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Type II Supernovae SN 1987A and SN 1993J

Roger A. Chevalier

The optical and ultraviolet emission from the type II supernova SN 1987A is currently powered by the radioactive decay of titanium-44. In contrast, the emission from SN 1993J is dominated by radiation from the interaction of the supernova shock wave with a dense, stellar wind released before the explosion. The dense wind around SN 1987A was displaced by the fast wind from the compact progenitor star, and the interaction of the supernova with dense gas is now being detected at x-ray and radio wavelengths. The expected neutron stars or black holes at the centers of these supernovae are not yet significant power sources.

Supernovae are cataclysmic stellar explosions that are accompanied by bright visual displays. The designation type II is used for supernovae that have hydrogen lines in their optical spectra, and type I is for those that do not. Type II supernovae have massive star progenitors, stars with masses $\gtrsim 8$ $M_\odot$, where $M_\odot$ is our sun's mass. The observational evidence is that type II supernovae are associated with regions of massive star formation. Calculations show that massive stars form a dense iron core that eventually collapses; the collapsing matter releases its gravitational binding energy in the form of neutrino emission. If a small fraction of the gravitational binding energy of the central core can be deposited in the central regions of the star, something very much like a type II supernova ensues. Models of explosions set off inside a massive star at the end of its life give results that agree with observations of the supernovae, including their light and spectral evolution (*1*).

The nearby supernova SN 1987A (*2*) in the Large Magellanic Cloud (LMC) provided confirmation of the basic picture of core collapse (*3*). The 19 neutrinos that were detected from this event were consistent with the approximately thermal radiation of neutrinos from the outer regions of a proto–neutron star. The fact that neutrinos were detected for 10 s shows that a proto–neutron star existed for at least that time because the formation of a black hole would have cut off the neutrino emission sooner. Although the neutrino observations of SN 1987A confirmed core collapse, they did not shed light on how 1% of the neutrino energy (about 10^{44} J) was deposited in the star to drive the explosion. This topic has been the subject of recent theoretical calculations, with an emphasis on neutrino-driven convection, but the results remain controversial (*4*).

At a distance of about 165,000 light-years, SN 1987A is extraordinarily close; most of the dozens of supernovae discovered every year are in galaxies tens of millions of light-years away. Because of their high intrinsic luminosity (about a billion times that of the sun for tens of days), it is possible to obtain spectra that give the spectral energy distribution and profiles of spectral lines for the distant supernovae. The energy distribution can be related to the angular size of the supernova. The line profiles yield the gas velocities and thus the linear size. The combination of these quantities yields the distance to the supernova, which, together with the redshift to the parent galaxy, gives the Hubble constant, or expansion rate of the universe. This method does not depend on uniform properties of the supernovae, but only on the physics of line and continuum formation in the spectra of individual supernovae. The method is best suited for the type II supernovae because their lines have less blending than those of type I supernovae and they are close to thermal equilibrium. A recent application of this method to type II supernovae yielded a Hubble constant of 73 ± 7 km s^{-1} Mpc^{-1} (*5*) [where 1 parsec (pc) = 3.26 light-years].

Here, I review developments in our observations and understanding of type II supernovae during the last 5 years. The emphasis is on the relatively nearby type II supernovae SN 1987A, in the LMC, and SN 1993J, in the galaxy M81. It is by detailed study of nearby events that we have learned the most about the range of physical processes relevant to supernovae. These processes include shock-wave heating, radioactive heating, and power from a central compact object. The two supernovae do have some nonstandard properties, but the same basic physical mechanisms are expected to operate in all type II supernovae.

SN 1987A and Its Surroundings

At an age of 10 years, SN 1987A has yielded some of its secrets, but a number of mysteries remain. Because of its proximity, we have an unprecedented view of the surroundings of a type II supernova (SN). The radioactive debris of SN 1987A, expanding with velocities up to several thousand kilometers per second, is at the center of several elliptical rings (6) (Fig. 1). The nebulosity is slowly moving gas that is the product of mass-loss processes before the SN. The emitting gas is relatively dense [up to 3×10^4 particles per cubic centimeter (*7*)] and was probably dark before the SN. It was

The author is with the Department of Astronomy, University of Virginia, Post Office Box 3818, Charlottesville, VA 22903, USA.

heated and ionized by the flash of radiation from the SN at the time of shock breakout.

The nebulosity appears to be the result of a fast stellar wind from the immediate progenitor of the SN sweeping up the slower, denser wind from an earlier red-supergiant phase. The early observations of the SN are most compatible with the explosion of a blue-supergiant star, that is, a relatively compact star (*3*). This view is supported by the few observations of the star from before the explosion (*8*). The dense gas around the SN, with its high abundance of nitrogen implying that it has been through the CNO nuclear burning process (*7*), provides the best evidence for an earlier red, highly extended stellar phase. The dense ring around the SN is circular, with a radius of 0.6 light-year. When this size is combined with the velocity of the ring, 10 km s^{-1}, the time since the red-supergiant phase is found to be about 20,000 years, which is short compared to the 10^7-year lifetime of the 20 $M_\odot$ progenitor star.

Early ground-based photographs of the SN showed that the dense ring is part of a more extended nebula, and models of the interaction of the fast blue-supergiant wind with an axisymmetric red-supergiant wind have been carried out (*9*). In order to obtain the central dense ring in the models, it is necessary to have the density of the slow wind in the equatorial plane be 20 times the density of the wind in the polar direction. The reason for such an aspherical, but axisymmetric, wind remains unclear, although similar structures are inferred to exist in planetary nebulae. One possibility is that a binary companion was involved in the equatorial mass loss. There is no direct evidence for a binary companion, although such a model may be attractive on other grounds, including mixing of the progenitor-star envelope and even the blueward evolution of the star before the explosion (*10*). The more conventional explanation for the unusual blueward evolution is a relation to the low heavy-element (*11*) abundances in the LMC (*3*). The outer rings (Fig. 1) present another challenging problem for the models. They are not the limb-brightened edge of an extended nebula because there is little emission from inside the rings (*6*).

The circumstellar medium is the surroundings into which the SN shock front is expanding. In the early evolution of SN 1987A, the peak velocities that were observed were about 40,000 km s^{-1}. At that speed, the outer shock radius in 1996 would have been 1.1 light-years, larger than the ring radius. The ring has not shown any sign of shock interaction, so the shock front must be decelerated by interaction with the medium inside the dense ring and its accompanying shell. This interaction is best observed by radio emission because the shock wave gives rise to the acceleration of relativistic electrons, resulting in radio synchrotron radiation; this type of emission is commonly observed in galactic SN remnants. In the standard wind-interaction model (*9*), the shock front first interacts with the free wind from the immediate progenitor star and subsequently with the shocked, fast wind inside of the dense nebula. The early radio emission from the SN was compatible with interaction with the progenitor wind (*12*). This emission faded below detectability after 200 days, as expected given the decreasing wind density.

In 1990, radio emission was again detected from SN 1987A. The size of the source was measured with the Australia Telescope, and it was found that the source radius expanded with an average velocity of 35,000 km s^{-1} during the first 1500 days, after which the velocity slowed by an order of magnitude (*13*). Since 1990, the radio flux has increased approximately linearly with time. There has been some modeling of the radio emission in terms of shock acceleration of electrons in a shock transition that is mediated by cosmic-ray protons (*14*), but the continued flux increase and constant spectral index of the emission (*13*) have not been explained. Although models for the production of synchrotron radiation are not well developed, the steady flux increase suggests an increase in the injection of electrons, and thus in the density of the material that the shock wave is encountering.

Further and more direct evidence for an increased density comes from the observed x-ray emission from the supernova. The x-ray emission has been increasing over the past few years in a way that is consistent with a turn-on at the same time as the radio turn-on in 1990 (*15*). The radio and x-ray behavior point to interaction of the shock front with higher density gas beginning in 1990. A possible source of such gas is photoionization of the swept-up red-supergiant wind by radiation from the blue-supergiant progenitor (*16*). The ionized region produced by the blue progenitor should extend inward from the dense ring and have a density of about 100 H atoms per cubic centimeter (Fig. 2). This model can approximately account for the radio turn-on and the luminosity of the x-ray radiation. The relatively low effective temperature of the observed x-ray emission can be explained by strong line emission (*17*). The N V (*18*) emission line at a wavelength of 123.8 nm should be detectable from the interaction with the denser gas (*17*); a search for the ultraviolet (UV) N V line will take place with the UV spectrometer recently installed on the Hubble Space Telescope (HST).

The interaction of the SN with the denser ionized gas is expected to delay the impact of the shock front with the dense gas in the bright ring, with estimates of the arrival time in the year 2005 ± 3 (*16*) and 2007 (*17*). Its arrival is eagerly anticipated because the cooling time for the gas will become less than the evolutionary time, and the shocked gas will cool from temperatures at which it primarily emits x-rays to temperatures at which it primarily emits

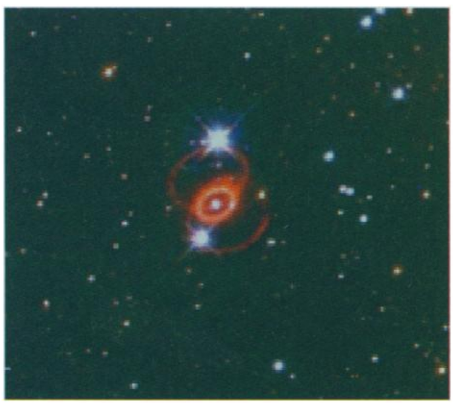

Fig. 1. An image of SN 1987A and its environment taken with the HST Planetary Camera. The image, which was taken on 6 February 1996, spans about 20 arc sec by 17 arc sec. The colors are a result of combining images taken in the B (centered on 440 nm), V (550 nm), I (900 nm), and [N II] (658.3 nm) wavelength bands. The nebulosity primarily emits in the [N II] line. [Courtesy of R. Kirshner, P. Challis, and the Space Telescope Science Institute]

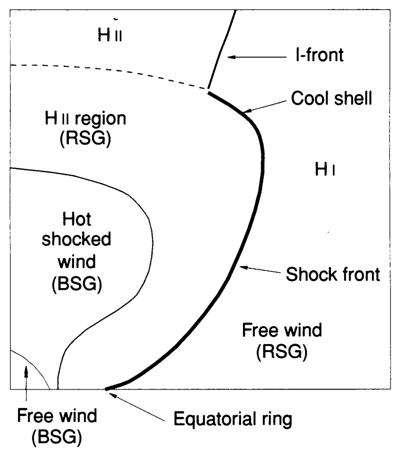

Fig. 2. A schematic picture of the inferred surroundings of SN 1987A (lower left corner) created by mass loss before the supernova. The horizontal axis is the equatorial plane, which contains the bright ring. The vertical axis is the polar axis, about which the nebula is axisymmetric. RSG and BSG refer to red-supergiant and blue-supergiant wind material, respectively, and I-front to an ionization front. The cool shell has a shock front at its outer boundary [schematic from (*16*), courtesy of the author].

UV and optical radiation. The resulting line emission from a shock front moving at several hundreds of kilometers per second will provide diagnostics for the shock-wave propagation (*19*). The ring brightening will be nonuniform because of the clumpy structure of the ring itself, instabilities in the shock interaction region, and effects related to the travel time of light.

Photo-ionization by the progenitor star may be important not only for propagation of the SN shock wave, but also for determining the overall structure of the wind-interaction nebula. As the nebula expands and the density drops, the same photo-ionizing flux from the progenitor star is able to ionize a larger mass of gas. Thus, the ionization front eats into the dense shell, and the ionized region occupies a larger volume of the nebula. In the polar direction, the gas column density through the swept-up red-supergiant wind shell is small, and the ionization front is expected to have broken through the shell (*16*) (Fig. 2). It then rapidly moves through the free red-supergiant wind. The ionization front break-out may explain the lack of observable nebulosity inside the outer rings (*6*).

The Inner Debris of SN 1987A

The optical emission from the SN debris lies far inside the shock front and has properties that are unrelated to the external interaction. The early observations of SN 1987A, particularly the early detection of x-rays and gamma rays from radioactivity, showed that heavy elements had to have mixed with the envelope material (*3*). The late spectra of the SN are valuable for investigating the SN debris because the gas becomes optically thin to continuum emission (except for dust absorption in the very central part of SN 1987A), and it is possible to infer the spatial extent of the heavy element layers from their velocities. The point is that within days or weeks after the explosion, there are no significant forces on the ejecta gas, so that the gas elements moved with constant velocity, and the velocity of a gas along our line of sight can be inferred from the Doppler shift in its emission line.

The luminosity of SN 1987A for the first 20 days can be attributed to shock heating of the envelope, but radioactivity subsequently became the dominant power source. The SN light curve over the first 1.5 years (Fig. 3) showed a decay compatible with power input from ^{56}Co decay (77-day half-life); gamma-ray line emission from this decay was directly observed by balloon-borne and satellite experiments (*3*). These observations showed that about 0.075 $M_\odot$ of ^{56}Ni, the parent nucleus of ^{56}Co, was formed in the explosion. As time passed, the longer lived radioactive species became the dominant power sources. The gamma-ray line emission from ^{57}Co was observed in 1991 by the Compton Gamma Ray Observatory, and 0.003 $M_\odot$ of this nuclide was inferred to exist (*20*). Another radioactive nuclide expected to have been formed in the explosion is ^{44}Ti, which has a half-life of several decades; its decay is negligible over the times of interest here. Recent nucleosynthesis calculations indicate that a star with a mass similar to that of the progenitor of SN 1987A should form at most 10^{-4} $M_\odot$ of ^{44}Ti, and the amount could be considerably less (*21*). The gamma-ray line emission from this amount is not detectable with current experiments.

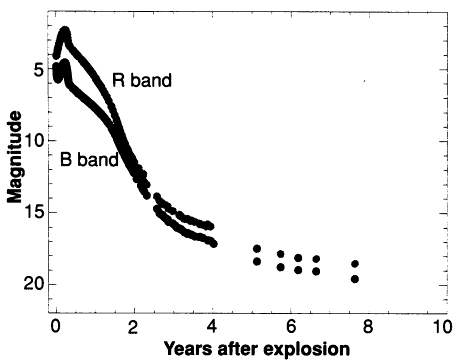

Fig. 3. The light curve of SN 1987A in the B band (centered on wavelength 440 nm) and the R band (700 nm) based on ground-based observations from the Cerro Tololo Inter-American Observatory (during the first 4 years of the supernova's existence) and observations from the HST Planetary Camera (after year 4). Five magnitudes correspond to a factor of 100 in flux. [Courtesy of P. Challis and R. Kirshner]

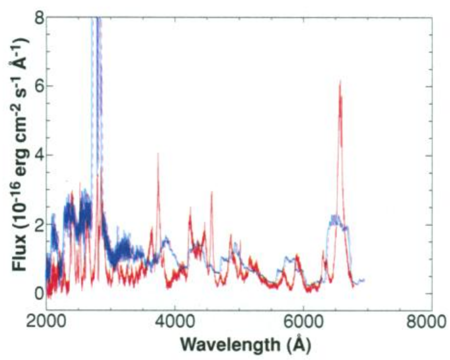

Fig. 4. Spectra of SN 1987A (red line, from October 1995) and SN 1993J (blue line, from February 1996) taken with the HST Faint Object Spectrograph. The optical data on SN 1993J are from the Keck Observatory. Prominent lines are Hα, at 656.3 nm, and Mg II, at 279.6 to 280.3 nm; the SN 1987A spectrum also contains many Fe II lines. [Courtesy of P. Challis, R. Kirshner, and A. Filippenko]

An analysis of the optical and UV spectrum of SN 1987A (Fig. 4) shows that the emission is consistent with power input from ~1 × 10^{-4} $M_\odot$ of ^{44}Ti (*22*). At the time of the analyzed spectrum (January 1995), the debris was optically thin to the gamma rays from radioactivity, so that the decay positrons deposited about 4 × 10^{29} J s^{-1} into the gas, as opposed to 10^{29} J s^{-1} for the gamma rays. With this small heating, the gas cooled by radiation and expansion to a temperature ≲300 K. Evidence for the cool temperature was found from the width of the Balmer discontinuity line at 365.0 nm. The positrons deposit energy into the Fe-rich gas, which primarily emits thermal radiation in the infrared (IR), especially the Fe II fine-structure line at 26 μm. About 10% of the positron power goes into the nonthermal excitation of optical and UV transitions of Fe, many of which are observed. The O lines are powered by the gamma rays from ^{44}Ti decays. The observed flattening of the light curve (Fig. 3) is consistent with the steady power input from ^{44}Ti decays.

Although the heavy element emission can be modeled by nonthermal excitation caused by radioactive power input, this mechanism cannot produce the H line emission. The likely mechanism here is the delayed recombination of the H because the recombination time scale has become longer than the evolution time of the supernova. This effect is also important for the He-rich region. The lines formed in this way made a significant contribution to the light curve of the SN (*20, 23*).

An analysis of the line emission from the Fe-rich gas yields the densities of the gas and the filling factors (*24*) of various heavy elements (*25*). The Fe-rich gas appears to fill much of the volume at velocities < 2500 km s^{-1}, with a filling factor of ≳30%. The O occupies blobs that are included in this medium (*26*). The large filling factor of Fe can be attributed to the Ni bubble effect, the fact that energy input from ^{56}Ni decay causes the Fe-rich gas to expand a few days after the explosion.

Early observations of SN 1987A showed velocity asymmetries in Fe line emission extending to ≳3000 km s^{-1} (*27*). Models for the high velocities appear to require instabilities during the initial explosion as well as during the expansion after the explosion (*4, 28*). An additional observational handle on asymmetries comes from the spatial structure of the ejecta determined from the HST. Recent results show that the ejecta are elongated along the north-south direction with a major- to minor-axis ratio of 1.2 (*29*). This elongated axis is in roughly the same direction as the minor axis of the bright ring around the SN. The relation of the asymmetry of the ejecta to that of the ring suggests that they have a common origin, perhaps in the rotation of the progenitor star.

The current spectrum of SN 1987A can be explained purely by radioactivity and sets a limit on the luminosity of any other power sources. This limit is surprising, because we know from the neutrino burst that there is a compact object at the center of the SN. The fact that the burst lasted for 10 s indicates that a neutron star was present for at least that amount of time. The problem with the continued existence of a neutron star is that if some mass falls back to the center, it may lead to an accretion luminosity in excess of that observed, although a high Fe opacity might reduce the luminosity below the detectable level (*30*). The region around the neutron star may have to be cleared of matter. An alternative is that material falling back to the center in the hours after the explosion, which could be 0.1 $M_\odot$ of material, led to collapse of the neutron star to form a black hole (*31*). Black hole accretion with a low radiative efficiency is possible. Unfortunately, the continued power input from ^{44}Ti is an impediment to the detection of the central source.

SN 1993J in M81

Supernova SN 1993J was discovered on 28 March 1993 in the galaxy M81, which lies about 10^7 light-years from Earth. Although it is a factor of 65 further away than SN 1987A, it is still relatively close for a SN and has been the subject of intense observational campaigns in a number of wavelength regions. The early evolution of its luminosity had some similarities to that of SN 1987A (Fig. 3), including a rapid drop from a peak level followed by a broad secondary maximum that could be attributed to power input from ^{56}Co decay. The light curve did not show the extended bright phase (called the plateau phase) that is seen in some type II supernovae and is attributed to the presence of a photosphere in a shock-heated massive envelope. SN 1987A did not show such a phase either, presumably because the small initial radius of the progenitor star led to a loss by adiabatic expansion of the energy from shock-wave heating, and the cool envelope rapidly became optically thin. In the case of SN 1993J, the early light curve indicated that the progenitor star was more extended, about 10 times larger than that of SN 1987A. The lack of a plateau phase in this case is attributed to the low mass of the hydrogen envelope, about 0.1 to 0.6 $M_\odot$ (*32*), although the initial stellar mass was probably $\sim$15 $M_\odot$. The reason for the small envelope mass is likely to be mass transfer from the progenitor star to a companion star in a binary system.

Red-supergiant stars in our galaxy are known to have slow, dense winds, and such a wind provides the medium into which the supernova expands. SN 1993J was observed as an x-ray and radio source within a week of the explosion, and the emission can be attributed to shock-wave interaction with a 10 km s^{-1} wind with a mass loss rate of $\sim 4 \times 10^{-5}$ $M_\odot$ year^{-1} (*33*). The radio emission was spatially resolved with very long baseline radio interferometry to show an expanding shell source (*34*), as expected for circumstellar interaction. These observations showed that the circumstellar interaction involved sufficiently dense gas that the shock front in the supernova ejecta should radiatively cool and collapse to form a dense shell in this region. Calculations showed that the optical to UV line emission comes from two distinct regions, both of which are irradiated by the x-ray emission from the cooling shock front (*35*). Downstream from the shock front, the emission from the dense shell is manifested as low-ionization lines such as Hα, Mg II (279.6 to 280.3 nm), and the H Lyman α line. On the inside of the shock front, the freely expanding supernova gas has a range of ionization stages, and the emission includes lines like the N III] line at a wavelength of 175 nm, N IV] at 148.6 nm, N V at 123.8 nm, and [O III] at 500.7 nm (*18*).

The early emission was dominated by gas heated by the radioactive decay of nuclei, but within a year of the explosion, the Hα line showed evidence for a broad, flat-topped profile in the spectrum, which is characteristic of circumstellar shell emission (*36*). The combined HST and Keck Telescope spectrum of SN 1993J obtained in February 1996 showed a strong Mg II line, as expected, and the overall spectrum provides an interesting contrast to the late spectrum of SN 1987A (Fig. 4). The far-UV part of the HST spectrum showed emission lines of N II, N III, and N IV, presumably from the freely expanding SN. The Lyman α line was strong, as expected. Analysis of the relative line strengths can yield the element abundances in the SN ejecta. As the various heavy element layers of the star move through the reverse shock front, we can learn about the abundance structure of the exploded star.

As late observations of other more distant supernovae have become possible, a number of them have shown evidence for circumstellar interaction (*37*). Some show strong line emission from early in their evolution, and circumstellar interaction appears to be the dominant power source from the beginning. Some of these show especially high radio and x-ray luminosities, which suggests that their circumstellar densities are at the maximum of what is found around late type stars.

Phases of Evolution of Supernovae

The evolution of the light from type II supernovae is believed to go through several phases, depending of what physical process is the most important for producing the power. Initially, the radiation is from an expanding photosphere that has been heated by the passage of the SN shock wave. This phase was relatively brief ($\lesssim$10 days) for SN 1987A, because the stellar envelope was initially so small that it suffered strong adiabatic expansion losses, and for SN 1993J, because the extended envelope had a small mass and rapidly turned optically thin. In the more commonly observed type II supernovae, the progenitors of which have massive, extended envelopes, this phase can last for many weeks (*1*).

In the next phase, radioactive decay of nuclei powers the luminosity. This phase has been especially well studied in SN 1987A, in which successive radioactive species with longer half-lives have been powering the ejecta. Titanium-44 is the dominant power source at the present time and probably will be for decades. The characteristics of the debris heated by radioactivity are a low temperature, emission predominantly in IR fine-structure lines, and some nonthermal excitation of optical and UV lines.

In SN 1993J, the radioactive phase was followed within a year by emission from shock-wave interaction with material shed before the supernova. This interaction is probably more typical than the case of SN 1987A, where the wind from the blue-supergiant progenitor star has displaced the dense circumstellar gas so that this phase of evolution will not commence until about 20 years after the explosion. At the other extreme, some type II supernovae appear to have such strong circumstellar interaction that the radioactive-dominant phase is absent (*37*). The energy is initially input in the form of x-rays for these supernovae.

Another potential power source with a relatively long decay time is a central compact object, either as a pulsar or as an accretion source. Despite intensive observations of SN 1987A, SN 1993J, and the late emission from other extragalactic supernovae, such a source has not yet been identified, and the youngest pulsar that we know of is the Crab pulsar, associated with SN 1054. The birth characteristics of neutron stars remains an important topic for the future.

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Type Ia Supernovae: Their Origin and Possible Applications in Cosmology

Ken'ichi Nomoto,* Koichi Iwamoto, Nobuhiro Kishimoto

Spectroscopic and photometric evidence indicates that Type Ia supernovae (SNe Ia) are the thermonuclear explosions of accreting white dwarfs. However, the progenitor binary systems and hydrodynamical models for SNe Ia are still controversial. The relatively uniform light curves and spectral evolution of SNe Ia have led to their use as a standard candle for determining cosmological parameters, such as the Hubble constant, the density parameter, and the cosmological constant. Recent progress includes the calibration of the absolute maximum brightness of SNe Ia with the Hubble Space Telescope, the reduction of the dispersion in the Hubble diagram through the use of the relation between the light curve shape and the maximum brightness of SNe Ia, and the discovery of many SNe Ia with high red shifts.

Supernovae are classified spectroscopically as Type I if they have no hydrogen lines in their optical spectra and Type II if they have hydrogen lines in their optical spectra. Type I supernovae (SNe I) are further subclassified into types Ia, Ib, and Ic on the basis of spectra observed early in their explosion (early-time spectra) (*1*). SNe Ia are characterized by the presence of a deep Si II absorption line near wavelength 6150 Å (Fig. 1), and their late-time spectra are dominated by strong blends of Fe emission lines. SNe Ib and Ic, in contrast, do not show this Si line. Moderately strong He I lines, especially at 5876 Å, distinguish SNe Ib from SNe Ic in early-time spectra; that is, SNe Ib exhibit absorption lines of He I, whereas these lines are weak or absent in SNe Ic (*1*). SNe II, Ib, and Ic are now generally thought to result from the explosion of massive stars—SNe II from single stars and SNe Ib and Ic from binary stars. There are spectroscopic and photometric indications that SNe Ia originate from white dwarfs that are composed of C + O with strongly degenerate electrons and have accreted sufficient mass from a companion to trigger an explosion.

However, the progenitor systems and hydrodynamical models for SNe Ia are still controversial. Many issues need to be resolved, including (i) double-degenerate (DD) versus single-degenerate (SD) scenarios, that is, whether the companion of the white dwarf is also an electron-degenerate white dwarf or is a nondegenerate [main sequence (MS) or evolved red giant] star; (ii) Chandrasekhar mass (Ch) (*2*) versus sub–Chandrasekhar mass (sub-Ch) models; and (iii) the explosion mechanism in the Ch models. The answers to these questions could lead to improved understanding of the complicated evolution of close binaries as well as the physics of thermonuclear explosions (*3*). The relatively uniform light curves and spectral evolution of SNe Ia have led to their use as a standard candle to determine the Hubble constant (H_0), the density parameter (Ω_M), and the cosmological constant (Ω_Λ) (*4*). SNe Ia are important standard candles because they are bright enough to be observed out to a red shift (z) of ~1. Variations of light curves and spectra among SNe Ia have recently received attention. SNe Ia with higher maximum brightnesses tend to show a slower decline in their light curves (*5*, *6*) (Fig. 2). This review summarizes our current understanding of SNe Ia and focuses on these controversial issues.

Progenitors

White dwarfs composed of C + O are formed from intermediate mass stars ($M < 8\ M_\odot$, where $M_\odot$ is the mass of our sun), undergo cooling, and eventually become

The authors are in the Department of Astronomy, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan.

*To whom correspondence should be addressed.