The Beauty in the Sky Above

Part 2 - Supernovae

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Introduction

A **supernova** (plural: *supernovae* or *supernovas*) is a stellar explosion. They are extremely luminous and cause a burst of radiation that often briefly outshines an entire galaxy before fading from view over several weeks or months. During this short interval, a supernova can radiate as much energy as the Sun could emit over its life span. The explosion expels much or all of a star's material at a velocity of up to a tenth the speed of light, driving a shock wave into the surrounding interstellar medium. This shock wave sweeps up an expanding shell of gas and dust called a supernova remnant.

Several types of supernovae exist that may be triggered in one of two ways, involving either turning off or suddenly turning on the production of energy through nuclear fusion. After the core of an aging massive star ceases to generate energy from nuclear fusion, it may undergo sudden gravitational collapse into a neutron star or black hole, releasing gravitational potential energy that heats and expels the star's outer layers. Alternatively, a white dwarf star may accumulate sufficient material from a stellar companion (usually through accretion, rarely via a merger) to raise its core temperature enough to ignite carbon fusion, at which point it undergoes runaway nuclear fusion, completely disrupting it. Stellar cores whose furnaces have permanently gone out collapse when their masses exceed the Chandrasekhar limit, while accreting white dwarfs ignite as they approach this limit (roughly 1.38 times the mass of the Sun). White dwarfs are also subject to a different, much smaller type of thermonuclear explosion fuelled by hydrogen on their surfaces called a nova. Solitary stars with a mass below approximately 9 solar masses, such as the Sun itself, evolve into white dwarfs without ever becoming supernovae.

On average, supernovae occur about once every 50 years in a galaxy the size of the Milky Way and play a significant role in enriching the interstellar medium with heavy elements. Furthermore, the expanding shock waves from supernova explosions can trigger the formation of new stars.

Nova (plural *novae*) means "new" in Latin, referring to what appears to be a very bright new star shining in the celestial sphere; the prefix "super-" distinguishes supernovae from ordinary novae, which also involve a star increasing in brightness, though to a lesser extent and through a different mechanism.

Observation History

The earliest recorded supernova, SN 185, was viewed by Chinese astronomers in 185 CE. The brightest recorded supernova was the SN 1006, which was described in detail by Chinese and Arab astronomers. The widely observed supernova SN 1054 produced the Crab Nebula. Supernovae SN 1572 and SN 1604, the last to be observed with the naked eye in the Milky Way galaxy, had notable effects on the development of astronomy in Europe because they were used to argue against the Aristotelian idea that the universe beyond the Moon and planets was immutable.

The true nature of the supernova remained obscure for some time. Observers slowly came to recognize a class of stars that undergo long-term periodic fluctuations in luminosity. Since the development of the telescope, the field of supernova discovery has enlarged to other galaxies, starting with the 1885 observation of supernova S Andromedae in the Andromeda galaxy.

Both John Russell Hind in 1848 and Norman Pogson in 1863 had charted stars that underwent sudden changes in brightness. However these received little attention from the astronomical community. In 1866, however, William Higgins made the first spectroscopic observations of a nova, discovering lines of hydrogen in the unusual spectrum of the recurrent nova T Coronae Borealis. Higgins proposed a cataclysmic explosion as the underlying mechanism, and his efforts drew interest from other astronomers.

In 1885, a nova-like outburst was observed in the direction of the Andromeda galaxy by Ernst Hartwig in Estonia. S Andromedae increased to 6th magnitude, outshining the entire nucleus of the galaxy, then faded in a manner much like a nova. However, in 1917, George W. Ritchey measured the distance to the Andromeda galaxy and discovered it lay much further than had previously been thought. This meant that S Andromedae, which did not just lie along the line of sight to the galaxy but had actually resided in the nucleus, released a much greater amount of energy than was typical for a nova.

Early work on this new category of nova was performed during the 1930s by Walter Baade and Fritz Zwicky at Mount Wilson Observatory. They identified S Andromedae, what they considered a typical supernova, as an explosive event that released radiation approximately equal to the Sun's total energy output for 10^7 years. They decided to call this new class of cataclysmic variables super-novae, and postulated that the energy was generated by the gravitational collapse of ordinary stars into neutron stars.

Although supernova are relatively rare events, occurring on average about once a century in the Milky Way, observations of distant galaxies allowed supernovae to be discovered and examined more frequently. The first spectral classification of these distant supernova was performed by Rudolph Minkowski in 1941. He categorized them into two types, based on whether or not lines of the element hydrogen appeared in the supernova spectrum. Zwicky later proposed additional types III, IV and V, although these are no longer used and now appear to be associated with single peculiar supernova types. Further sub-division of the spectra categories resulted in the modern supernova classification scheme.

In the aftermath of the Second World War, Fred Hoyle worked on the problem of how the various observed elements in the universe were produced. In 1946 he proposed that a massive star could generate the necessary thermonuclear reactions, and the nuclear reactions of heavy elements were responsible for the removal of energy necessary for a gravitational collapse to occur. The collapsing star became rotationally unstable, and produced an explosive expulsion of elements that were distributed into interstellar space. The concept that rapid nuclear fusion was the source of energy for a supernova explosion was developed by Hoyle and William Fowler during the 1960s.

Some of the most distant supernovae recently observed appeared dimmer than expected. This has provided evidence that the expansion of the universe may be accelerating.

Discovery

Because supernovae are relatively rare events, occurring about once every 50 years in a galaxy like the Milky Way, many galaxies must be monitored regularly in order to obtain a good sample of supernovae to study.

Supernovae in other galaxies cannot be predicted with any meaningful accuracy. Normally, when they are discovered, they are already in progress. Most scientific interest in supernovae—as standard candles for measuring distance, for example—require an observation of their peak luminosity. It is therefore important to discover them well before they reach their maximum. Amateur astronomers, who greatly outnumber professional astronomers, have played an important role in finding supernovae, typically by looking at some of the closer galaxies through an optical telescope and comparing them to earlier photographs.

Towards the end of the 20th century, astronomers increasingly turned to computer-controlled telescopes and CCDs for hunting supernovae. While such systems are popular with amateurs, there are also larger installations like the Katzman Automatic Imaging Telescope. Recently, the Supernova Early Warning System (SNEWS) project has also begun using a network of neutrino detectors to give early warning of a supernova in the Milky Way galaxy. A neutrino is a particle that is produced in great quantities by a supernova explosion, and it is not absorbed by the interstellar gas and dust of the galactic disk.

Supernova searches fall into two classes: those focused on relatively nearby events and those looking for explosions farther away. Because of the expansion of the universe, the distance to a remote object with a known emission spectrum can be estimated by measuring its Doppler shift (or redshift); on average, more distant objects recede with greater velocity than those nearby, and so have a higher redshift. Thus the search is split between high redshift and low redshift, with the boundary falling around a redshift range of $z = 0.1–0.3$, where z is a dimensionless measure of the spectrum's frequency shift.

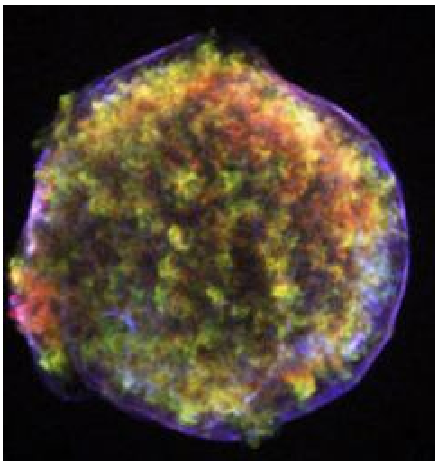
High redshift searches for supernovae usually involve the observation of supernova light curves. These are useful for standard or calibrated candles to generate Hubble diagrams and make cosmological predictions. At low redshift, supernova spectroscopy is more practical than at high redshift, and this is used to study the physics and environments of supernovae. Low redshift observations also anchor the low distance end of the Hubble curve, which is a plot of distance versus redshift for visible galaxies.

Classification

As part of the attempt to understand supernovae, astronomers have classified them according to the absorption lines of different chemical elements that appear in their spectra. The first element for a division is the presence or absence of a line caused by hydrogen. If a supernova's spectrum contains a line of hydrogen (known as the Balmer series in the visual portion of the spectrum) it is classified *Type II*; otherwise it is *Type I*. Among those types, there are subdivisions according to the presence of lines from other elements and the shape of the light curve (a graph of the supernova's apparent magnitude versus time).

Current models

Type Ia



A *Type Ia supernova* is a sub-category of cataclysmic variable stars that results from the violent explosion of a white dwarf star. A white dwarf is the remnant of a star that has completed its normal life cycle and has ceased nuclear fusion. One model for the formation of this category of supernova is a close binary star system. The progenitor binary system consists of main sequence stars, with the primary possessing more mass than the secondary. Being greater in mass, the primary is the first of the pair to evolve onto the asymptotic giant branch, where the star's envelope expands considerably.

If the two stars share a common envelope then the system can lose significant amounts of mass, reducing the angular momentum, orbital radius and period. After the primary has degenerated into a white dwarf, the secondary star later evolves in a red giant and the stage is set for mass accretion onto the primary. During this final shared-envelope phase, the two stars spiral in closer together as angular momentum is lost. The resulting orbit can have a period as brief as a few hours. If the accretion continues long enough, the white dwarf may eventually approach the Chandrasekhar limit.

Physically, white dwarfs with a low rate of rotation are limited to masses that are below the Chandrasekhar limit of about 1.38 solar masses. This is the maximum mass that can be supported by electron degeneracy pressure. Beyond this limit the white dwarf would begin to collapse. If a white dwarf gradually accretes mass from a binary companion, its core is believed to reach the ignition temperature for carbon fusion as it approaches the limit. If the white dwarf merges with another star (a very rare event), it will momentarily exceed the limit and begin to collapse, again raising its temperature past the nuclear fusion ignition point. Within a few seconds of initiation of nuclear fusion, a substantial fraction of the matter in the white dwarf undergoes a runaway reaction, releasing enough energy (1-2 × 10^{44} joules) to unbind the star in a supernova explosion.

This category of supernovae produces consistent peak luminosity because of the uniform mass of white dwarfs that explode via the accretion mechanism. The stability of this value allows these explosions to be used as standard candles to measure the distance to their host galaxies because the visual magnitude of the supernovae depends primarily on the distance.

Type Ib and Ic

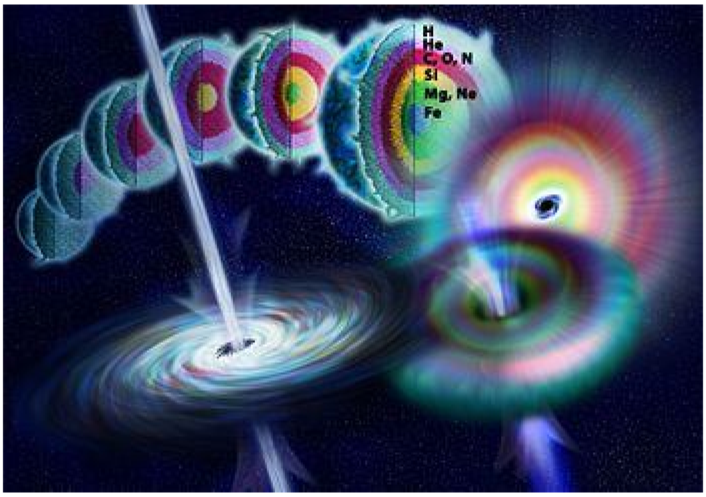
Supernovae of the general category *Type I* are classified based on the lack of hydrogen lines in their spectra, as compared to a *Type II* supernovae which display lines of hydrogen. *Type Ib* is distinguished from *Type Ia* due to the lack of an absorption line of singly-ionized silicon at a wavelength of 635.5 nanometres. As a *Type Ib* supernova ages, it also displays stronger spectral features of helium than *Type Ia* supernovae. Eventually the *Type Ib* spectrum contains lines from elements such as oxygen, calcium and magnesium. In contrast, *Type Ia* spectra become dominated by lines of iron.

Type Ib supernovae are believed to originate in an event nearly identical to a *Type II* supernova, in which a massive star suffers collapse at the core. However the progenitor star of a *Type Ib* supernova has expelled its outer shell of hydrogen prior to explosion. Instead the outer shells of these stars consists primarily of helium, resulting in a spectrum more like a *Type Ia* supernova. *Type Ic* supernovae are distinguished from *Type Ib* in that the former also lacks lines of helium.

Prior to becoming a supernova, an evolved massive star is organized in the manner of an onion, with layers of different elements undergoing fusion. The outermost layer consists of hydrogen, followed by helium, carbon, oxygen, and so forth. Thus when the outer envelope of hydrogen is shed, this exposes the next layer that consists primarily of helium (mixed with other elements). This can occur when a very hot, massive star reaches a point in its evolution when significant mass loss is occurring from its stellar wind. Highly massive stars (with 25 or more times the mass of the Sun) can lose up to 10^{-5} Solar masses each year (or the equivalent of a solar mass every 100,000 years.)

The progenitors of *Types Ib and Ic* have lost most of their outer envelopes due to strong stellar winds or else from interaction with a close companion of about 3–4 solar masses. *Type Ib* supernovae are thought to be the result of the collapse of a massive Wolf-Rayet star. There is some evidence that a few percent of the *Type Ic* supernovae may be the progenitors of gamma ray bursts (GRB), though it is also believed that any hydrogen-stripped *Type Ib or Ic* supernova could be a GRB, dependent upon the geometry of the explosion.

As they are formed from rare, very massive stars, the rate of *Type Ib and Ic* supernovae occurrence is much lower than the corresponding rate for *Type II* supernovae. They normally occur in regions of new star formation, and have never been observed in an elliptical galaxy. Because they share a similar operating mechanism, *Type Ib, Ic* and the various *Type II* supernovae are collectively called core-collapse supernovae.



Drawing of a massive star collapsing to form a black hole. Energy released as jets along the axis of rotation forms a gamma ray burst.

Type II

Stars with at least nine solar masses of material evolve in a complex fashion. In the core of the star, hydrogen is fused into helium and the thermal energy released creates an outward pressure, which maintains the core in hydrostatic equilibrium and prevents collapse.

When the core's supply of hydrogen is exhausted, this outward pressure is no longer created. The core begins to collapse, causing a rise in temperature and pressure which becomes great enough to ignite the helium and start a helium-to-carbon fusion cycle, creating sufficient outward pressure to halt the collapse. The core expands and cools slightly, with a hydrogen-fusion outer layer, and a hotter, higher pressure, helium-fusion center. (Other elements such as magnesium, sulfur and calcium are also created and in some cases burned in these further reactions.)

This process repeats several times, and each time the core collapses and the collapse is halted by the ignition of a further process involving more massive nuclei and higher temperatures and pressures. Each layer is prevented from collapse by the heat and outward pressure of the fusion process in the next layer inward; each layer also burns hotter and quicker than the previous one – the final burn of silicon to nickel consumes its fuel in around one day, or a few days. The star becomes layered like an onion, with the burning of more easily fused elements occurring in larger shells.

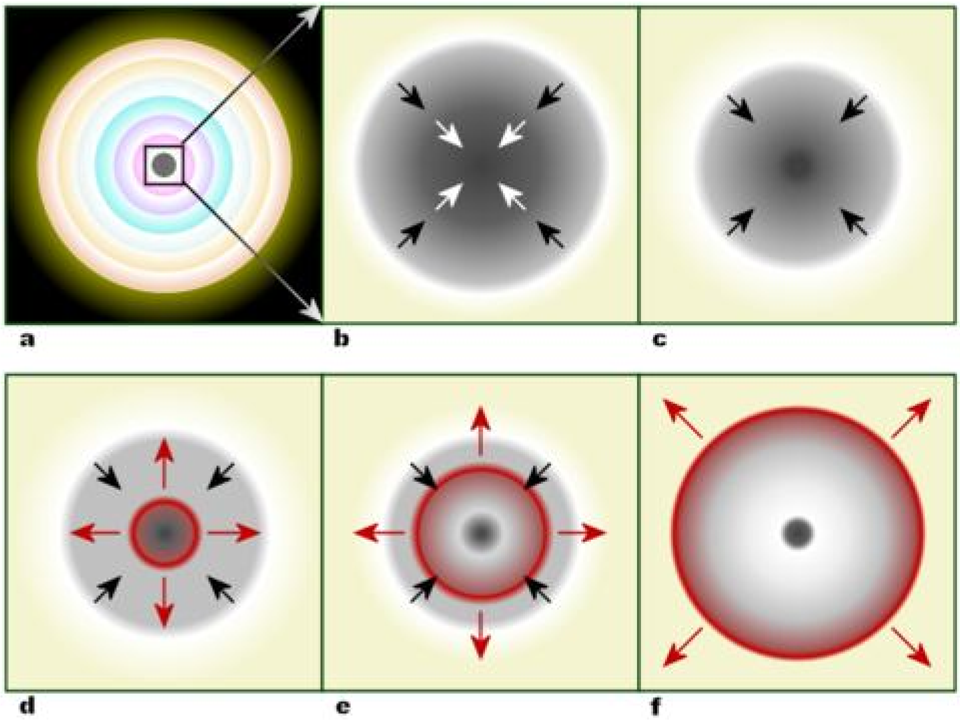
In the later stages, increasingly heavier elements undergo nuclear fusion, and the binding energy of the relevant nuclei increases. Fusion produces progressively lower levels of energy, and also at higher core energies photodisintegration and electron capture occur which cause energy loss in the core and a general acceleration of the fusion processes to maintain equilibrium. This escalation culminates with the production of nickel-56, which is unable to produce energy through fusion (but does produce iron-56 through radioactive decay). As a result, a nickel-iron core builds up that cannot produce any further outward pressure on a scale needed to support the rest of the structure. It can only support the overlaying mass of the star through the degeneracy pressure of electrons in the core. If the star is sufficiently large, then the iron-nickel core will eventually exceed the Chandrasekhar limit (1.38 solar masses), at which point this mechanism catastrophically fails. The forces holding atomic nuclei apart in the innermost layer of the core suddenly give way, the core implodes due to its own mass, and no further fusion process can ignite or prevent collapse this time.

Core Collapses

The core collapses in on itself with velocities reaching 70,000 km/s (0.23c), resulting in a rapid increase in temperature and density. The energy loss processes operating in the core cease to be in equilibrium. Through photodisintegration, gamma rays decompose iron into helium nuclei and free neutrons, absorbing energy, whilst electrons and protons merge via electron capture, producing neutrons and electron neutrinos which escape.

In a typical Type II supernova, the newly formed neutron core has an initial temperature of about 100 billion kelvin (100 GK); 6000 times the temperature of the sun's core. Much of this thermal energy must be shed for a stable neutron star to form (otherwise the neutrons would "boil away"), and this is accomplished by a further release of neutrinos. These 'thermal' neutrinos form as neutrino-antineutrino pairs of all flavors, and total several times the number of electron-capture neutrinos. About 10^{46} joules of gravitational energy—about 10% of the star's rest mass—is converted into a ten-second burst of neutrinos; the main output of the event. These carry away energy from the core and accelerate the collapse, while some neutrinos may be later absorbed by the star's outer layers to provide energy to the supernova explosion.

The inner core eventually reaches typically 30 km diameter, and a density comparable to that of an atomic nucleus, and further collapse is abruptly stopped by strong force interactions and by degeneracy pressure of neutrons. The infalling matter, suddenly halted, rebounds, producing a shock wave that propagates outward. Computer simulations indicate that this expanding shock does not directly cause the supernova explosion; rather, it stalls within milliseconds in the outer core as energy is lost through the dissociation of heavy elements, and a process that is not clearly understood is necessary to allow the outer layers of the core to reabsorb around 10^{44} joules (1 foe) of energy, producing the visible explosion. Current research focuses upon a combination of neutrino reheating, rotational and magnetic effects as the basis for this process.



Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming an iron core (b) that reaches Chandrasekhar-mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

When the progenitor star is below about 20 solar masses (depending on the strength of the explosion and the amount of material that falls back), the degenerate remnant of a core collapse is a neutron star. Above this mass the remnant collapses to form a black hole. (This type of collapse is one of many candidate explanations for gamma ray bursts - producing a large burst of gamma rays through a still theoretical hypernova explosion.) The theoretical limiting mass for this type of core collapse scenario was estimated around 40–50 solar masses.

Pair-instability Supernovea

Above 50 solar masses, stars were believed to collapse directly into a black hole without forming a supernova explosion, although uncertainties in models of supernova collapse make accurate calculation of these limits difficult. In fact recent evidence has shown stars in the range of about 140–250 solar masses, with a relatively low proportion of elements more massive than helium, may be capable of forming pair-instability supernovae without leaving behind a black hole remnant. This rare type of supernova is formed by an alternate mechanism (partially analogous to that of Type Ia explosions) that does not require an iron core.

A *pair instability supernova* occurs when pair production, the production of free electrons and positrons in the collision between atomic nuclei and energetic gamma rays, reduces thermal pressure inside a supermassive star's core. This pressure drop leads to a partial collapse, then greatly accelerated burning in a runaway thermonuclear explosion which blows the star completely apart without leaving a black hole remnant behind.

Pair instability supernovae can only happen in stars with a mass range from around 130 to 250 solar masses and moderate metallicity (low abundance of elements other than hydrogen and helium). The recently observed object SN 2006gy is hypothesized to have been a pair instability supernova.

As described above, the hotter a star's core becomes, the higher energy the gamma rays it produces. Once these reach gamma energies where pair production starts to become the dominant mechanism in gamma ray capture in the gas, then the distance that gamma rays travel in the gas starts to decrease instead of increasing. This decrease in the distance that gamma rays travel is an instability, and causes a feedback loop: as gamma travel distance decreases, the temperature at the core increases, and this increases the gamma energy and further decreases the distance that gammas can travel.

Asymmetry

A long-standing puzzle surrounding supernovae has been a need to explain why the compact object remaining after the explosion is given a large velocity away from the core. (Neutron stars are observed, as pulsars, to have high velocities; black holes presumably do as well, but are far harder to observe in isolation.) This kick can be substantial, propelling an object of more than a solar mass at a velocity of 500 km/s or greater. This displacement is believed to be caused by an asymmetry in the explosion, but the mechanism by which this momentum is transferred to the compact object has remained a puzzle. Some explanations for this kick include convection in the collapsing star and jet production during neutron star formation.

One explanation for the asymmetry in the explosion is large-scale convection above the core. The convection can create variations in the local abundances of elements, resulting in uneven nuclear burning during the collapse, bounce and resulting explosion. Another explanation is that accretion of gas onto the central neutron star can create a disk that drives highly directional jets, propelling matter at a high velocity out of the star, and driving transverse shocks that completely disrupt the star. These jets might play a crucial role in the resulting supernova explosion. (A similar model is now favoured for explaining long gamma ray bursts.)

Initial asymmetries have also been confirmed in *Type Ia* supernova explosions through observation. This result may mean that the initial luminosity of this type of supernova may depend on the viewing angle. However, the explosion becomes more symmetrical with the passage of time. Early asymmetries are detectable by measuring the polarization of the emitted light.

Vis-à-vis Core Collapse

Because they have a similar functional model, *Types Ib, Ic* and various *Types II* supernovae are collectively called Core Collapse supernovae. A fundamental difference between *Type Ia* and Core Collapse supernovae is the source of energy for the radiation emitted near the peak of the light curve. The progenitors of Core Collapse supernovae are stars with extended envelopes that can attain a degree of transparency with a relatively small amount of expansion. Most of the energy powering the emission at peak light is derived from the shock wave that heats and ejects the envelope.

The progenitors of *Type Ia* supernovae, on the other hand, are compact objects, much smaller (but more massive) than the Sun, that must expand (and therefore cool) enormously before becoming transparent. Heat from the explosion is dissipated in the expansion and is not available for light production. The radiation emitted by Type Ia supernovae is thus entirely attributable to the decay of radionuclides produced in the explosion; principally nickel-56 (with a half-life of 6.1 days) and its daughter cobalt-56 (with a half-life of 77 days). Gamma rays emitted during this nuclear decay are absorbed by the ejected material, heating it to incandescence.

As the material ejected by a Core Collapse supernova expands and cools, radioactive decay eventually takes over as the main energy source for light emission in this case also. A bright Type Ia supernova may expel 0.5–1.0 solar masses of nickel-56, while a Core Collapse supernova probably ejects closer to 0.1 solar mass of nickel-56.

Interstellar Impact

Source of heavy elements

Supernovae are a key source of elements heavier than oxygen. These elements are produced by nuclear fusion (for iron-56 and lighter elements), and by nucleosynthesis during the supernova explosion for elements heavier than iron. Supernova are the most likely, although not undisputed, candidate sites for the r-process, which is a rapid form of nucleosynthesis that occurs under conditions of high temperature and high density of neutrons. The reactions produce highly unstable nuclei that are rich in neutrons. These forms are unstable and rapidly beta decay into more stable forms.

The r-process reaction, which is likely to occur in *type II* supernovae, produces about half of all the element abundance beyond iron, including plutonium, uranium and californium. The only other major competing process for producing elements heavier than iron is the s-process in large, old red giant stars, which produces these elements much more slowly, and which cannot produce elements heavier than lead.

Role in Stellar evolution

The remnant of a supernova explosion consists of a compact object and a rapidly expanding shock wave of material. This cloud of material sweeps up the surrounding interstellar medium during a free expansion phase, which can last for up to two centuries. The wave then gradually undergoes a period of adiabatic expansion, and will slowly cool and mix with the surrounding interstellar medium over a period of about 10,000 years.

In standard astronomy, the Big Bang produced hydrogen, helium, and traces of lithium, while all heavier elements are synthesized in stars and supernovae. Supernovae tend to enrich the surrounding interstellar medium with *metal*s, which for astronomers means all of the elements other than hydrogen and helium and is a different definition than that used in chemistry.

Supernova remnant N 63A lies within a clumpy region of gas and dust in the Large Magellanic Cloud.

These injected elements ultimately enrich the molecular clouds that are the sites of star formation. Thus, each stellar generation has a slightly different composition, going from an almost pure mixture of hydrogen and helium to a more metal-rich composition. Supernovae are the dominant mechanism for distributing these heavier elements, which are formed in a star during its period of nuclear fusion, throughout space. The different abundances of elements in the material that forms a star have important influences on the star's life, and may decisively influence the possibility of having planets orbiting it.

The kinetic energy of an expanding supernova remnant can trigger star formation due to compression of nearby, dense molecular clouds in space. The increase in turbulent pressure can also prevent star formation if the cloud is unable to lose the excess energy.

Evidence from daughter products of short-lived radioactive isotopes shows that a nearby supernova helped determine the composition of the Solar System 4.5 billion years ago, and may even have triggered the formation of this system. Supernova production of heavy elements over astronomic periods of time ultimately made the chemistry of life on Earth possible.

Impact on Earth

A *near-Earth supernova* is an explosion resulting from the death of a star that occurs close enough to the Earth (roughly fewer than 100 light-years away) to have noticeable effects on its biosphere. Gamma rays are responsible for most of the adverse effects a supernova can have on a living terrestrial planet. In Earth's case, gamma rays induce a chemical reaction in the upper atmosphere, converting molecular nitrogen into nitrogen oxides, depleting the ozone layer enough to expose the surface to harmful solar and cosmic radiation. The gamma ray burst from a nearby supernova explosion has been proposed as the cause of the end Ordovician extinction, which resulted in the death of nearly 60% of the oceanic life on Earth.

Speculation as to the effects of a nearby supernova on Earth often focuses on large stars as *Type II* supernova candidates. Several prominent stars within a few hundred light years from the Sun are candidates for becoming supernovae in as little as a millennium. One example is Betelgeuse, a red supergiant 427 light-years from Earth. Though spectacular, these "predictable" supernovae are thought to have little potential to affect Earth.

Recent estimates predict that a *Type II* supernova would have to be closer than eight parsecs (26 light-years) to destroy half of the Earth's ozone layer. Such estimates are mostly concerned with atmospheric modeling and considered only the known radiation flux from SN 1987A, a *Type II* supernova in the Large Magellanic Cloud. Estimates of the rate of supernova occurrence within 10 parsecs of the Earth vary from once every 100 million years to once every one to ten billion years.

Type Ia supernovae are thought to be potentially the most dangerous if they occur close enough to the Earth. Because *Type Ia* supernovae arise from dim, common white dwarf stars, it is likely that a supernova that could affect the Earth will occur unpredictably and take place in a star system that is not well studied. One theory suggests that a *Type Ia* supernova would have to be closer than a thousand parsecs (3300 light-years) to affect the Earth. The closest known candidate is IK Pegasi (see below).

In 1996, astronomers at the University of Illinois at Urbana-Champaign theorized that traces of past supernovae might be detectable on Earth in the form of metal isotope signatures in rock strata. Subsequently, iron-60 enrichment has been reported in deep-sea rock of the Pacific Ocean by researchers from the Technical University of Munich.

Possible milky-way candidates

Several large stars within the Milky Way have been suggested as possible supernovae within the next few thousand to hundred million years. These include Rho Cassiopeiae, Eta Carinae, RS Ophiuchi, the Kitt Peak Downes star KPD1930+2752, HD 179821, IRC+10420, VY Canis Majoris, Betelgeuse, Antares, and Spica. Many Wolf-Rayet stars, such as Gamma Velorum, WR 104, and those in the Quintuplet Cluster, are also considered possible precursor stars to a supernova explosion in the 'near' future.

The nearest supernova candidate is IK Pegasi (HR 8210), located at a distance of only 150 light-years. This closely-orbiting binary star system consists of a main sequence star and a white dwarf, separated by only 31 million km. The dwarf has an estimated mass equal to 1.15 times that of the Sun. It is thought that several million years will pass before the white dwarf can accrete the critical mass required to become a *Type Ia* supernova.