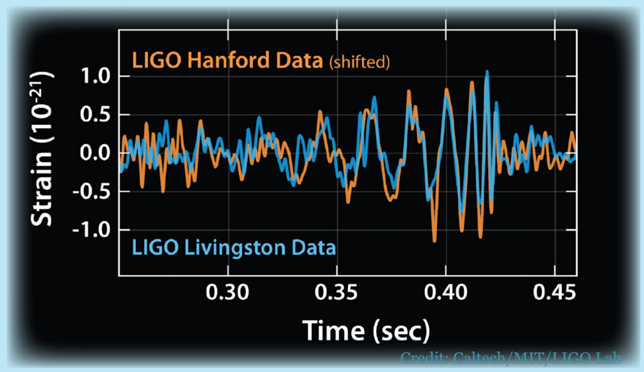


Figure 18.21 This figure shows the data received by the twin LIGO observatories at Livingston, Louisiana and Hanford, Washington. After corrections in the data are applied for orientation and for the travel time of the gravitational wave signals (the signal was observed 7 milliseconds earlier in Livingston) the results matched very well, demonstrating that both detectors witnessed the same event.

neutron stars was predicted theoretically, it took many decades for astronomers to observe neutron stars. This is because they are very faint as a result of their small size, and the X-rays they emit are blocked by the Earth's atmosphere.

In 1967 a Cambridge University graduate student named Jocelyn Bell discovered pulses from a radio source that seemed very peculiar. The radio pulses were very regular in time with very short intervals of 1.337 seconds. Because the pulses were so rapid and extremely regular, there were some speculations that they could be from an extraterrestrial civilization. The source was first nicknamed LGM, standing for Little Green Men. After a few more similar pulsating sources were found in other regions of the sky, the extraterrestrial intelligence origin hypothesis was abandoned and the sources were dubbed **pulsars**.

The true nature of pulsars was finally unveiled when astronomers discovered one at the heart of the Crab Nebula, a supernova remnant (see chapter opening image). Theory predicted that a supernova would leave a neutron star behind. Together with the pulsars' short periods, this was enough evidence to explain pulsars as rapidly rotating neutron stars.

Due to their strong magnetic fields, pulsars emit intense beams of radiation along their magnetic axis. The neutron star does not actually pulse, rather the observed pulses originate as the star rotates and the beams of radiation sweep around the sky just like a lighthouse. The pulse is only observed if the beam points toward Earth (see Figure 18.19). If the pulsar is very energetic the pulses are also observed not just in radio but also at shorter wavelengths in the visible part of the spectrum.

Some pulsars are not isolated but belong to a binary system, a pulsar with a companion. Binary pulsars provide a special environment in which astronomers can test general relativity. According to Einstein, the motion of two compact objects orbiting each other should release **gravitational waves**, which are ripples in the fabric of spacetime. As gravitational waves are emitted the system loses energy, thus the stars draw closer to each other and the orbital period decreases. The two compact objects will gradually spiral toward each other until they merge.

Measurements of a binary pulsar orbital period over time showed that a decrease in period does indeed occur, giving the first indirect evidence for the existence of gravitational waves. The first direct detection of gravitational waves was announced in 2016 by the LIGO collaboration (see frame First Detection of Gravitational Waves by Colliding Black Holes) and in 2017 the first gravitational waves produced by the collision of two neutron stars were detected (see frame The "Goldmine" of Neutron Star Mergers).

A newborn pulsar rotates very fast, about 100 times a second. The precision of the pulses makes pulsars important astronomical clocks. As the pulsar ages it slowly loses energy and the rotation rate is

The "Goldmine" of Neutron Star Mergers

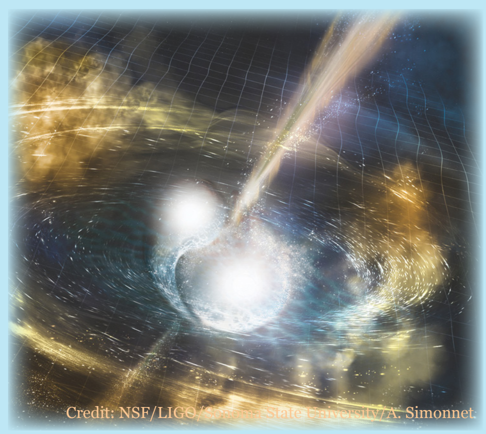


Figure 18.22 Artist's illustration of a pair of merging neutron stars. Such a cataclysmic event produces gravitational waves and gamma ray bursts.

In 2017 a burst of gravitational waves was detected by the LIGO and VIRGO facilities, signaling the merger of a pair of neutron stars in a galaxy 130 million light-years away. The chirp produced by the collision lasted approximately 100 seconds, much longer than chirps produced by black hole mergers, which last a fraction of a second. Moments before the collision, the binary neutron stars spiraled towards each other increasingly faster and releasing energy in the form of gravitational waves. The cosmic merger of neutron stars is a cataclysmic explosion nicknamed a **kilonova**.

A flash of light in the form of gamma rays was detected about two seconds after the gravitational waves detection. This was the first time that a cosmic event had ever been observed both in gravitational waves and electromagnetic waves (light) — a milestone for **multi-messenger astronomy**.

Many telescopes around the world observed the kilonova afterglow in different wavelengths and found signatures of heavy elements. Astronomers estimate that in this cataclysmic collision the amount of gold produced was equivalent to several times the mass of the Earth and demonstrated for the first time that neutron star mergers are more efficient in creating very heavy elements than supernovae. Astronomers now think that kilonovae are the main source of very heavy elements like gold, silver, lead, platinum, and radioactive elements such as uranium and plutonium. The gold in your jewelry contains samples of material produced in a cataclysmic collision of stellar corpses that happened long ago.

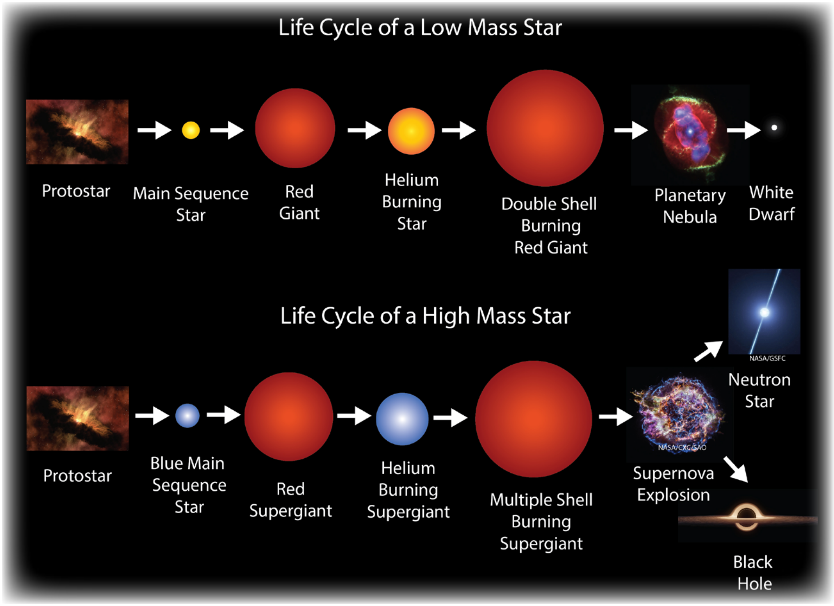


Figure 18.23 Summary of the life cycle of low and high mass stars. Low mass stars remains are white dwarfs, whereas high mass stars leave behind neutron stars or black holes.

Figure 18.24 Artistic conception of a magnetar. Magnetars are a special kind of neutron stars which have very powerful magnetic fields, hundreds of trillions of times more powerful than the Earth's.

gradually reduced. Their periods increase about a few billionths of a second per day.

Usually, young pulsars blink faster than old pulsars. However, older pulsars in binary systems, where mass transfer occurs from a companion star, can speed up. These are known as **millisecond pulsars** since the time between radio pulses is very short, close to a mere millisecond. The fastest known millisecond pulsar spins more than 700 times a second!

Binary pulsars can also emit flares of X-rays due to the mass transfer process. When matter composed of light elements (hydrogen and helium) is accreted onto the surface of a neutron star, it piles up and becomes very compressed and hot. Eventually the temperature is high enough to trigger thermonuclear fusion, and the reactions make the system glow in X-rays. New flares recur after a new layer of material accumulates.

Some fast pulsars, dubbed **black widows,** lack a companion. It is thought that after transferring mass to the pulsar, the companion was evaporated by the extremely intense radiation and high energy particles emitted from the neutron star.

Neutron stars have very powerful magnetic fields that can be billions or even hundreds of trillions of times that of the Sun. If the magnetic field strength is about 1,000 times stronger than normal pulsars, then astronomers call it a **magnetar**. A magnetar's magnetic field is so strong that it could wipe out the information from all credit cards on Earth from a distance halfway to the Moon. These ultra-magnetized neutron stars can produce flares that arise from twisting magnetic fields, which can crack the surface open, releasing an enormous amount of energy. Astronomers call these **starquakes**. Flares in magnetars also seem to be an explanation for at least some of the mysterious and powerful bursts of energy referred to as **fast radio bursts (FRBs)** that were first discovered in 2007.

Magnetars are a rare class of neutron stars and just a handful of them have been discovered in our galaxy.

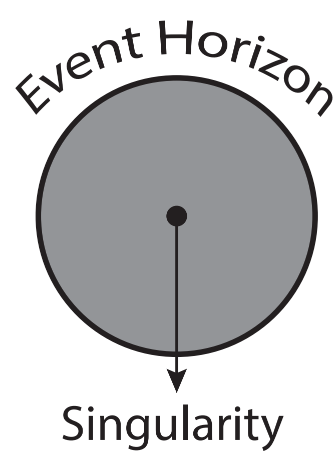


Figure 18.25 The event horizon around a black hole is the surface that marks the point of no return, the point at which not even light can escape.

Black Holes

The life of a star is characterized by the struggle between two opposing forces: gravity that tends to make the star contract and internal pressure that tries to make the star expand. Black holes represent the ultimate victory of gravity.

When a left over compact object has more than three solar masses the pressure of degenerate neutrons can no longer support its weight and the object collapses. No known force is able to stop the collapse and all the matter collapses to a single point. If all the mass is packed into a zero radius the density is infinite, which is difficult to imagine. Astronomers call this a **singularity**.

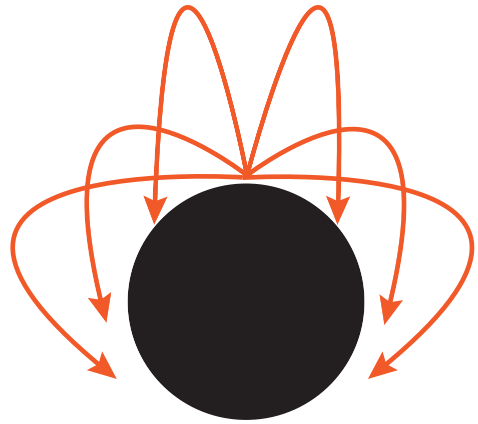


Figure 18.26 At the event horizon of a black hole, not even light, which travels at about 300,000 km/s, can escape its gravitational pull.

If you throw a pebble up into the air, it will sooner or later fall back. When space agencies launch rockets, they do not want the rocket to come back, but rather to escape from Earth's gravity into space. For an object to break free from the gravitational pull of Earth it needs to be launched at the **escape velocity**. This is the minimum initial speed needed for an object to escape the gravitational pull of a massive body. For an object on Earth's surface the escape velocity is 11 km/s (25,000 mph).

For a black hole, the escape velocity is even higher than the speed of light! Black holes are so named because not even light can escape (Figure 18.26). No radiation and no information can leave the object. The inside of a black hole is completely disconnected from the outside world. The boundary that defines the region of no return is called the **event horizon** (Figure 18.25).

The radius of the event horizon is called the **Schwarzschild radius** for non-rotating black holes. The Schwarzschild radius is defined by the mathematical equation:

$R_s = 2GM/c^2$ where **G** is the gravitational constant, $G = 6.674 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$
M is the black hole mass in kg
c is the speed of light in vacuum in m/s

Any object could become a black hole if squeezed to the size of its Schwarzschild radius. For Earth this radius is only one centimeter. For the Sun it is about 3 km. However, the Sun is a low mass star and its core will not have enough mass to cause it to collapse. But even if the Sun would become a black hole, our planet would not be sucked into it. Earth would keep the same orbit around the one solar mass object. Only objects that come too close to a black hole are forever trapped.

Black holes have only three properties: the mass, the electrical charge, and the spin. As matter enters the black hole the information about the accreted matter is lost. The chemical composition of the accreted matter is of no consequence. Only the black hole's total mass affects the outside world.

A black hole with an electrical charge is expected to quickly discharge by attracting matter with the opposite charge. Therefore, astronomers are mainly focused on determining a black hole's mass and spin.

Figure 18.27 Artistic conception showing the accretion disk around a black hole. The inner region of the disk has a very high temperature and thus emits X-rays. Material is also ejected in an out flowing jet of very energetic particles.

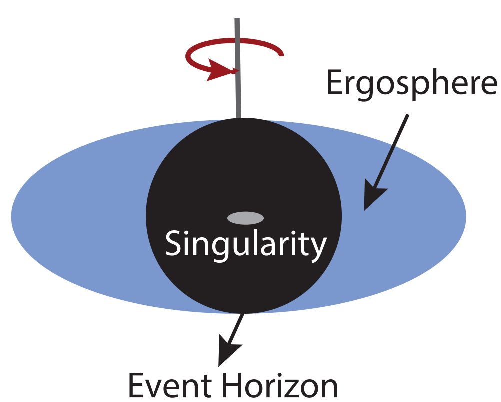


Figure 18.28 A rotating black hole has a region outside the event horizon called the ergosphere, where an object can gain energy from the black hole.

A black hole that spins will have a slightly more complex structure with a ring-shaped singularity instead of a point, and a somewhat doughnut-shaped **ergosphere** outside the event horizon. The ergosphere is a very bizarre region, where theoretically one could extract energy from the black hole (Figure 18.28). An object moving into this region could be ejected at tremendous speed, actually extracting energy from the black hole's rotation.

Although black holes cannot be directly observed (only their surroundings), as they do not emit any light, their effects on other objects can be detected. Some black holes are not isolated but are part of a binary system. As matter from the companion flows into the black hole it forms an **accretion disk** (Figure 18.27). The temperature in the inner disk can reach a few million Kelvin due to friction and hence emit X-rays.

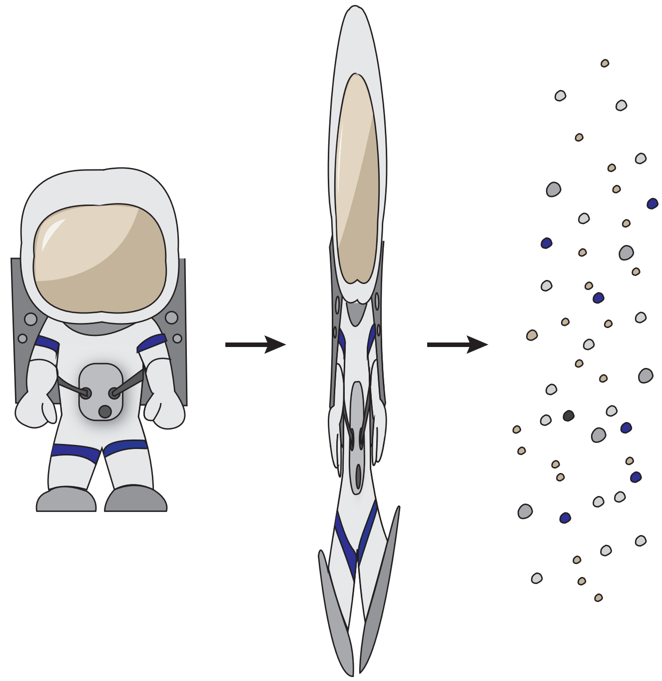


Figure 18.29 As a fictitious astronaut approaches a stellar black hole, the extreme tidal forces stretch the astronaut like spaghetti. Eventually the astronaut is pulverized into a cloud of dust.

As matter spirals around the black hole accretion disk, bipolar jets are ejected at amazing velocities, which are significant fractions of the speed of light. The mechanism that produces these jets involves magnetic fields; however, the details are not yet well understood.

Astronomers have detected some binary systems that are X-ray sources where one of the objects is invisible and has a mass greater than three solar masses. One such system is called Cygnus X-1. It is composed of a supergiant B0 star and an invisible compact object with a mass ten times the mass of the Sun. The system emits X-rays and the only explanation is that the compact object is a black hole.

Approaching a black hole would be a very unpleasant and fatal experience. For black holes of stellar mass, the journey would include extreme tidal forces, which decrease with the cube of the distance. If an astronaut were to leap feet first into a black hole, their feet, which are closer to the black hole, would feel a much stronger gravitational pull compared to their head. The final effect would stretch the astronaut's body until it was disrupted into a cloud of dust. This stretching due to tidal forces around black holes is often called "**spaghettification**" or the noodle effect (Figure 18.29).

Because black holes severely distort space-time some bizarre effects occur that can be studied using Einstein's general relativity. One such effect is known as **time dilatation**. If you observed an astronaut falling into a black hole you would see him falling more and more slowly because time slows down in the vicinity of massive objects. However, for the astronaut leaping into the black hole the journey would be fast and he would not experience this strange effect.

Some black holes are much more massive than black holes formed from the collapse of a massive star. Supermassive black holes can be millions to billions solar masses. As you will learn in Chapter 20, most galaxies have supermassive black holes in their centers. The first image of a supermassive black hole was released in 2019 by the Event Horizon Telescope Collaboration, which sowed the immediate surroundings of the supermassive black hole in the center of galaxy M87 (more details in Chapter 20). The image confirmed predictions by the general theory of relativity, showing a dark shadow surrounded by a photon ring (Figure 18.30).

Figure 18.30 The first image of the shadow of a supermassive black hole in M87 released by the Event Horizon Telescope Collaboration.

Another strong evidence that black holes indeed exist came in 2016 when LIGO announced the first direct detection of gravitational waves produced by the merger of a pair of black holes. The gravitational signal received from the death spiral prior to the merger closely matched the supercomputer models of black hole collisions (see frame First Detection of Gravitational Waves by Colliding Black Holes). Since then, many more mergers have been detected and the study of gravitational waves has opened a window for exploring these mysterious and bizarre objects.

Figure 18.31 Illustration showing how a black hole merger would appear to our eyes if we could watch it up close.

Gamma-Ray Bursts

Gamma-Ray bursts are the most powerful explosions in the universe. They were discovered during the Cold War by American military satellites which were monitoring nuclear weapons testing by the Soviet Union and other countries. The satellites were designed to look for gamma-rays coming from Earth; instead, they found flashes of gamma-rays coming from different regions of space about once a day.

The uniform distribution of gamma-ray bursts all over the sky eventually showed their sources came from distant galaxies. If the sources were located inside the Milky Way there would have been a larger concentration close to our galaxy's disk, similar to the distribution of stars.

There are two main types of gamma-ray bursts: long duration bursts which are more common and last 2 seconds to a few minutes, and short duration bursts which last less than 2 seconds.

The study of gamma-ray bursts poses challenges as these flashes occur without any warning and fade very quickly. To overcome this problem, when a gamma-ray burst is detected by a satellite an alert is sent to many astronomers in charge of large telescopes so that they can quickly observe the afterglow. Observations of the afterglow of long duration bursts resemble a type of supernova explosion.

According to theoretical models a very massive star at the end of its life can collapse to form a black hole and blast out beams of highly energetic radiation. Observational evidence has pointed clearly to hypernovae as the source of long duration bursts.

Short duration bursts on the other hand, seem to be associated with magnetars, and mergers between two neutron stars in a binary system or between a neutron star and a black hole. In 2017 astronomers detected gravitational waves and a gamma ray burst emitted by the merger of two neutron stars confirming theoretical predictions (see frame The "Goldmines" of Neutron Star Mergers) for the first time.

Key Concepts

★ Massive stars live short lives and end their days in catastrophic explosions known as supernovae. What is left from the blast is an expanding cloud of gas and a compact object, either a neutron star or a black hole.

★ White dwarfs in close binary systems can also detonate in a supernova explosion as they accrete mass from a companion and exceed the Chandrasekhar limit.

★ Supernova explosions and neutron star collisions play a key role in enriching the interstellar material with heavier elements.

★ Neutron stars can be observed as pulses of radio signals if the beam of radiation points toward Earth as the star rotates.

★ Neutron stars are supported against their weight by the pressure of degenerate neutrons. They cannot be more massive than about 2 or 3 solar masses. Objects that exceed this limit collapse to form a black hole.

★ Black holes are the ultimate victory of gravity; not even light can escape. The event horizon is the boundary of no return.

★ Black holes cannot be directly observed as they emit no light. Only their surroundings and their effects on a companion in a close binary system can be detected.

★ The first image of the 'shadow' of a supermassive black hole by the Event Horizon Telescope and the first direct detection of gravitational waves generated by colliding black holes gave strong evidence that these objects indeed exist and opened new ways to explore them.

★ Gamma ray bursts signal cataclysmic events in the universe, such as hypernova explosions announcing the birth of black holes, collisions of neutron stars or neutron stars with black holes, and magnetar flares.

Vocabulary:

Accretion disk
Black widow pulsar
Event horizon
Gravitational waves
Luminous Blue Variable
Neutron star
Shock wave
Starquake
Supernova
Wolf Rayet
Angular momentum
Escape velocity
Fast radio bursts
Hypernova
Magnetar
Pulsar
Singularity
Superconductivity
Supernova remnant
Black hole
Ergosphere
Gamma-Ray burst
Kilonova
Millisecond pulsar
Schwarzschild radius
Spaghettification
Superfluidity
Time dilatation

INTERVIEW: Astronomer Heino Falcke

Professor of Astroparticle Physics and Radio Astronomy
Radboud University, Nijmegen, The Netherlands

Dr. Falcke received many awards for his outstanding scientific achievements including the **Henry Draper Medal** of the US National Academy of Sciences in 2021 for his pioneering work for imaging black holes and the **Spinoza award** — the highest scientific award in the Netherlands.
In 2000, he demonstrated with calculations that, at the edge of a black hole, there would be a 'black hole shadow', which could be detected with a network of radio telescopes. He is the co-founder of the Event Horizon Telescope, which captured the **first-ever image of a black hole** in 2019. He is the author of the best-selling book *Light in the Darkness: The Black Hole, the Universe and Us*, about the quest for the first image of a black hole. He is also an ordained lay clergy in the protestant church in Germany.

What is the most exciting astronomical discovery you have made or been a part of?
Twenty years ago, together with two colleagues, including Eric Agol, another active Christian researcher, we predicted that we should be able to see the shadow of a supermassive black hole with a global network of radio telescopes. On April 10, 2019, I had the privilege to present the first image of a black hole at a big press conference in Europe on behalf of the global Event Horizon Telescope collaboration. The image captured the imagination of people around the world — 4.5 billion people saw that image in these days. To finally see something that was only a prediction for so long was one of the most amazing moments in my scientific career. However, before we presented the image, we underwent a very stressful period of critically checking our results. Nothing is so dangerous and seductive as a result that you long for so much!

What does your Christian faith mean to you personally? When and how did you come to your beliefs? I was brought up in a Christian home. Our family had devout Christians for many generations. However, God was for me an abstract concept, nothing that I considered very close. But the moment came when I realized that God was personal and loving. I could relate to Him. It was not about knowing something but someone. I did not take things for granted and started to read and study the Bible. I became a kind of experimental Christian. I wanted to know if I could trust God and if faith would hold up in life, and it did. My faith became the foundation of my entire life.
I think that without my faith I would not be where I am today. It gives me stability and confidence to go through moments of frustration and also embrace the world more openly. It helps me to try new things and to dare to do things I would not dare to do without faith. It is a solid foundation to stand on, to know (if you fall) you cannot fall deeper than into God's hands.

Who has been the most important role model in your life? Who is your hero?
Jesus. I don't need many others. I also identify with the Apostle Paul. Paul was smart, he was an academic, an Einstein of theology.

What advice would you give to Christian students interested in a career as a scientist?
Don't be afraid of science, don't be afraid or intimidated by people. If you kneel before God, then don't bow before any person. Invest your talents and make sure you do your best. There may be times when science may seem to go against your beliefs. Have patience, in time you will learn how it all fits together. Don't let religious prejudice influence your science or your science prejudice influence your faith.

Are you married? Do you have children? Yes, I'm married with three kids. When we moved to Germany my oldest daughter started crying because in Germany there was no Sunday school for kids. So, we started a Sunday school for my daughter and other children. When I look back, I realize this was very important to them. She chose to study theology. We didn't force them but provided opportunities.

Image Credit: NASA/JPL-Caltech/R. Hurt (SSC)

Exercises

18.8 A massive star will explode as a supernova after the last fusion reaction that releases energy and produces:
a) silicon in the core.
b) neon in the core.
c) iron in the core.
d) carbon in the core.
e) helium in the core.

18.9 The event horizon of a black hole represents:
a) the region of infinite density inside the black hole.
b) the disk of accretion that feeds the black hole.
c) the region around a black hole where light gets bent.
d) the boundary within which nothing can escape.

18.10 Which of the following is false about pulsars?
a) They have strong magnetic fields.
b) They are very big objects.
c) They spin fast.
d) They are very dense objects.

18.11 The diameter of the supernova remnant shell in Figure 18.32 is about 23 light-years. The star exploded 400 years ago for Earth viewers. What is the average speed of the material ejected in km/s?
(1 light-year = 9.46×10^{12} km)

Figure 18.32 This supernova remnant resulted from a Type Ia supernova explosion in the Large Magellanic Cloud.

18.12 The Crab Nebula is the remnant of a supernova explosion that was observed in 1054. At the center is a rapidly spinning pulsar, which flashes 30 times a second as it spins (the period is 0.033s). As pulsars grow older, they slow down. The equation below predicts the pulsar's spin rate in the future.

$$P = 0.033 + 0.000013\,T$$ where P is the period in seconds
T is the number of years from now

a) How long would it take for the pulsar to slow to a period of 1 second?

b) How fast will the pulsar spin in 1,000 years from now?

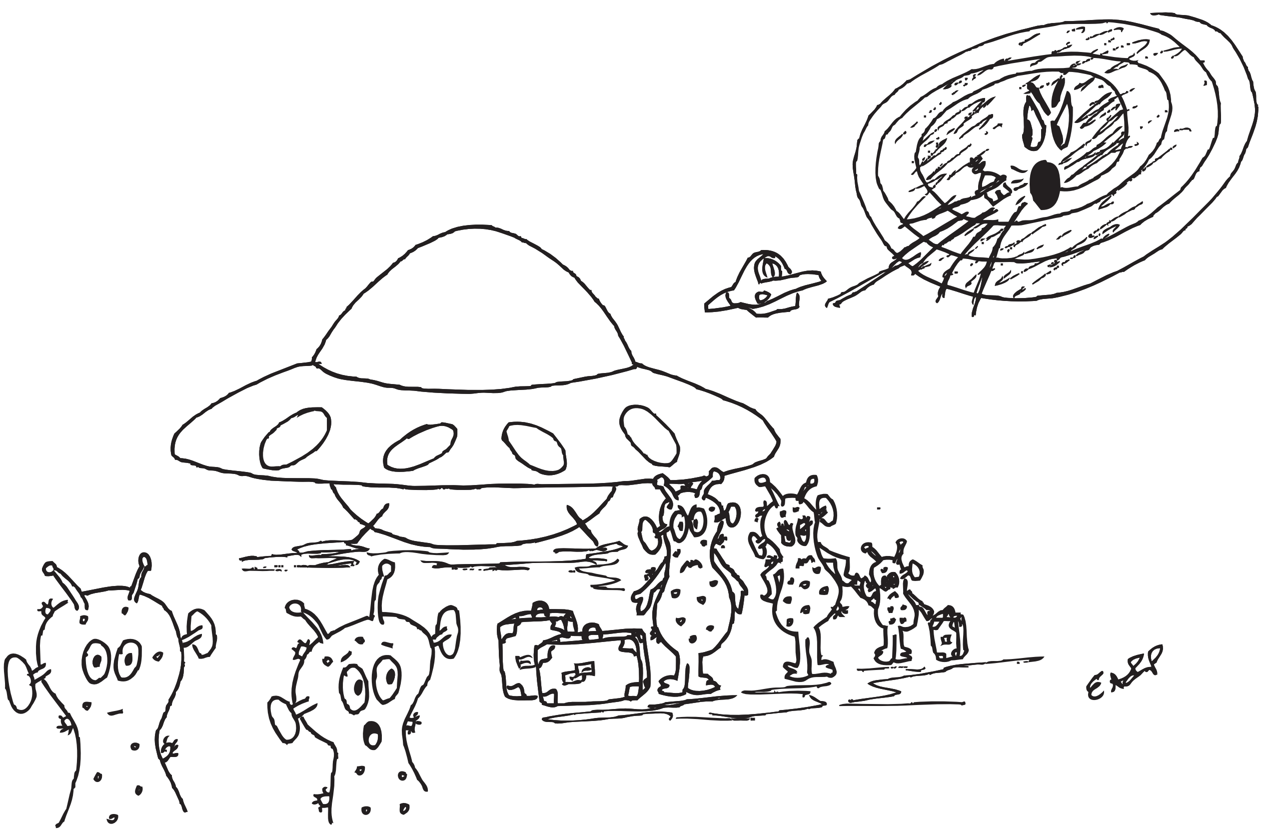
18.13
a) Calculate the size of a non-rotating black hole (the Schwarzschild radius) with 40 times the solar mass (1 solar mass = 1.99×10^{30} kg; c = 3.0×10^{8} m/s). Convert the value to astronomical units (1 AU is about 150,000,000 km).

b) Calculate the size of a black hole with the Sun's mass and one with the Earth's mass (Earth's mass = 5.97×10^{24} kg).

18.14 Calculate the escape velocity (the speed needed to break free from the gravitational field of a body) at the surface of a neutron star of mass 1.6 solar masses and radius 12 km. Use the formula below. Compare the escape velocity you calculated to the speed of light (c = 300,000 km/s).

$v_{escape} = (2GM/r)^{1/2}$ where G is the gravitational constant $G = 6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$
M is the mass of the body in kilograms
r is the radius in meters

18.15 The Crab Nebula (see chapter opening image) is a supernova remnant in the constellation of Taurus. Chinese astronomers observed and recorded this supernova explosion in 1054. Given the size (radius = 5.5 light-years) and expansion velocity of the nebula (1,500 km/s), how old is it? Is that consistent with the time it was observed by Chinese astronomers?



\- *They are moving to another stellar system.
Their home was sucked by a black hole.*

Reflections on Science & Faith

Astronomy shows us that the atoms that make up our bodies were cooked inside stars. Carbon was cooked in medium mass stars that swelled to become giant stars and shed their outer layers outward into space. Heavier elements such as the calcium in our bones, and the iron in our blood were the result of catastrophic supernova explosions prior to the formation of the Solar System. If stars did not die, we would not be here. The atoms that compose our bodies and our planet came from stardust. However, if we are stardust, then what makes us significant?

The Bible does not claim that our bodies are made of any special substance. In fact, it confirms that our bodies are made of dust.

"...for he knows how we are formed, he remembers that we are dust..." Psalm 103:14, NIV

However, we are not just dust. We are much more than the physical stuff that our bodies are made of. Just like the Mona Lisa painting is not just some paint on a canvas, the way we were knitted together makes us a wonderfully made work of art with God's signature!

"...for You created my inmost being;
you knit me together in my mother's womb.
I praise you because I am fearfully and wonderfully made..." Psalm 139:13-14, NIV

Furthermore, our identity is not limited to how wonderfully our bodies were made, but who we are in Him. His love, His calling, His care fills our lives with significance and a reflected splendor.