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SUPERNOVAE: AN IMPRESSIONISTIC VIEW

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Abstract

This article, derived from a talk given at the AAVSO 75th anniversary meeting, presents an overview of the current status of supernova research, addressing the issues of which stars become supernovae, how they do it, and how the results affect other astronomical objects and us.

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1. Introduction

The first question one has to ask is "why do we bother about supernovae; what are they good for apart from keeping otherwise-unemployed astronomers off the streets?" There are several answers. First, nuclear reactions in the explosions are responsible for the synthesis of elements heavier than iron, including gold, silver, uranium, thorium, and other things you know and love. Many of these are made by the addition of neutrons to iron nuclei as the supernovae are going off.

Next, supernova explosions distribute heavy elements - not just the ones beyond iron, but also carbon, oxygen, neon, magnesium, silicon, iron, and many others that were produced inside the parent stars throughout their whole lives. These are spread through the interstellar gas by expanding remnants of the explosions and thereby become raw materials for new generations of stars and planets. Thus, nearly every atom in your body, except the hydrogen, has at some time been through a supernova explosion. If you happen to be reading this early on a Monday morning, you can undoubtedly believe it.

In addition to heavy elements, supernova explosions feed heat and kinetic energy into the interstellar medium. This is important because, if the gas had been left to its own devices, it would long since all have cooled, collapsed, and formed stars, and our galaxy would contain no stars as young as the sun to warm life-bearing planets. On the other hand, an expanding supernova remnant, by colliding with an interstellar cloud, can sometimes compress the cloud and cause it to start collapsing and forming stars. Decay products of short-lived, radioactive nuclides in the solar system provide some evidence that the star-formation event in which our sun was born may have been triggered in this way.

Some fraction of the energy of expansion of a typical supernova is channeled into a very small number of particles which, therefore, achieve enormously high speeds and energies. These are called cosmic rays. They continuously bombard the earth's upper atmosphere, generating unstable secondary particles, some of which reach the surface and are an important source of mutations in terrestrial living creatures. Thus, through cosmic rays, supernovae are partially responsible for the evolution of amoebas into astronomers.

Finally, a subset of supernova explosions leaves behind pulsars and neutron stars. Because modeling these requires a thorough understanding of quantum mechanics and nuclear physics as well as general relativity, they are particularly effective in keeping theorists out of mischief, not to mention providing acid tests of the underlying theory.

2. Properties of Supernovae

What does a supernova look like? Not much actually (see Figure 1), unless it happens to go off very close to you, in which case it may even be briefly visible by day. About seven supernovae have occurred in the last thousand years in the part of our galaxy accessible to naked eye observations. This translates into about one per 40±10 yr for the whole Milky Way, a rate that is confirmed by statistical studies of other large galaxies.

All of these historical supernovae have left remnants that now emit visible, radio, and x-ray light in patterns showing rapid expansion. The best known is the Crab Nebula, shining where the Chinese reported a "guest star" in 1054. The pattern of galactic supernova dates (1006, 1054, 1181, 1480, 1572, 1604, and circa 1685) gives one a distinct impression that we are overdue for a naked-eye event. It used to be said that when there was another astronomer as great as Kepler (who studied SN 1604), there would be a supernova for him to observe. This cliche has been spoiled by the possibility that Flamsteed may have recorded SN 1685, which became Cas A. Somehow there doesn't seem to be much competition for the title "greatest astronomer since Flamsteed."

Since we have seen no galactic supernovae for several centuries, modern research is based largely on events discovered telescopically in other galaxies. S Andromedae in 1885 was the first of these recorded, and lists now contain more than 600 confirmed supernovae, many of them discovered through the searches inaugurated by Fritz Zwicky using the 18" (from 1940) and 48" (from 1948) Schmidt telescopes at Palomar. The discovery rate fell precipitously after Zwicky's death in 1974, and is only now picking up again as a result of new, deliberate search strategies. Two of the most notable of these are the visual observations of Robert Evans of New South Wales, who has found more than a dozen supernovae, and the Berkeley automated search, which recorded its first event (1986i in M99) on 17 May 1986.

The simple spotting of a supernova in a particular place provides some information about the kinds of galaxies and stellar populations that can give rise to supernovae. Statistics of supernova discoveries tell us that late-type spirals produce about one every 30 years for each 10^{10} solar luminosities they radiate. Early-type spirals and elliptical galaxies are less prolific. Most of our detailed knowledge comes, however, from comparing observed light curves and spectra with models that make different assumptions about how much energy is released, what processes produce it, and how much material the energy has to work its way through in the outer parts of the parent star.

The light curves tell us that supernovae flare up in a matter of days, radiate at least 10^{49} ergs in visible light alone (as much as the sun does in a hundred million years), and fade away in months to years. The spectra reveal that 1 - 10 solar masses of material is being blown out at speeds of 3000 to 10,000 km/s, so that the kinetic energy, about 10^{51} ergs, is larger still than the light energy.

More careful examination shows that there are at least two different kinds of supernovae, Type I's which occur among Population II (old, halo) stars, and Type II's, which occur among Population I (young, disc) stars. This is not the result of deliberate malevolence. It's just that the supernovae were classified by Rudolph Minkowski (on the basis of their spectra) and the stars by Walter Baade (on the basis of velocities, metal abundances, and locations in the galaxy) at different times and for different purposes.

Type II supernovae occur only in the arms of spiral galaxies, fade rather quickly, and have spectra dominated by lines of hydrogen, the commonest element in the universe. The Type I's occur in both ellipticals and spirals, have long exponential tails on their light curves, and show lines of common elements like silicon, magnesium, oxygen, iron, and calcium, but no hydrogen. Types I and II are roughly equally common in the spiral galaxies where both occur. Work in the last few years suggests division of the Type I's into subtypes Ia and Ib (or I and Ipeculiar), the latter being a bit dimmer, occurring more often in spirals, lacking a couple of characteristic spectral lines (but still no H), and emitting radio waves as well as visible light. Zwicky also defined Types III, IV, and V, with only a couple of examples each (V's in particular may come from very massive stars). There is a rumor that he defined three more types with no examples at all, but this is a foul calumny.

Figures 2 and 3 show a couple of characteristic supernova light curves and optical spectra. These can be fit by detailed models of the explosions (see **Reviews of Modern Physics 54**, 1183, 1982 and **55**, 511, 1983 for more about these than you ever wanted to know or cared to ask). The fits reveal that we will get something that looks like a Type I if about one solar mass of carbon and oxygen burns explosively to Ni^{56}, which then decays via Co^{56} to Fe^{56} (the energy from these slow decays powering the long tail on the light curve). The parent star does not survive this trauma. Type II's on the other hand result when the iron core of an evolved, massive star collapses to nuclear densities and bounces, depositing about 10^{51} ergs at the base of the star's extended, red supergiant envelope.

The famous names that belong in any brief history of supernovae include Chadwick, who discovered the neutron in 1932, and Landau, who lit upon the concept of neutron stars almost immediately thereafter (although Gordon Bym tells me that the standard folklore version cannot be correct as Landau was not actually in Copenhagen at the time Chadwick's preprint arrived there); Baade and Zwicky, who, in 1933, separated super-novae from common novae and suggested that the energy source must be the collapse of a normal star to a neutron star (and that part of the energy would make cosmic rays and a remnant neutron star be located in the Crab Nebula); Oppenheimer and Volkoff, who calculated the first accurate neutron star models in 1939; Minkowski, who separated the two types in 1940; Jocelyn Bell and Anthony Hewish, who discovered pulsars in 1967/68; and Cocke, Disney, and Taylor, who, in 1968, confirmed the presence of a pulsar in the Crab Nebula, thus verifying the connection between neutron stars and at least some supernovae, and enabling Zwicky to say "I told you so," (which he did, but no oftener than he was entitled to).

3. Supernova Progenitors

In order to produce a supernova explosion, a star needs to release at least 10^{51} ergs rather quickly. There are two major kinds of energy available to astronomical objects, gravitational and nuclear. Each can be liberated rapidly under some circumstances. To get a burst of gravitational energy, it is necessary to remove pressure support in the core of a massive object. This happens when a property of the core gas, called ratio of specific heats, drops below a critical value of 4/3.

Nuclear energy, on the other hand, comes out explosively when a fuel has become degenerate before it ignites. Degeneracy is not a moral judgement on the gas, but a description of the velocity distribution of its electrons. Roughly, atoms are crowded together as tightly as the laws of quantum mechanics permit. The result is that, when a nuclear reaction starts up, the gas is heated, but does not expand and cool the way a normal gas would (this is what keeps our sun stable). Instead, the gas gets hotter, increasing the rate of the reaction, which heats the gas more, which speeds up the reaction, and so forth, until the gas suddenly finds itself non-degenerate and expands in an all-mighty explosion.

Reducing the ratio of specific heats below 4/3 and igniting a nuclear fuel degenerately both imply certain conditions on the central temperature and density of an evolving star. Thus we turn to Figure 4. It is a plot of central temperature vs. central density, divided into zones as explained in the caption. The solid lines trace the evolutionary history of stars across these zones as a function of initial stellar mass. In brief, most stars more massive than 8±2 solar masses will, after some millions of years, cross into one of the "less than 4/3" regimes and experience core collapse, becoming Type II supernovae and (usually) leaving neutron stars behind.

It looks as if less massive stars of 3 - 7 solar masses should ignite carbon degenerately and make Type I events (after longer periods of time, since the smaller the star, the slower its evolution). But there is a catch. Most of these same stars are known from observations to lose their outer layers in winds (perhaps pulsationally driven, as discussed by Lee Anne Willson elsewhere in these proceedings) and planetary nebulae. The loss turns off nuclear reactions before carbon ignition can occur, and leaves behind a white dwarf made of carbon and oxygen. To get the process started again, a close binary companion to the white dwarf must transfer material onto it, slowly increasing its mass up to the Chandrasekhar limiting mass. Only then will degenerate carbon ignition occur, disrupting the entire star and producing a Type I supernova. Notice that there can be a long delay between white dwarf formation and the onset of mass transfer. This permits Type I supernovae to occur among very old stellar populations, unlike Type II's, which must occur when short-lived, massive stars first die or not at all, and so are seen only in spiral arms where star formation has happened recently.

4. Residual Difficulties

It sounds as if we can account for the two main types of supernovae in terms of processes that must occur in known kinds of stars. I believe this is basically true and that we probably have the outline right. But there remains a major difficulty with each type.

To make a Type II, we must deposit at least 10^{51} ergs at the base of the supergiant envelope. Energy supply is not a problem. The collapse to neutron star densities releases 100 times that much. Energy and momentum transport are more difficult; neutrinos and gravitational radiation carry away much in forms that cannot interact with the rest of the star. A shock forms when the core bounces and starts outward in a very promising way, but tends to die before actually reaching the envelope. Groups of astrophysicists at Lawrence Livermore Lab, Chicago, Munich, and many other places are actively hunting for ways to keep the shock going or to re-energize it after it stalls. Neutrinos may help, and so may various kinds of instabilities. But none of the suggestions is yet widely accepted, and the problem of how to get enough of the available energy into the right part of a Type II progenitor remains unsolved.

The physics of Type I events, on the other hand, seem to be in pretty good shape (apart from some bickering about whether the wave of nuclear burning moves through the degenerate star at subsonic or supersonic speed). But there is real difficulty in identifying enough progenitors. The novae, dwarf novae, and other assorted cataclysmic variables discussed extensively at this meeting sound like the right sort of thing. A partially-evolved companion is busily transferring material to a white dwarf as required.

Unfortunately, if the transferred hydrogen is required to ignite explosively to make a nova explosion every 10^5 yr or so, it cannot also burn quiescently and remain behind to increase the mass of the white dwarf. A very promising alternative, first suggested by Bohdan Paczynski, is a pair of white dwarfs. Then the donor provides helium, carbon, and oxygen, rather than hydrogen, and there will be no minor nova explosions to mess things up, but only, eventually, the one big supernova explosion. For this to work, we need two white dwarfs whose masses add up to more than 1.4 solar masses, close enough to each other for mass transfer to occur within the age of the universe. Known binary white dwarfs include massive wide visual pairs (like G107-70) and low mass interacting pairs (like AM CVn), but we have found no close, massive pairs, even after some deliberate searching among white dwarfs that seemed to have variable radial velocity, and so might be spectroscopic binaries.

Apparently, then, we have plenty of progenitors for Type II supernovae, but some difficulties with the physics of energy transport, while, for the Type I's, the basic physics are under control, but we have not succeeded in identifying a sufficient number of suitable progenitors.

5. **Valedictory**

Since there are two main types of supernovae, there ought to be two conclusions. I would like, therefore, to leave you with thoughts from two of the pioneers of the field. Sir Fred Hoyle (who, with Geoffrey and Margaret Burbidge and William Fowler, first sorted out the nuclear reactions that occur in massive stars) has said, "I can see no reason to disbelieve something just because it is impossible." And Professor Tom Gold (who was perhaps the first to recognize that pulsars must be magnetic, rotating neutron stars) has said, "If we are all going in the same direction, it must be forward." This would seem to apply to the general agreement about degenerate carbon ignition as the triggering event for Type I supernovae and perhaps to other bits of astronomical research as well.

Figure 1. Photograph, taken shortly after maximum light, of the Type I supernovae 1986g, discovered 3 May 1986 in NGC 5128 (= radio galaxy Cen A). The supernova is the star that looks most isolated in the dark central lane. The other stars are, of course, foreground ones in our own galaxy. Photograph generously supplied by the discoverer, Robert Evans, who sent his greetings to the participants at the 75th anniversary meeting and his regrets at not being able to be present.

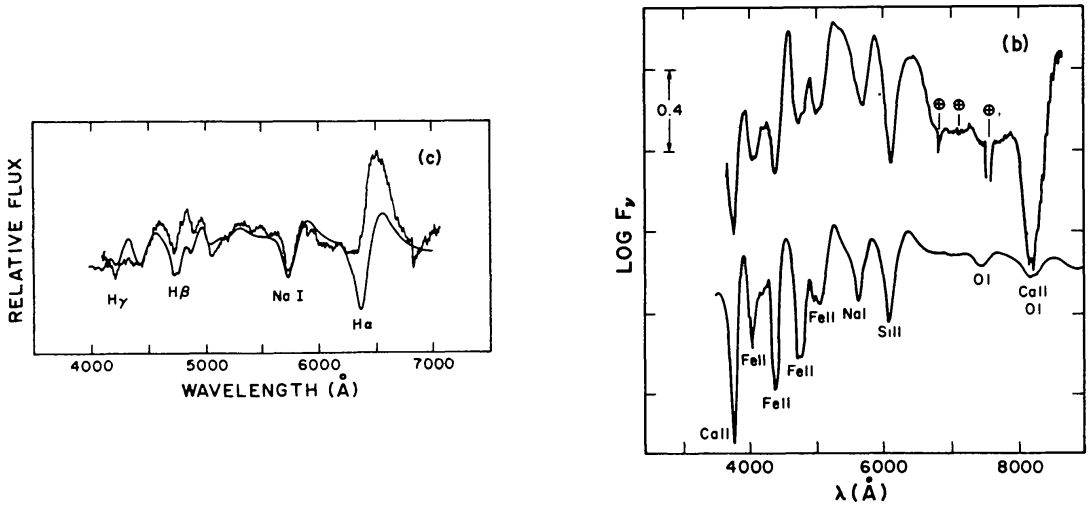

Figure 2. Supernova spectra (Type II to left, Type I to right). The wigglier line in each shows data, the smoother line a model calculated by David Branch. Features to note, in addition to the generally good fits (indicating that we have more or less understood what is going on) include the great widths of the lines (showing that gas is exploding outward at thousands of km/s) and the presence of hydrogen lines (labelled Hα, Hβ, etc.) in the Type II but not in the Type I spectrum.

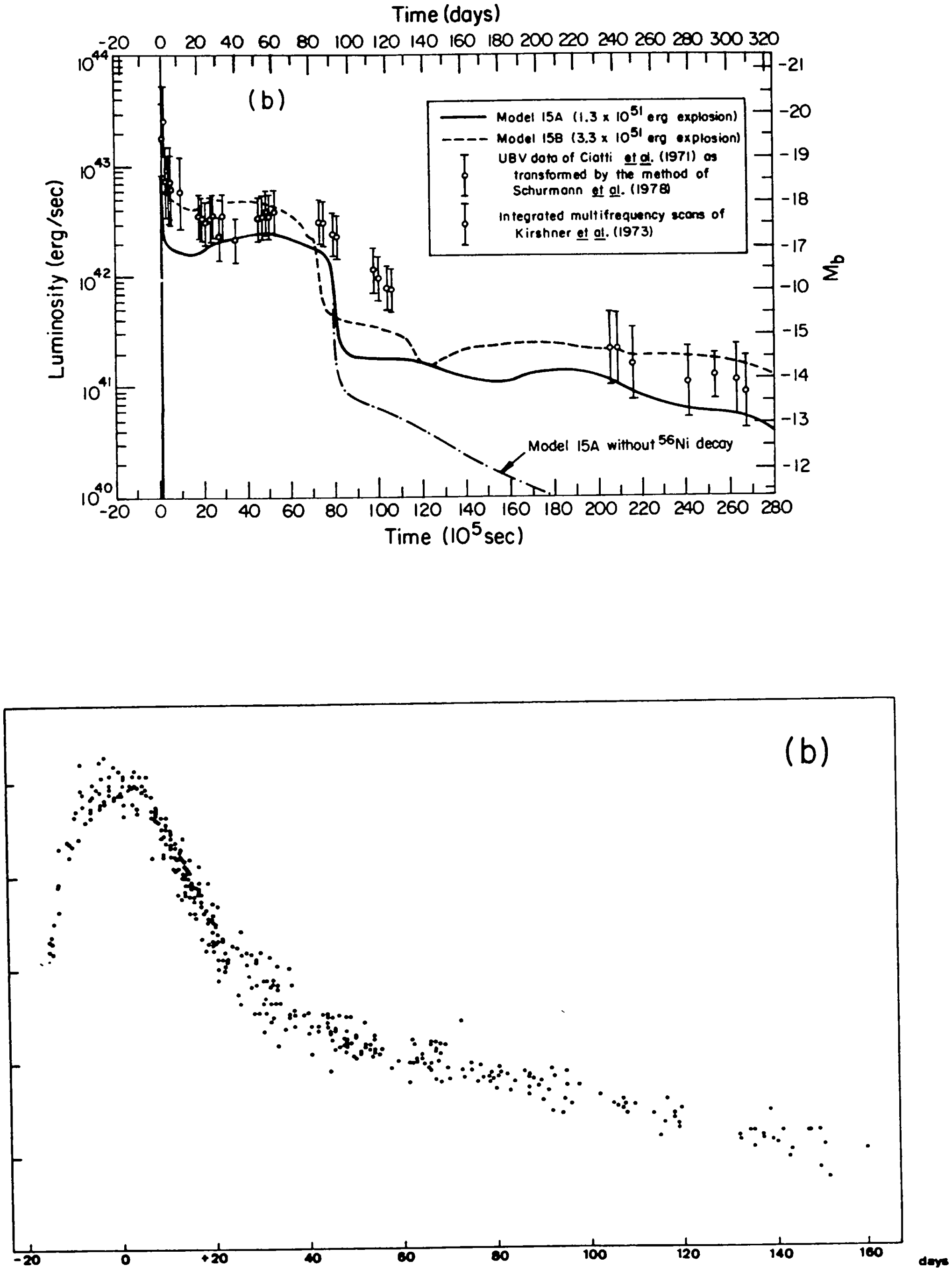

Figure 3. Supernova light curves (Type II above, Type I below). The points are data and the smooth line a model (calculated by Tom Weaver and Stan Woosley). Type I models (not shown) pass elegantly through the range of observed points. Features to note include the relatively rapid rise (as energy from the stellar core works its way through the outer parts of the star) and the slower decline as expanding gas cools. The long tail on the Type I light curve is maintained by energy of radioactive decays of Ni^{56} via Co^{56} to Fe^{56}.

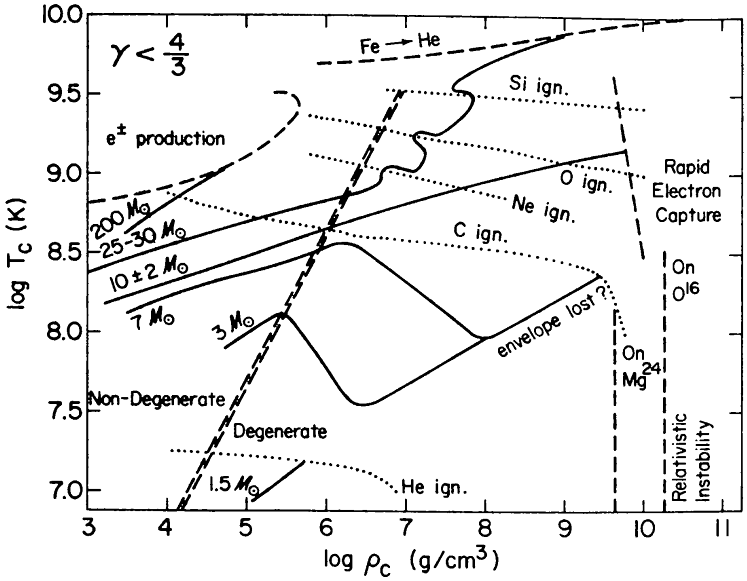

Figure 4. Pre-supernova evolution in the central temperature - central density plane. Dotted lines show loci of nuclear fuel ignition (energy liberated exceeds energy lost by neutrinos) for helium, carbon, neon, oxygen, and silicon fuels. Dashed lines mark off regions of instability due to electron-positron production (upper left), photodisintegration of iron (top), and electron capture and relativistic instabilities (far right). Solid lines are the (slightly simplified) evolutionary tracks for the masses indicated. Stars above about 8 solar masses hit the instability lines and collapse to make neutron stars and Type II supernovae. Less massive stars would ignite carbon degenerately and explode, were it not for the loss of their envelopes in winds and planetary nebulae, which terminates their nuclear reactions. Type I events, therefore, seem to occur most often in binary systems, where mass transfer onto a white dwarf can drive the recipient star to the degenerate carbon ignition line.