Supernovae
from Virginia Trimble

Supernovae as a class of astronomical events releasing 1049 ergs in visible light over a year or two were identified and defined by Fritz Zwicky and Walter Baade in 1934. A surprising amount of what they said then remains credible, including the division into Type I and Type II events (due, most astronomers now believe, to the release of nuclear and gravitational energy respectively), the association with rapidly expanding gas clouds (supernova remnants), and the association, at least sometimes, with collapsed objects at nuclear densities (neutron stars and pulsars), as outlined by R. Kirshner (University of Michigan) at a recent meeting•.

Type I events go off within relatively old stellar populations, in elliptical galaxies and between the arms of spirals. Their immediate progenitors are generally thought to be degenerate cores of C, 0, Ne, Mg group elements, covered by a thin or thick envelope of helium. Such cores can arise either through mass transfer onto a white dwarf in a closed binary system or through stellar winds removing the hydrogen envelope from a 4-8 solar masses ($M_\odot$) star as it evolves. The explosions, reviewed by J.C. Wheeler (University of Texas), W .D. Arnett (University of Chicago), K. Nomoto (NASA-Goddard Space Flight Center), T.A. Weaver (Lawrence Livermore Laboratory), P. Sutherland (University of Texas) and S.R. Schurmann (University of Michigan), result from detonation or deflagration of the degenerate core, the fuel burning rapidly at high temperature. The dominant product is 0.2-1.4 $M_\odot$ of ^{56}Ni, which is radioactive and decays to ^{56}Co and then ^{56}Fe, with half lives of about 6 and 60 days respectively.

Gamma rays from these decays, greatly downgraded by scattering through the helium envelope, are then responsible both for the initial light outburst and for its exponential decay, also with a half -life of about 60 days. The spectra of such events, reviewed by T. Axelrod (Lawrence Livermore Laboratory) and D.R. Branch (University of Oklahoma), show no evidence of hydrogen, but essentially normal ratios of N, Mg, Na, S, Ca and so on, presumably embedded in helium, from the unburned envelope. After about 70 days, lines attributable to Co and Fe appear, the Co gradually giving way to the Fe on a time scale comparable with its half-life.

This coherent picture is somewhat disturbed by the implications of X-ray observations of several galactic remnants. According to discussions by F. Winkler (Middlebury College), J.M. Shull (University of Colorado) and F. Seward (Center for Astrophysics), the remnants Pu p A, Tycho and Cas A show excesses of intermediate weight elements (0, Ne, Si, and so on) but not of Fe; and the Tycho and Cas A remnants have masses near 15 $M_\odot$. None of these, admittedly, is known with certainty to have been a Type I, but Tycho especially is often advertized as such.

Type II events occur only within very young stellar populations, such as in spiral arms. They apparently terminate the lives of massive stars (8-100 $M_\odot$) with extended ($\sim 10^{15}$ cm) hydrogen envelopes. The basic instability arises when nuclear burning produces an inert iron core in excess of the Chandrasekhar mass. Electron capture sets in, 'deleptonizing' the core and removing the degenerate electron pressure support that has been holding it up. Quite a modest amount of this is enough to send the central 0.6 $M_\odot$ or so of the core hurtling inwards. Neutrinos are trapped within the core and their degeneracy temporarily halts electron capture when the number of neutrons is roughly 1.4 times the number of protons (most of them still in rather exotic nuclei). As the inner core reaches nuclear densities, its equation of state suddenly stiffens, sending a shock wave back out into the remaining iron. This is called core bounce.

Just what happens next and how core bounce produces an observable supernova is both rather complex and rather uncertain. It was one of the special pleasures of the NATO meeting to hear several of the pioneers of nuclear astrophysics address these issues. H. Bethe (Cornell University) reviewed calculations of the propagation of the shock wave and formation of a compact object. W.A. Fowler (Caltech) discussed electron capture cross-sections and shell-blocking, and their implications for deleptonization, and S.A. Colgate (Los Alamos) addressed the problem of fall-back of the outer stellar layers on to the neutron core. Other aspects of the problem were reviewed by Weaver, G. Brown (NORDITA), A. Yahil (State University of New York, Stony Brook), W. Hillebrandt (University of Munich), J. H. Applegate (Caltech) and S.E. Woosley (Lick Observatory). To make a proper Type II supernova light curve, spectrum and expanding remnant, the shock must get out through many solar masses of material, spread over $\sim 10^{15}$ cm, still carrying at least 10^{51} ergs. The hardest barrier to overcome is the remaining iron in the outer core, which extracts energy from the shock via photodissociation to helium and free neutrons. Rotation, magnetic fields and nuclear burning in the outer parts of the star (first discussed in 1960 by Fowler and Sir Fred Hoyle, who was also at the meeting) can all help, but whether or not the shock breaks out is a near thing, and must depend critically on details of the core structure. The answers may come from a new generation of two- (and three-) dimensional hydrodynamic codes now being developed in several places. Type II light curves are well modelled by the shock moving through an extended stellar envelope; and the spectra show the normal, hydrogen-rich composition of the envelope blown out by the shock at 10-20,000 km s-1 • The core presumably ends up as a pulsar, unless fall-back drives it over the stable mass limit for neutron stars into a black hole (perhaps most likely for the most massive progenitors).

Early in the history of the Universe, a third sort of stellar explosion may have occurred. Because the progenitors could have been very massive objects (100-500 $M_\odot$) essentially devoid of heavy elements, we might call them Type III supernovae. In such objects, as discussed by Woosley, R. Bong (University of California, Berkeley), B. Carr (University of Cambridge) and W. Ober (University of Munich), the dominant instability results from electron-positron pair production in the hot, relatively low-density, core. Material expelled from such objects early in galactic evolution could plausibly raise the heavy element abundance of the remaining gas to 1-3 per cent of its present value, mostly in the form of intermediate-weight elements (0-Si) rather than Fe.

An urgent need in the field of supernova research is detailed observations of objects of both types just before and after maximum luminosity, in all spectral ranges. (Young extragalactic supernovae have now been seen as radio, X-ray and ultraviolet sources, as well as optical ones, according to K. Weiler (NSF), C. Fransson (NORDITA), N. Panagia (University of Bologna) and C. Canizares (MIT).) Early identification requires deliberate, organized supernova searches. R. Muller (University of California, Berkeley) and Colgate described the status of their respective automated search projects.

Given adequate funding, both could be in operation within about 2 years, finding supernovae out to the Virgo cluster at a probable rate of several dozen a year. Most of these would be caught several days and several magnitudes before maximum luminosity. Such rapid discovery is particularly important if the Gamma Ray Observatory (with a projected life of only 2 years) is to probe nucleosynthesis by supernovae. E. Kibblewhite and M. Cawson (University of Cambridge) reported a slightly different kind of automated search, now in progress, that can find larger numbers of more distant events on photographic plates, also within a few days of maximum luminosity. Having a large, systematically acquired sample of supernovae will facilitate their use to determine the cosmological parameters H_o and q_o via model atmosphere, standard candle, or Baade-Wesselink methods, outlined by R.V. Wagoner (Stanford University). This latter search should also help enormously to pin down the rates of the two types of event in different kinds of galaxy and, therefore, the nature of the progenitors.

Within our own Galaxy, rates of supernovae and their products now seem to be largely agreed upon, if not understood. G. Tammann (University of Basel) reported a total rate of 1 every 20 years (I: II in a ratio 5:4) based on both historically observed events and extrapolations from the extragalactic rate. A.G. Lyne (Jodrell Bank Observatory) concluded that one pulsar is born every 28 years (probably a lower limit and subject to 50 per cent error) and D. Helfand (Columbia University) noted that the supernova remnant birthrate is only about 1 every 80 years (but is considerably higher, per unit mass, in the Large Magellanic Cloud). In addition, no pulsar or neutron star is associated with many of the historical supernova, if neutron stars cool along the lines outlined by S. Tsuruta (University of Montana), though some intermediate-age remnants (RCW 103, CTB 109, G 21.5, G 74.9, 3C58, Vela and 4C 21.53W) do contain compact, probably non-thermal, X-ray sources, perhaps attributable to relativistic electron acceleration by a pulsar, according to Helfand and R.H. Becker (Columbia University).

The straightforward interpretation of these numbers and observations is that visible supernovae, remnants and pulsars can all be produced independently of the others, though two of the three must occur together frequently and all three occasionally, as in the Crab Nebula, which inspired Baade and Zwicky to some of their original suggestions. The assorted rates are reasonably consistent with the birthrates of the probable progenitors and with what is needed to build up the observed heavy element abundance of the Galaxy over its lifetime.

Each of the expanding supernova remnants has $\sim 10^{51}$ ergs ($\sim 10^{42}$ ergs s^{-1}) to dispose of. A few per cent of this, as discussed by R. Blandford (Caltech), goes into cosmic rays and other non-thermal sinks, but most of it eventually leaves the Galaxy as electromagnetic radiation. It does so by a rather devious route. R. Chevalier (University of Virginia) and C. McKee (University of California, Berkeley) reviewed supernova remnant models in a way that made clear that the expanding remnants and the lumpy surrounding interstellar medium must be treated in a self-consistent way, including transfer of mass, energy and momentum between them. In particular, large, old remnants probably pervade a large fraction of the galactic disk, and should, therefore, be treated as a third, high-temperature, low-density component of the interstellar medium. This may sometimes erupt from the disk as a 'galactic fountain', according to F. Kahn (University of Manchester) and S. Ikeuchi (Hokkaido University).

Still further removed from the initial event, supernova explosions have been blamed collectively for triggering galaxy formation, as explicated by J.P. Ostriker (Princeton University), and the formation of the Solar System. D.D. Clayton (Rice University) presented an impressive body of evidence, drawn largely from chemical and isotopic abundances in meteorites, in opposition to the latter view. He believes that the cloud that collapsed to form our Sun did so as part of the normal, orderly evolution of the interstellar medium, which preserves in dust grains atoms synthesized in many supernovae over many billions of years. We are, indeed, made of starstuff, but very ordinary sorts of starstuff.

*The NA TO Advanced Study Institute on Supernovae was held 29 June-10 July J981 at the Institute of Astronomy, Cambridge.

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