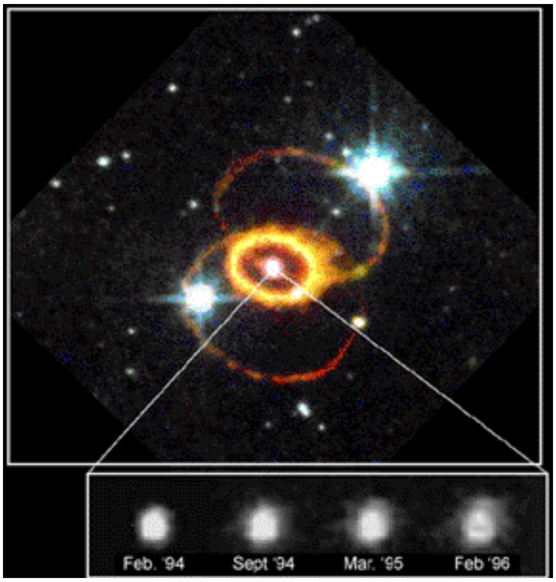
Supernova

The catastrophic, explosive death of a star, accompanied by the sudden, transient brightening of the star to an optical luminosity comparable to that of an entire galaxy.

Illustration The region of the Tarantula Nebula in the Large Magellanic Cloud before (left) and with (right) Supernova 1987A. (Anglo−Australian Telescope Board; photograph by David Malin)

Illustration The region of the Tarantula Nebula in the Large Magellanic Cloud with Supernova 1987A. (Anglo−Australian Telescope Board; photograph by David Malin)

Illustration Hubble Space Telescope image of Supernova 1987A and its vicinity, showing ring structures. Three rings are visible; their origin is uncertain. Panel at bottom shows evolution of the debris from the supernova from February 1994 to February 1996.



A supernova shines typically for several weeks to several months with a luminosity between 2 10^8 and 5 10^9 times that of the Sun, then gradually fades away. Each explosion ejects from one to several tens of solar masses at speeds ranging from thousands to tens of thousands of kilometers per second. The total kinetic energy, 10^{44} joules (2.5 10^{28} megatons of high explosive), is about 100 times the total light output, making supernovae some of the highest−energy explosions in the universe. Unlike its fainter relative, the nova, a supernova does not recur for the same object. See also: Nova

Supernovas may be grouped according to either their observational characteristics or their explosion mechanism. Basically, type I supernovae have no hydrogen in their spectrum; type II supernovae do. Two mechanisms are involved: thermonuclear explosion in white dwarfs and gravitational collapse in massive stars. Type I supernovae of different subclasses can occur by either mechanism, but it is thought that most type II supernovae are powered by gravitational collapse. Type II supernovae eject more mass than type I but, on the average, at lower speeds. The energy of the matter ejected in both events is, by coincidence, the same.

Observational characteristics

For the observer, the various classes of supernovae are distinguishable upon the basis of their optical spectra, light curves, and, to a lesser extent, their radio emission and environment. Type II supernovae display prominent lines of hydrogen in their spectra (Fig. 1). Their light curves (Fig. 2) are irregular, ranging from those with enduring emission at a nearly constant rate for several months (type II−P) to those that begin to fade almost immediately in a quasi−linear way (type II−L). Type II supernovae are found in spiral and irregular galaxies (but never in ellipticals) and, within those galaxies, are associated with the spiral arms and other regions of active star formation. They are frequently strong radio sources. In two cases, SN 1987A and SN 1993J, the progenitor star of the supernova was observed before the explosion and was clearly massive, roughly 20 times that of the Sun. Thus the case is sound that type II supernovae come from massive stars, still in possession of their hydrogenic surface layers, that die neither far from nor long after their birth. The radio emission reflects the collision of the supernova with the recent mass loss of the presupernova star. See also: Astronomical spectroscopy; Galaxy, external; Light curves; Radio astronomy

Fig. 1 Optical spectra of four supernovae, all about 1 week old, are shown, with types indicated in parentheses. The Si II line is used to identify type Ia spectra. (*Alex Fiippenko*)

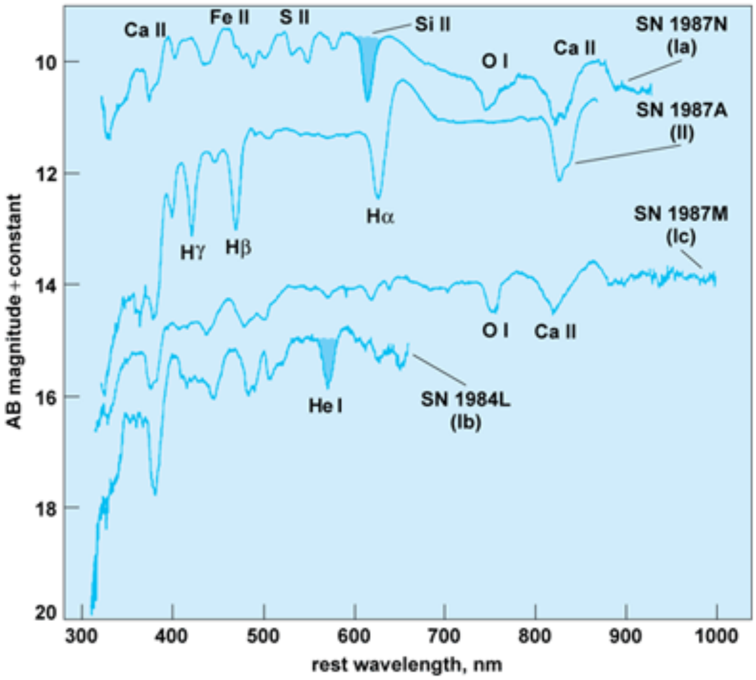
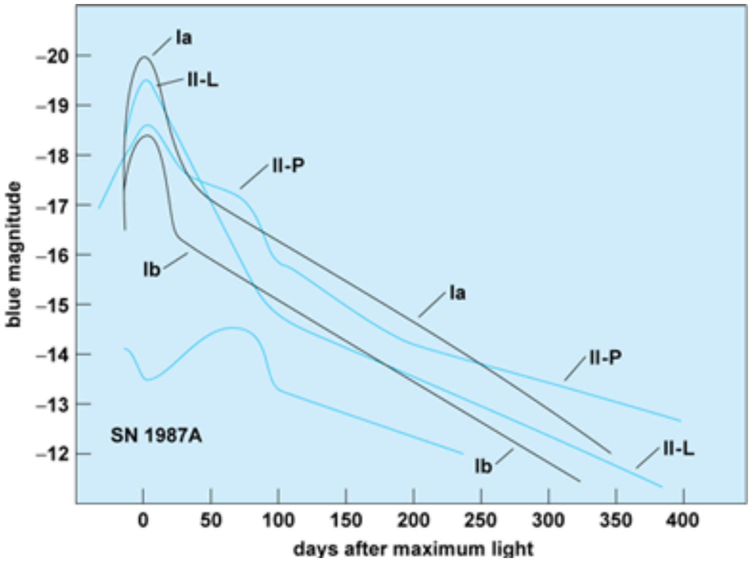


Fig. 2 Schematic light curves for supernovae of four types and for SN 1987A. The absolute values of magnitude are quite approximate as each curve depends upon uncertain distances and there can be considerable variation within each subclass (less in type Ia than in others). Each magnitude is a factor of 2.51 in brightness. (*Craig Wheeler*)



Type Ia supernovae, on the other hand, occur in all types of galaxies, show no strong preference for star−forming regions, and have more regular light curves than type II, rising smoothly to maximum about 2 weeks after the explosion and declining quasi−exponentially thereafter. They are not radio sources. Their spectrum at peak light shows strong lines of the intermediate−mass elements silicon, sulfur, and calcium, as well as iron. The late−time spectrum is dominated by broad emission lines of iron and cobalt. Line widths imply velocities from 7000 to 20,000 km/s (4000 to 12,000 mi/s), with the highest velocities seen early on. All these facts are consistent with an old, low−mass population of progenitor stars, void of a hydrogen envelope. Exploding white dwarfs fit these characteristics. See also: White dwarf star

Like type II, type Ib supernovae seem to be associated with star−forming regions and are also frequently strong radio sources. Unlike type Ia, the spectrum at peak light lacks the strong line feature at 615.0 nanometers due to ionized silicon. Type Ib supernovae are approximately a factor of 4 fainter than type Ia, and their light curve is a little broader and slower to decline. At late times, the spectrum displays, in addition to iron emission, broad lines of oxygen and calcium. All these observational facts are consistent with origin from massive stars devoid of hydrogen.

Type Ic supernovae resemble type Ib closely but have a weak or absent line of neutral helium at 587.6 nm. This may indicate either a deficiency of helium in the explosion or a lack of sufficiently energetic nonthermal radiation to excite the line.

During the last thousand years, there have been approximately seven supernovae visible to the unaided eye, in 1006, 1054, 1181, 1408, 1572, 1604, and 1987. SN 1006 may have been as bright as the quarter moon. The first six of these occurred in the Earth's vicinity of the Milky Way Galaxy. But the last, and only, naked−eye supernova since the invention of modern instrumentation occurred in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way about 160,000 light−years away. Many more supernovae are discovered in other, more distant galaxies at a rate of about 150 per year. The total rate in the Milky Way Galaxy is uncertain because most are obscured by dust. But various arguments based upon the supernova rate in other galaxies, the birth rate of pulsars, nucleosynthesis, and the historical observations suggest that about two type II supernovae per century and one type Ia every other century occur in the entire Milky Way Galaxy. See also: Magellanic Clouds; Milky Way Galaxy

Theory of type Ia supernovae

Type Ia supernovae may be regarded as nature's largest thermonuclear bombs. They occur when an accreting white dwarf, composed of carbon and oxygen, grows to a mass 1.38 times that of the Sun, almost the critical mass that can be supported by electron degeneracy pressure, and ignites carbon fusion near its center. The accreted matter must be provided by a nearby companion star, and the accretion rate must be moderately high, about 10^{-7} solar mass per year. For lower accretion rates, the same kind of system would have an unstable hydrogen or helium burning shell and make recurrent novae, not supernovae. Ignition occurs when carbon fusion at the center releases energy faster than neutrinos can carry it away, that is, at a central temperature of about 3 10^8 K and at density 2 10^{12} kg/m^3. Because the pressure at these extreme conditions is insensitive to the temperature, a nuclear runaway occurs. Fusion releases energy, which raises the temperature, which makes fusion go faster, but the gas cannot expand and cool. Eventually, when the temperature reaches 9 10^9 K, the material finally expands, but by then fusion has proceeded all the way to completiona state of thermal nuclear equilibrium. See also: Binary star; Cataclysmic variable; Nuclear fission; Neutrino; Thermonuclear reaction

The nuclear runaway begins near the middle of the star, but spreads in about 1 second through the rest of the star as a nuclear powered flame moves along, turning carbon and oxygen into iron−group elements (roughly 0.5−1 solar mass). In the outer parts of the white dwarf, where the density is less, the temperature of the flame is lower, and intermediate−mass elements prominent in the spectrumsilicon, sulfur, and calciumare also produced (roughly 0.2−0.3 solar mass). The energy released by all this nuclear burning is more than enough to completely blow the white dwarf apart with high velocity. Nothing remainsno neutron star, no black hole, and no burst of neutrino emission. Unlike type II supernovae, no progenitor of a subsequent type Ia supernova has ever been observed, and that makes the exact nature of the accreting binary uncertain. Even more uncertain are the details of how the fusion flame moves through the white dwarf. Its speed is amplified by instability and by turbulence in a way that is difficult to calculate from first principles.

As the explosive debris expands from a few thousand to a few billion kilometers, as is necessary before light can begin to diffuse out, the internal energy of the original explosion is cooled to the point that a type Ia supernova would be quite invisible were it not for a new source of energyradioactive decay. Carbon and oxygen have equal numbers of neutrons and protons. When they burn to completion, they produce the nucleus with the greatest binding per nucleon. This is not ^{56}Fe but ^{56}Ni, which has a closed shell of both neutrons and protons ($Z = N = 28$). The decay of ^{56}Ni first to ^{56}Co ($_{1/2}$ = 6.1 days), and then of ^{56}Co to ^{56}Fe ($_{1/2}$ = 77.1 days), produces enough energy to power the entire optical display of about 10^{42} joules. Because each supernova starts from a white dwarf star of the same mass and makes a similar amount of ^{56}Ni, the light curves are very regular, rising to a peak as expansion allows the energy from ^{56}Ni decay to diffuse out, and then declining as the slower ^{56}Co decay powers the light output and gamma rays begin to emerge from the expanding debris. The peak luminosity, about 1.5 10^{36} watts, is just a measure of the mass of ^{56}Ni made in the explosion. See also: Radioactivity

Theory of type II supernovae

A typical type II supernova results from a star somewhat over 8 solar masses, on the main sequence, that spends its last years as a red supergiant burning progressively heavier fuels in its center (see table). The radius of the star, after hydrogen has burned and the star is part way through helium burning, is roughly 500 solar radii, and its luminosity as death nears is already prodigious, about 100,000 times that of the Sun. Each burning stage is shorter than the previous one because of losses to neutrinos produced in the high−temperature core by electron−positron pair annihilation. Finally, a last stage of burning turns silicon and sulfur into a ball of roughly 1.4 solar masses of iron. Once iron has been produced, no more nuclear energy is available. See also: Supergiant star

Fuel	Main product	Secondary products	Temperature, 10^9 K	Duration, years
H	He	N	0.02	10^7
He	C, O	^{18}O, ^{22}Ne, s−process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3.0
O	Si, S	Cl, Ar, K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02

A combination of instabilities now leads to the implosion of the iron core to a neutron star. Electron capture occurs as electrons are squeezed into nuclei of iron−group atoms making heavier isotopes with more neutrons than protons. This reduces the electron pressure responsible for supporting the iron core. Photodisintegration also occurs as the intense radiation partly tears apart iron nuclei into helium and lighter elements. Both instabilities accelerate the collapse of the ball of iron ash until it is falling with a speed one−fourth that of light. When the density at the center reaches several times that of the atomic nucleus ($2.7\ \ 10^{17}$ kg/m^3), the collapse halts and briefly springs back owing to the short−range repulsive component of the nuclear force. But the energy of this bounce is soon dissipated by neutrinos and further photodisintegration, and a hot young neutron star remains which, over the next few seconds, radiates away its heat and binding energy as neutrinos. See also: Strong nuclear interactions

The energy output in these neutrinos is enormous, about $3\ \ 10^{46}$ joules or 15% of the rest mass of the Sun converted to energy, rivaling the luminosity of the rest of the observable universe in light. Calculations show that a small fraction of these neutrinos, about 0.3%, are absorbed in reactions with neutrons and protons in the regions just outside the neutron star and deposit their energy. Even this small amount of energy is much greater than the gravitational binding of the remaining part of the star external to the newly formed neutron star. A bubble of radiation is inflated by the neutrino energy deposition, the outer boundary of which expands supersonically, driving a shock wave through the rest of the star and ejecting it with high velocity. The main energy of the explosion, though, is carried away as neutrinos. This general picture was confirmed when a bright neutrino burst of the predicted energy and duration was detected February 23, 1987, from the Large Magellanic Cloud in conjunction with SN 1987A. See also: Neutrino astronomy; Shock wave

The optical display of the supernova begins as the shock wave created at its center erupts through the surface of the star about a day later. A brief ultraviolet transient is emitted lasting a few thousand seconds, followed typically by a long plateau of emission at near−constant luminosity. It is while on this plateau that the supernova is generally discovered. Light is emitted as the expanding hydrogen envelope releases the energy trapped there when the shock went through. Finally, after a few months, the shock energy has been completely radiated away and a final stage of emission occurs, powered by the nuclear fallout from the explosion, chiefly the decay of radioactive ^{56}Co to ^{56}Fe.

A variation on this same theme makes type Ib and Ic supernovae except that those stars have lost their hydrogen envelopes, either to companion stars or to a stellar wind. The light curve is thus entirely a result of radioactive decay just as in type Ia. All these supernovae, however, since they are powered by gravitational collapse, must leave behind a tightly bound remnant, either a neutron star or, should the mass of the neutron star grow too large during the explosion, a black hole. See also: Black hole; Gravitational collapse; Neutron star

Nucleosynthesis

Supernovae are major element factories, responsible for producing most of the elements in nature heavier than nitrogen. The largest yields are of the more abundant elements, including oxygen, silicon, magnesium, neon, iron, and a portion of carbon, but dozens of other elements are also made. Iron is produced, chiefly as a product of radioactive ^{56}Ni, in comparable amounts by both type I and type II supernovae; the former make more per event but occur less frequently. Oxygen is definitely a product of type II supernovae, as are most of the other elements between oxygen ($Z = 8$) and yttrium ($Z = 28$). Type II supernovae may also be the site of the rapid neutron capture process (r−process) responsible for about half of all the elements heavier than zinc. The other elements not made in supernovae come either from the big bang (hydrogen and helium) or from the evolution of lower−mass stars. See also: Nucleosynthesis

Type Ia cosmological applications

Because of their brightness and the regularity of their light curves, type Ia supernovae have long been used as standard candles to survey cosmological distances. More recently it has been realized that the relatively small variation that occurs in the peak brilliance of such supernovae may be correlated with their decline rates. That is, brighter supernovae decline more slowly. Use of this so−called Phillips relation allows even greater precision in distance determination. Just why this empirical relation exists is not well understood, but it may reflect the fact that a higher luminosity requires the presence of more radioactive ^{56}Ni. The larger energy input from radioactive decay also keeps the expanding supernova hotter and may increase its opacity, causing a delay in the escape of trapped radiation.

Using type Ia supernovae in this fashion gives a current value for Hubble's constant of around 60−70 km s^{-1} Mpc^{-1} but also reveals a surprising result. Two independent analyses show that the expansion rate of the universe is not slowing as might be expected long after the big bang, but is actually accelerating. The pull of gravity can only cause deceleration, so the acceleration is attributed to an invisible form of dark energy that enters into the cosmological equations as a repulsive term. This is very similar to the cosmological constant introduced into these same equations by Albert Einstein in 1917 to allow the existence of a static universe in which gravity was balanced by an unknown repulsive agent. Nowadays it is known that the universe is not static but expanding, and this term has the effect of accelerating the expansion. Current analysis of type Ia supernova light curves is consistent with a universe composed of 30% matter and 70% dark energy, with an age of 14−15 billion years. See also: Astrophysics, high−energy; Cosmology; Hubble constant; Relativity; Star; Stellar evolution; Universe; Variable star

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How to cite this article

Suggested citation for this article:

Stan E. Woosley, "Supernova", in AccessScience@McGraw−Hill, http://www.accessscience.com, DOI 10.1036/1097−8542.669600, last modified: December 15, 2004.

For Further Study

Topic Page: » **Astronomy &Space Science:** » **Astronomy − general**

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Bibliography

- D. Branch and G. A. Tammann, Type Ia supernovae as standard candles, *Annu. Rev. Astron. Astrophys.*, 30:359−389, 1992
- A. Burrows, Supernova explosions in the universe, *Nature*, 403:727−733, 2000
- W. Hillebrandt and J. C. Niemeyer, Type Ia supernova models, *Annu. Rev. Astron. Astrophys.*, 38:191−230, 2000
- S. Woosley and T. Weaver, The physics of supernova explosions, *Annu. Rev. Astron. Astrophys.*, 24:205−253, 1986

Additional Readings

- Type Ia Supernovae as Standard Candles
- Supernovae and Supernova Remnant Pages on the WWW
- MDA Hydro Gang: Supernova Models
- Mr. Galaxy's Supernovae
- List of Recent Supernovae (Links to IAU Circulars)
- Supernova (Goddard Space Flight Center)
- Kopernik Space Images: Novae and Supernovae
- Asiago Supernova Catalogue (Complete List of All Supernovae Discovered So Far)
- Chandra Resources: Animations and Video: X−ray Sources: Supernovae and Pulsars

- X−Ray Astronomy Field Guide: Supernovae and Supernova Remnants
- ASCI Flash Center: Science Summary (Models of X−ray Bursts, Novae, and Type Ia Supernovae)
- Supernova Cosmology Project (Lawrence Berkeley National Laboratory)
- High−Z Supernova Search
- Hubble Space Telescope Images: Novae and Supernovae