Supernovae. Part I: the events

Virginia Trimble

Astronomy Program, University of Maryland, College Park, Maryland 20742
and Department of Physics, University of California, Irvine, California 92717

Since the heroic era of Baade and Zwicky, our understanding of supernovae has advanced in hops and skips rather than steadily. The most recent jump has been into fairly general agreement that observations of Type I's can be interpreted as the manifestation of the decay of about $1 M_\odot$ of Ni^{56} and observations of Type II's as the manifestation of $\gtrsim 10^{51}$ ergs deposited at the bottom of a supergiant envelope by core bounce as a central neutron star forms. This paper explores the history of these and other ideas of what is going on in supernovae, the presupernova evolution of the parent stars and binary systems, observed properties of the events, and models for them. A later paper (Part II: the aftermath) will address the results of supernovae—their remnants, production of cosmic rays and gamma rays, nucleosynthesis, and galactic evolution—and the future of supernova research.

CONTENTS

I. HISTORICAL INTRODUCTION

A. The heroic age

Supernovae (like Olbers' paradox and the expansion of the universe) must, in one sense, have been discovered by a Zinjanthropan named Og, as naked-eye ones occur half a dozen or so times per millenium (Clark and Stephenson, 1981). In the modern sense of stellar explosions releasing $\gtrsim 10^{49}$ erg in electromagnetic radiation over a year or two, supernovae came gradually to light between 1920 and 1934.

Lundmark (1920), a pioneer here as in many other things, seems to have been the first to realize that, if the spiral nebulae were extragalactic star systems, then some "novae" got very bright. He noted that his 650 000-light-year distance for the Andromeda Nebula implied $M_v = -15$ for S Andromeda (the "nova" of 1885, now called SN 1885*a*; light curve in de Vaucouleurs and Buta, 1981), and suggested that some stars could flare up to luminosities thousands of times larger than those of the nebula concerned. Curtis (1921) took the next step. In the context of the historic Curtis-Shapely debate on the nature of the spiral nebulae, he stated that "the dispersion of the novae in spirals and probably also in our own galaxy may reach at least 10^m, as is evidenced by a comparison of S And with the faint novae found recently in this spiral. A division into two magnitude classes is not impossible." To this period belongs also the first suggestion (Lundmark, 1921) of an association between the Crab Nebula and the Chinese "guest star" of 1054.

Baade and Zwicky (1934a, 1934b, 1934d) drew the definitive distinction between "common novae," with peak brightnesses $M_V \gtrsim -11$, and "super-novae," with peak absolute magnitudes near -13, based on the old ($H_0 = 536$ km sec^{-1} Mpc^{-1}) extragalactic distance scale. The word super-novae was coined in connection with a Caltech lecture course in 1931 (Zwicky, 1940), first appeared in public at the December 1933 American Physical Society meeting (Baade and Zwicky, 1934c), and lost its hyphen in 1938 (Zwicky, 1938a, 1938b). The defining papers included an assortment of prescient suggestions: (a) that the total energy released was $3\times10^{51}-10^{55}$ erg, far in excess of the "nuclear packing fraction"; (b) that "a supernova represents the transition of an ordinary star into a neutron star consisting mainly of neutrons" and having gravitational packing energy $\gtrsim 0.1\ mc^2$; (c) that "supernovae emit cosmic rays, leading to a very satisfactory agreement with some of the major observations of cosmic rays" (including the right flux, if one supernova exploded in the galaxy each 1000 years, releasing 10^{53-54} erg in cosmic rays, which flowed freely out of the galaxy); and (d) that "ionized gas shells are expelled from them at great speeds" so that the cosmic rays should contain nuclei of heavy elements.

Points (a), (b), and (d) stand today. Point (c) requires modification only to the extent that current estimates of the supernova rate ($\sim\frac{1}{30}$ yr; Tammann, 1981) and the cosmic-ray confinement time ($\sim10^7$ yr; Garcia-Munoz, Mason, and Simpson, 1977) reduce the production requirements to $\sim10^{49}$ erg event^{-1}. The total energy suggested in point (a) depended critically on Baade and Zwicky's belief that the visible light was coming from a photosphere only about 10^{13} cm across (like that of a "common nova"), so that the observed flux implied a blackbody temperature of 10^{5-6} K and enormous amounts of flux in the then-unobservable uv and x-ray regions.

Their conclusions were based on 12 supernovae (six in the Virgo cluster, six elsewhere), accidentally discovered between 1900 and 1930, plus S And, Z Cen (SN 1895*b* in NGC 5253), and Tycho's "new star" of 1572, with at most a few points on the light curve of each and no spectral data worth mentioning. More objects and more information on each were clearly needed!

Zwicky (1965, and reminiscences many other places) began deliberate, organized searching for supernovae in 1934, with a $3\frac{1}{4}$-in. Wollensak lens camera, mounted on the roof of Robinson Astrophysics Lab at Caltech, and in 1936 at Palomar with the 18-in. Schmidt telescope acquired for this purpose. The 48-in. Palomar Schmidt search, lineal descendant of his project, finally closed up shop in 1975, 281 supernovae later, 122 of them having been discovered by Zwicky himself (Kowal, Huchra, and Sargent, 1976, and previous reports in that series). Charles Kowal (private communication) found his 100th supernova a couple of years ago. No other observer is currently in the running for a record (but see Sec. VIII!). Figure 1 shows the rate of discovery of supernovae as a function of time.

Initially, Zwicky catalogued supernovae by numbering the early ones in order of occurrence, then continuing the sequence as he and his colleagues found additional events. A few discoveries on old plate material required one extensive renumbering to keep the catalog in historical order. With the advent of the Palomar Sky Survey, discoveries out of chronological order multiplied rapidly. Zwicky *et al.* (1963) eventually proposed the modern system, in which events are assigned a year corresponding to the time of their maximum light output and a letter, reflecting the order of their discovery (not occurrence) for that year. So far, only one year (1954) has yielded more than 26 supernovae. The two extras were dubbed 1954*aa* and *ab*.

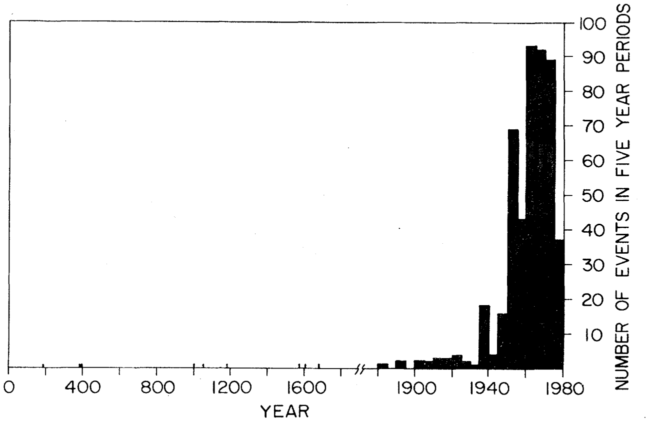

FIG. 1. Rate of discovery of supernovae as a function of time. Bars show number of events known to have gone off in five-year intervals. Some were discovered many years after they occurred on Palomar Observatory Sky Survey plates and other archival material. The time axis changes scale after 1800. Events before that time were all within the Milky Way; events after 1880 all in external galaxies. The rapid increases about 1935 and 1950 indicate the beginning of deliberate supernova searches by Zwicky and collaborators, using first the 18-in. Schmidt then the 48-in. Schmidt telescopes at Palomar.

B. Spectra and their interpretation

A few spectrograms had been recorded by chance before the Palomar search began producing results with 1937*a* in March. Humason (1936) and Baade (1936) discussed the spectra of 1926*a* and 1936*a* (both now thought to have been Type II's) and believed that they were seeing Balmer lines and, probably, NIII at λ 4650, with widths of some 6000 km sec^{-1}. Payne-Gaposchkin (1936a, 1936b) described the spectra of *S* And and Z Cen (the former reported verbally by visual observers and of unknown type; the latter a Type I recorded on a single objective prism plate). She concluded that supernova spectra were really rather like those of common novae, but with much broader lines ($\sim$10 000 km sec^{-1}). Thus, she said (Payne-Gaposchkin, 1936c), supernovae ought to have photospheric temperatures like those of common novae ($\lesssim$20 000 K), radii larger in proportion to the larger linewidths (10^{14-15} cm), and total light outputs of only $\sim10^{48}$ erg. These numbers, allowing for the change in the extragalactic distance scale, agree reasonably well with modern values.

But though Payne-Gaposchkin won the battle, she lost the war. For Zwicky (1936a, 1936b, 1936c) bounced back with the argument that these velocities, plus the amount of mass needed to keep something that big optically thick for a year or more, implied kinetic energies much larger than the visible light output, not to mention, he scolded, the large energies associated with the neutron star, nonvisible radiation, and cosmic rays. In addition, he derived relationships among linewidths, maximum brightness, total visible light output, and duration of outburst that seemed to apply to both novae and supernovae and strongly implied that the latter must be enormously more energetic events. That Nova Lacertae 1936 produced no discernible increase in the cosmic-ray flux received at the Earth (Barnothy and Forro, 1936), seemed at the time also to point to a large energy difference, though the modern reader, thinking of diffusion time scales in the galactic magnetic field, is no longer impressed.

In 1937 came the brightest ($m_v \sim 8.4$) supernova of this century, 1937*c*, in the dwarf irregular galaxy IC 4182. Popper (1937) took one hard look at the spectrum and bravely declared that he couldn't make heads or tails of it. Nor could anyone else, for almost 30 years (Pskovskii, 1969; Mustel, 1972; Branch and Patchett, 1973; Gordon, 1972).

But 1937*c* remained visible for almost two years and, with SN 1937*d* in NGC 1003, formed the basis for the first systematic discussions of supernova light curves (Baade and Zwicky, 1938) and spectroscopy (Minkowski, 1939). Both these (and a couple of other objects for which fragmentary data existed at the time) happened to be Type I events. (Zwicky did not find a Type II until his 36th supernova.) Thus Minkowski concluded that, although the spectra consisted of wide emission bands of unknown origin, they were at least very similar for all supernovae at a given time after maximum light. And the dispersion in maximum luminosity seemed to be very small (Baade, 1938), leading Wilson (1939) and Zwicky (1939) to suggest the use of supernovae as distance indicators for external galaxies. Baade also noted that the late-type spiral galaxies had produced 72% of the (dozen or so) supernovae known to him. The modern number (e.g., Tammann, 1974) is 66%.

The simple picture collapsed with the discovery of 1940*c* in NGC 4725, which Minkowski (1940) described as having a spectrum "entirely different from any nova or supernova previously observed" (at least by him). He proposed, therefore (Minkowski, 1941), a provisional separation into two groups, Type I's, of which he knew (but did not list) nine examples, with the IC 4182 event as prototype, and Type II's, with five examples and the NGC 4725 event as prototype. SN 1941*a* in NGC 4559 belonged, he believed, to neither class. The basic distinction (based primarily on spectra) and the uncertainty about whether additional fundamentally different classes exist persist to the present (Oke and Searle, 1974).

In simplest terms, what counts is the presence (Type II) or absence (Type I) of hydrogen lines in the spectrum near maximum light. As a result, no pre-telescopic supernova can confidently be assigned to either class. A possible connection between outburst type and remnant structure (Weiler and Panagia, 1978) agrees with the traditional assignment of Tycho's and Kepler's new stars to Type I (Baade, 1943, 1945) and requires the supernovae of 1054 and 1181 to have been Type II (cf. Chevalier, 1977). This is not inconsistent with what little is known about their light curves.

C. Supernova remnants and theories

Very few supernova remnants were identified prior to the advent of radio astronomy. Apart from the Crab, Hubble (1937) suggested the Cygnus Loop, and Baade (1943, 1945) found faint emission filaments at the position of Kepler's event. The Tycho field also revealed faint filaments on a 1949 Baade plate (van den Bergh, 1971), which were finally identified as the supernova remnant (SNR) by Minkowski (1959) from a radio position (Baldwin and Edge, 1957).

The Crab Nebula received detailed attention from Baade (1942) and Minkowski (1942). They agreed that the "south preceding star" (i.e., the pulsar; Cocke, Disney, and Taylor, 1969) was quite likely to be the exciting star, based on its color (late *B*) and absence of spectral lines. They estimated a mass of 1 $M_\odot$ for it, on the assumption that the nebular excitation must be due to thermal ultraviolet radiation from the star. Minkowski noted the faintness of the Balmer lines in the nebular spectrum and correctly attributed it to hydrogen deficiency (Davidson, 1979). He calculated a nebular mass of 15 $M_\odot$, and so 16 $M_\odot$ for the presupernova star. The modern number is 9 $M_\odot$, but with considerable mass loss before the explosion (Nomoto, in NATO81; Murdin and Clark, 1981; Davidson *et al.*, 1982).

On the theoretical front, Zwicky's (1938a, 1939) attempts to calculate neutron star binding energies, surface redshifts, and so forth were overtaken by Oppenheimer and Volkoff's (1939) more complete formulation of the problem. The latter yielded a maximum mass of 0.7 $M_\odot$ (neglecting effects of the nuclear force) and binding energy $\sim 10^{53}$ erg (about 10% of mc^2). Zwicky had found 100 $M_\odot$ (an independent discovery, by difficult methods, of the Eddington argument for the maximum mass of a star) and $0.58mc^2$ (roughly analogous to the maximum gravitational redshift from the surface of a stable configuration, as calculated by Bondi, 1964).

The various physical processes included in current models of supernovae and their remnants were first suggested by a host of workers, many still actively engaged in the field. Gamow and Schönberg (1941) attributed the triggering of the collapse of a stellar core to neutrino production, while Hoyle (1946) and Burbidge *et al.* (1957) (better known as B^2FH) blamed photodisintegration of iron, the dominant constituent of the cores of their massive, evolved stars. Hoyle and Fowler (1960) drew attention to the possibility of triggering a supernova by a thermonuclear explosion in a degenerate stellar core, as well as to the energy contributed by nuclear burning in the outer layers of a star whose core collapses. Whipple's (1939) stellar collision model seems to have left no descendants in the supernova field, but has some distant offspring in the realm of quasar models (Woltjer, 1964; Gold, Axford, and Ray, 1965).

The problem of transporting the energy of a supernova explosion from where and when it is released to where and when we see it has not yet been solved to everyone's satisfaction. Baade *et al.* (1956) proposed radioactive decay of Cf^{254} made in the explosion as a way of stretching out the energy releases. More recently, Colgate and McKee (1969), following a suggestion from J. Truran, have cast Ni^{56} in the same role for Type I events. Type II light curves, on the other hand, can be fit by a shock wave moving out through the extended, massive envelope of the progenitor supergiant (Grasberg, Imshennik, and Nadyozhin, 1971, and previous papers cited therein). Colgate and White (1966) suggested that neutrinos produced in the collapsing core would deposit momentum outside it and make such a shock. More recent calculations (Wilson, 1980) blame core bounce for the shock.

The existence of nonthermal (synchrotron) radiation in supernova remnants was predicted by Shklovskii (1953) and verified by Dombrovsky (1954) via the detection of large polarization of the optical continuum radiation from the Crab Nebula. Shklovskii (1960b) also calculated the evolution of an isolated, expanding supernova remnant, while van der Laan (1962) called attention to the importance of interactions with the interstellar medium, particularly for shell sources.

D. Historical literature

The first published review of supernovae (Zwicky, 1940) appeared in these very pages more than 40 years ago. Others (Hubble, 1941, Bertaud, 1941) quickly followed. Additional reviews now largely of historical interest include ones of supernovae-in-general by Payne-Gaposchkin (1957) and Zwicky (1958, 1965); of stellar evolution leading up to supernova explosions by Cameron (1960); of the explosions by Schatzman (1965); and of supernova remnants by Minkowski (1964). Recent reviews, focused on narrower topics, will be noted later in the sections to which they apply. Conference proceedings and monographs covering a wide range of supernova topics include Shklovskii (1968), Brancazio and Cameron (1969), Davies and Smith (1971), Cosmovici (1974), Schramm (1977), and sections in the proceedings of recent "Texas" symposia.

The critical reader will note that the author draws the line between "history" and "current events" precisely where everyone else does — at the start of her own graduate research career. Unfortunately, this line does not correspond to the same year for all of us; and I apologize to those for whom my choice seems either strangely late or ridiculously early.

II. PRESUPERNOVA EVOLUTION OF STARS

A. Single stars

Left to its own devices, a gravitationally bound blob of (mostly) hydrogen gas would proceed through a well-defined series of nuclear reactions as the gas at its center gets hotter and denser under the continued action of gravitation. Each reaction ignites near the center of the star and feeds on the ashes of its predecessors, which continue to occur further out. Laboratory measurements of reaction cross sections versus temperature and density show that the natural sequence is:

hydrogen→helium (via either proton–proton chain or C-N-O cycle)

helium→carbon and oxygen

carbon→neon (and smaller amounts of magnesium, etc.)

neon→magnesium and silicon

oxygen→silicon (and smaller amounts of sulfur, argon, calcium)

silicon→iron (or nickel)

Some real (meaning computer-modeled) stars complete this sequence before getting into serious difficulties (Arnett, 1977a, and references therein). These will turn up again in Sec. II.A.7 below. For many others, the sequence is interrupted.

What happens when and to whom can be organized qualitatively from the following considerations: (1) because gravitational potential energy scales as M^2, the more massive a star is, the more energy per gram available as it contracts, and, therefore, the lower the central density at which it achieves a given central temperature; and, (2) the burning of a degenerate fuel is likely to be explosive because its pressure does not immediately respond to increases in its temperature as energy is released. The next few sections explore interruptions to the natural sequence, with their consequences for supernova production.

1. Electron-positron pair production in stars $\gtrsim 100\ M_\odot$

Souffrin (1960) demonstrated that there is a regime (shown in Fig. 2) near $T=2\times10^9$ K and $\rho<10^6\ \mathrm{g\,cm^{-3}}$, where copious electron-positron pair production lowers the adiabatic index γ below $\frac{4}{3}$. The edges of the regime are set by: (a) at low temperature, few pairs are made; (b) as the density is increased, the pressure comes increasingly from ions and degeneracy, which leaves no room for new pairs except at very high energy, which can only be made at still higher temperatures; but (c) at very high temperatures, pair production is a minor drain on the total energy supply and makes little difference to γ.

Barkat, Rakavy, and Sack (1967) and Rakavy and Shaviv (1967) showed that the cores of massive stars will enter this regime while their dominant constituent is still oxygen. Fraley (1968) and Arnett (1973) also followed massive cores through pair production.

When enough of the core has $\gamma<\frac{4}{3}$, it begins to collapse on a time scale of minutes. As it heats, oxygen

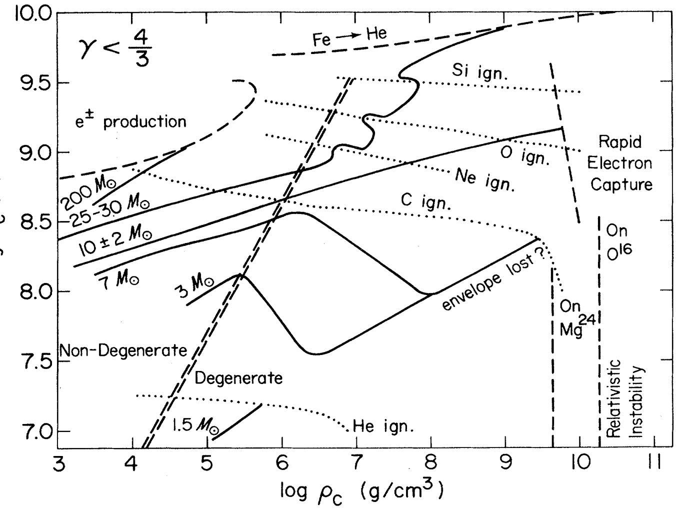

FIG. 2. Presupernova stellar evolution in the central-temperature—central-density plane. Dotted lines show loci of ignition (energy liberated exceeds energy lost by neutrino production, etc.) of helium, carbon, neon, oxygen, and silicon fuels. Double dashed line separates nondegenerate from degenerate conditions. Dashed lines mark off regions of instability due to electron-positron pair production and photodisintegration of iron (upper left) and electron capture and relativistic instabilities (far right). Solid lines are the (slightly simplified) evolutionary tracks for stars of 1.5, 3, 7, 8—12, 25—30, and 200 $M_{\odot}$. Collapse triggered by $e^{\pm}$ production gives way to collapse triggered by photodisintegration at about 100 $M_{\odot}$; photodisintegration of iron gives way to electron capture on lighter elements near 12 $M_{\odot}$; and stars below about 8 $M_{\odot}$ either lose their outer layers before carbon can burn or ignite it explosively. Data taken from Sugimoto and Nomoto (1980); Mazurek and Wheeler (1980); Wheeler (1981a, 1981b).

burning sets in, releasing energy, heating the gas still further, and burning more oxygen, until the equation of state stiffens and the collapse stops and reverses itself. Many cores clearly release enough energy to disrupt the entire star ($\gtrsim 10^{52}$ erg). Various models have yielded ejection speeds of 5000—15 000 km sec^{-1} for the outer layers. Partial disruption can also occur. In the smallest cores subject to the instability, oxygen burning doesn't set in until the center is too tightly bound to be torn apart by nuclear energy release. The inner part of the star then burns on up to iron and perhaps ends up like the "uninterrupted" stars of Sec. II.A.6. In the largest cores that have been modeled, again the disruption is not complete, partly because the gravitational binding scale as M^2 and the energy available from oxygen burning only as M, and partly because the core gets so hot that the products of oxygen burning are photodisintegrated, dropping γ below $\frac{4}{3}$ again. In both cases, the residual cores are in excess of the Chandrasekhar limit, and black holes may result.

What range of stellar masses makes electron-positron explosions? Rakavy and Shaviv (1967) found that 30 $M_{\odot}$ of pure oxygen experienced the instability, while Arnett's (1977a) 32 $M_{\odot}$ of helium just missed it and passed safely on to oxygen and silicon burning. And, at the other end, Fraley (1968) suggested that 100 $M_{\odot}$ of oxygen was about the largest core that could completely disrupt itself. More recently, Woosley and Weaver (in NATO81) had carbon-oxygen cores of 60, 80, and 100 $M_{\odot}$ blow up, while 200 $M_{\odot}$ made a black hole. And, at the low-mass end, where they followed stars all the way from hydrogen burning, 150 $M_{\odot}$ made an electron-positron "supernova," while 100 $M_{\odot}$ was stable at least up to silicon burning. Thus their unstable range corresponds to initial main sequence masses of $\sim$ 100—300 $M_{\odot}$. Ober *et al.* (1982) found a somewhat wider unstable range when the stars began without any heavy elements at all (pure hydrogen and helium, or Population III composition).

The observable consequences of stars in this mass range are rather uncertain. The stars may never form or, if they do, may not stay massive long enough to complete the computed history. The largest well-determined masses of stars in binary orbits are all just under 50 $M_{\odot}$ (Batten, Fletcher, and Mann, 1978; Bohannan and Conti, 1976; Milano *et al.*, 1981). But, more optimistically, comparison of observed HR diagrams for our own and other galaxies with evolutionary tracks (Humphreys and Davidson, 1979; Hutchings, 1980; Garmany and Massey, 1981; Maeder, 1981) indicates that main sequence stars $\gtrsim$ 100—120 $M_{\odot}$ do form, but that they lose mass (down to $\lesssim 60$ $M_{\odot}$) before evolving to red supergiants.

How mass loss affects the nuclear evolution of a star depends on whether it occurs before or after the completion of core hydrogen burning. Early mass loss makes the star mimic a smaller one in its nuclear evolution (as well as making it look fainter near the main sequence because some energy is lost kinetically rather than as light). Late mass loss can change a star's track on the HR diagram, but does not much modify interior evolution.

It is, therefore, consistent to claim that mass loss prevents us from seeing very massive red supergiants, but does not prevent pair production supernovae from occurring. Eta Carinae (Andriesse, Donn, and Viotti, 1978) and R136 (the core of 30 Doradus; Cassinelli *et al.*, 1981) have been suggested as candidates for very massive stars ($\sim$160 $M_{\odot}$ and $\gtrsim$300 $M_{\odot}$) in the midst of this scenario. Alternatively, one might also consistently claim that mass loss prevents pair-production supernovae now, but did not earlier in galactic history. This is possible because mass loss is probably dominated by radiation-driven stellar winds (cf. Papaloizou, 1973, on pulsational mass loss), whose strength depends on the opacity of the stellar envelope and so on its metal abundance, Z. Apparently, Ober, El Eid, and Fricke's $Z=0$ stars all lost their hydrogen envelopes before becoming supergiants (but still reached the instability regime), while Woosley and Weaver's 300 $M_{\odot}$ $Z=0$ and 150 $M_{\odot}$ normal-Z stars both kept their envelopes as a result of the boundary conditions adopted, which does not much help us in choosing between the two cases.

In either case, stars of $M > 100$ $M_{\odot}$ are presently so rare that they cannot give rise to any significant fraction of observed supernovae. Thus we will complete the discussion of the models and comparison with observations for these stars here and not refer to them again except in passing. No detailed work on the light curves to be expected from pair production events seem to have been done; but the Woosley and Weaver explosions will be about 10 times as bright as normal Type II supernovae (if they keep their hydrogen envelopes until the instability sets in), and should be visible out to a redshift of 3—5 with a space-based infrared telescope. Chevalier (1981b, p. 47) has suggested that the "Type V" SN 1961*v*, which was only 0.4^m fainter than its parent Sc galaxy, may have had a progenitor mass near 500 $M_\odot$.

Stars with $M > 100\ M_\odot$ may have been much commoner in the past than they are now, owing to the dependence of Jeans mass on temperature and so on the abundance of the heavy elements that cool astrophysical plasmas. If so, then their contributions to nucleosynthesis early in galactic history may be important. Not surprisingly, they eject large amounts of oxygen and its explosive burning products (Arnett, 1973) and very little iron or heavier elements. In addition, convection between the C-O and He-rich regions results in some nitrogen production (Woosley and Weaver, in NATO81). Both are interesting. The less massive, more normal stars of Sec. II.A.6 probably do not make as much of the Si-Ca (oxygen product) group as we see. And there is observational evidence that very old, metal-poor stars are less deficient in oxygen and its products than in iron (Cohen, 1980), meaning that the former were, on average, made earlier in galactic history. Finally, Edmonds and Pagel (1978) have suggested that, contrary to the usual view that nitrogen is secondary (i.e., made from carbon and oxygen in second-generation stars), at least some of it is primary (i.e., made from hydrogen in a single stellar generation) and co-produced with oxygen. Thus nucleosynthesis in electron-positron supernovae can qualitatively explain some otherwise puzzling observations

Ober *et al.* (in NATO81) calculate that reasonable pregalactic or early galactic processing of gas through 50—500 $M_\odot$ objects can raise the overall heavy element abundance to 1%—2% of its present value, thus providing at least a partial explanation of the total absence of $Z = 0$ stars among even the oldest ones we see. There is, however, some doubt about the stability of supermassive $Z = 0$ stars against pulsational mass loss (Ibrahim, Boury, and Noels, 1981).

It is not improbable that still more massive objects, subject to still more exotic instabilities, may have formed early in galactic history. Their relics, in the form of microwave photons, invisible mass (black holes), and helium (up to two-thirds of what we now see, according to Carr in NATO81) may be conspicuously here even today. But objects with $M \gtrsim 1000\ M_\odot$ are not reasonably describable as stars and their explosions will probably not have resembled observed supernovae very much, so we will leave them for some other reviewer.

2. Degenerate ignition of hydrogen and helium in stars $\lesssim 2\ M_\odot$

Pre-main-sequence contraction of low-mass stars raises their central densities to rather high values. But if the stars don't get hot enough to burn hydrogen nondegenerately, then they will never burn it at all. For, once the electrons are degenerate, then further contraction must cool the ions to supply energy to the electrons. For stars $\lesssim 0.07\ M_\odot$, the maximum ion temperature achieved is less than the 10^7 K at which hydrogen ignites, and this occurs at densities $\leq 10^3\ \mathrm{g\,cm^{-3}}$ (Kumar, 1963), much less than the $10^7\ \mathrm{g\,cm^{-3}}$ needed for pycnonuclear (zero-temperature) degenerate hydrogen burning (Rosenbluth *et al.*, 1973).

Following core hydrogen exhaustion, which terminates the main sequence phase for all stars, the inert helium core contracts and heats; and the star, provided it still has enough hydrogen-rich envelope, evolves toward redgianthood. Three cases are possible. (1) For $\lesssim 0.35\ M_\odot$, the helium becomes degenerate before getting hot enough to burn, and so, like the hydrogen in the previous paragraph, never does, unless the star gains mass through accretion from a binary companion. These stars end up as helium white dwarfs. Do not spend too much time looking for them, though, as the main sequence lifetime of single stars in this mass range is considerably longer than the present age of the universe. (2) For masses $\gtrsim 2\ M_\odot$, the helium ignites nondegenerately, and the star continues the sequence outlined at the beginning of Sec. II.A. (3) For intermediate masses, $\sim 0.35-2\ M_\odot$, helium ignites while partially degenerate, explosively (see Fig. 2). This "helium flash" can produce core expansion velocities as large as the speed of sound, but always much less than the escape velocity (Cole and Deupree, 1980, 1981). Thus the star is shaken up (to horizontal branch or "clump" star structure), but is not disrupted.

Evidently, then, degenerate hydrogen and helium ignition are not important to the supernova problem. They are, however, respectively, the most likely mechanisms for outbursts of "common" novae (Schatzman, 1949; Gallagher and Starrfield, 1978) and x-ray bursters (Joss, 1980).

3. The white dwarf-supernova mass cut

At the next stage of evolution, stars in the 0.35—2 $M_\odot$ mass range exhaust core helium and ascend the asymptotic giant branch while burning helium in a thin shell, but then find their cores of helium-burning products (carbon and oxygen) still too cool to ignite when they become degenerate. Such stars, therefore, end as carbon-oxygen white dwarfs (presumably the commonest sort), after ejecting their remaining hydrogen-rich envelopes as planetary nebulae. They then pass out of our story unless mass transfer from a binary companion (Sec. II.B below) increases their masses and temperatures.

Stars with initial masses larger than 2 $M_\odot$ can also achieve this peaceful end point if mass loss (due to winds, pulsational instabilities, or planetary nebula ejection) strips them down far enough to turn off helium shell burning before the carbon-oxygen core is dense, hot, and massive enough ($\gtrsim 1.4\ M_\odot$) to ignite. The precise maximum mass for which this can occur determines both the numbers and the ages (populations) of stars available to undergo degenerate carbon explosions of various kinds, and is, therefore, of importance.

The number is in some dispute, van den Heuvel (1975) having found 4 $M_\odot$ from the number of white dwarfs in the Hyades, and Romanishin and Angel (1980) $6-7$ $M_\odot$ from several younger clusters, though the cluster membership and white dwarf nature of some of their stars have been questioned (Koester and Reimers, 1981). Calculations of the maximum envelope mass ejectable by dynamical instabilities and the C-O core mass at the time of ejection yield dividing lines of $3-6$ $M_\odot$, depending on mixing length parameter (Fujimoto, Nomoto, and Sugimoto, 1976) and metal abundance (Becker and Iben, 1980), which in turn affect how much of the burned core is eroded away by the convective envelope. Small mixing length and large Z lower the mass limit. Pulsational instabilities can also strip away stellar envelopes in a way that may raise the mass cut to 6 $M_\odot$ or more, even for Population I abundances (Tuchman, Sack, and Barkat, 1979).

My own prejudice is that the upper limit to the mass of stars that can evolve to white dwarfs is genuinely a function of rotation speed, magnetic field strength, initial composition, and (probably) other things, so that there is no real contradiction among the various observational and theoretical determinations. Unfortunately, the resulting conclusion that all (single, unmixed) stars below 3 $M_\odot$ and none above 7 $M_\odot$ become white dwarfs is of very little use for comparison with observed rates of supernovae of various types.

4. Mixing on or near the main sequence

All stars are at least partially convective some time in their lives. Modern evolutionary calculations take account of the mixing produced by convective cores, shells, and envelopes, and sometimes mixing from semiconvection and meridional circulation as well. Such calculations perhaps yield enough mixing to account for the elemental and isotopic abundance anomalies (in C-N-O, lithium, *s*-process products, etc.) seen in giant and asymptotic giant branch stars (discussion in, for example Lambert, Dominy, and Silvertsen, 1980). But no models stir enough hydrogen in toward the core early enough to affect either lifetimes or overall nuclear evolution significantly (Sugimoto, 1971).

Nevertheless, several rare classes of stars have observed properties that it is very tempting to interpret as the result of extensive mixing in $1-3$ $M_\odot$ stars on or near the main sequence. Such classes include the R CrB variables and other helium stars (Paczyński, 1971a) and the blue stragglers (Wheeler, 1979). Extensive mixing, when artificially induced in models and if it occurs in nature, greatly extends the main sequence lifetime, raises the eventual helium (etc.) core mass to anything up to essentially the total initial mass of the star, and depletes or exhausts envelope hydrogen, depending on where and when the mixing is supposed to occur (Saio and Wheeler, 1980).

The subsequent evolution of these stars has not yet been much studied for its own sake. But the work of Paczyński (1971a) and others on low-mass helium stars and the underlying philosophy of Arnett's (1977a) studies of massive isolated helium cores strongly suggest that it ought to be very like the late evolution of similar-mass cores arrived at by normal evolution of more massive progenitors.

Perhaps the most significant point is that, because little stars are much commoner than big stars, evolution of this sort occurring either in a very narrow mass range or in a small bit of rotation-magnetic-field-whatever parameter space could considerably increase the supply of stars capable of degenerate carbon ignition, etc., without noticeably affecting statistics of white dwarfs or planetary nebulae. I confess to a sneaking, somewhat shamefaced fondness for this sort of scenario.

5. Degenerate carbon ignition in $4-8$ $M_\odot$ stars

Of the various interruptions to the natural sequence of nuclear reactions, degenerate carbon ignition is undoubtedly the most devastating. Hoyle and Fowler (1960) suggested that something of the sort might well be the mechanism of Type I explosions. Rose (1969) noted that carbon ignition would occur when his 1.45 $M_\odot$ core was still extended enough for the available nuclear energy to disrupt an entire star. And Arnett (1969) followed carbon detonation in a 5 $M_\odot$ star (with no mass loss), concluding that an outgoing shock wave was formed and the star could indeed be torn apart with sufficient kinetic energy to match observed Type I supernova velocities and light outputs.

Such a carbon detonation supernova cannot help contributing $0.5-1.0$ $M_\odot$ of iron-peak elements to the interstellar medium, since the burning takes place at very high temperature. And it leaves no neutron star. Thus, when Paczyński (1970) showed that the cores of $\sim 3-8$ $M_\odot$ stars would, in the absence of mass loss, all evolve to essentially identical and explosive carbon-oxygen configurations, it sounded as if we were in imminent danger of drowning in iron and having all our pulsars taken away from us (Ostriker, Richstone, and Thuan, 1974).

The core convergence is a result of the unique density-pressure relation of degenerate matter and the balance between neutrino energy losses and hydrogen-helium burning energy production, and is not readily avoided. It consists of the core becoming degenerate while the mass of CO is still less than the Chandrasekhar mass of 1.44 $M_\odot$ (at which point it would ignite nondegenerately) and then gradually growing to the ignition mass as hydrogen and helium shell burning work their way out through the star. Thus stars massive enough to make 1.44 $M_\odot$ of nondegenerate C-O are safe, as are ones where mass loss turns off shell burning before the core grows too big. The traditional risk zone is $4-8$ $M_\odot$.

What, if anything, can avert catastrophe? Core cooling by neutrino emission can produce a temperature inversion and off-center carbon ignition (Boozer, Joss, and Salpeter, 1973) in the smallest carbon-burning cores. Like the analogous off-center ignition of helium (Cole and Deupree, 1980), neon (Sparks and Endal, 1980), oxygen (Woosley, Weaver, and Taam, 1980), and silicon (Nomoto *et al.*, 1979a), this serves to complicate the calculations without much changing the results.

Disruptions of stars by carbon detonation would be avoided if ignition could somehow be postponed until the core was so dense that nuclear energy release could no longer unbind it, thus trapping the newly synthesized iron in a neutron star and solving both halves of the problem at once. Most efforts to achieve this so far have failed (Sugimoto and Nomoto, 1980; Mazurek and Wheeler, 1980; Iben, 1982); but see Sec. IV.D. for a dissenting view.

The early calculations assumed that detonation, in which burning drives a shock wave that initiates further burning, must occur and included such a shock as one of the initial conditions. This yields a self-consistent solution. But real cores apparently do not form the shock (Chechetkin *et al.*, 1977). Instead, heat is carried outward by convection and conduction, and fresh fuel inward by Rayleigh-Taylor instabilities, yielding what is called a carbon deflagration. The outcome depends largely on the rate at which burned and unburned materials come together, the limit of rapid transport tending toward detonation again. Buchler and Mazurek (1975) found that a deflagrating star ejected its hydrogen and helium envelopes, but retained a partially burned core that eventually proceeded to iron and rejoined the scenario of Sec. II.A.7. Nomoto, Sugimoto, and Neo's (1976) deflagration, on the other hand, completely disrupted the star, though iron production was considerably reduced from the detonation case.

Nevertheless, few astronomers still awaken at 3 a.m. worrying about the problem. Partly we have got used to it. But partly also it has come to seem less acute for several reasons: (1) The lower mass limit for degenerate carbon ignition has crept up a bit, as discussed in Sec. II.A.4. (2) The mass cut between explosive and peaceful carbon burning is amenable to being shoved down to ~ 6 $M_\odot$ if envelope convection does not penetrate and erode the core during double shell burning (discussion in Barkat, 1977). (3) Recent, lower, estimates of the pulsar formation rate (1/40 yr, Manchester, 1982) can be matched by deaths of a narrower range of stellar masses, (e.g., $M \gtrsim 7$ $M_\odot$). (4) When due account is taken of the uncertainties in current star formation rates and all the other parameters that enter, the galaxy proves capable of tolerating up to 1 $M_\odot$ of iron per Type I supernova (Tinsley, 1980a).

Thus our present state of knowledge remains consistent with anywhere from none to all of the single stars in the traditional risk zone of $4-8$ $M_\odot$ giving rise to carbon detonation (or deflagration) supernovae. My guess is that enough of them do so to contribute to the population statistics of Type I supernovae discussed in Sec. III.A., but that most of them either terminate as white dwarfs or make it to Sec. II.A.6 below. Detailed models of carbon explosions and their relation to observed events will be expanded upon in Sec. IV.C.

6. Ignition of degenerate oxygen, neon, and silicon and electron-capture instability in $8-12$ $M_\odot$ stars

It has frequently been supposed that, if a star escapes carbon detonation, it is then safe until an iron core grows to instability. This seemed to be the case for the $2-32$ $M_\odot$ helium cores studied by Arnett (1977a), although the 2 and 4 $M_\odot$ ones (corresponding to main sequence masses of ~ 8 and 14 $M_\odot$) followed a fairly complex course. It is still thought to be the case for stars that leave the main sequence with masses $\gtrsim 13$ $M_\odot$ (Weaver, Zimmerman, and Woosley, 1978).

There are, however, at least two other classes of possibilities in the $8-12$ $M_\odot$ range. These are detonation/deflagration of some fuel beyond carbon, leading to disruption of all or part of the star, and instability triggered by electron capture, leading to dynamical core collapse, as proposed by Barkat, Reiss, and Rakavy (1974) for $1.1-1.45$ $M_\odot$ C-O cores, corresponding to $7-10$ $M_\odot$ stars in their calibration. Which occurs, if either, in a given model is currently as much a function of modeler as of main sequence mass.

Weaver, Axelrod, and Woosley's (1980) 9 $M_\odot$ star is apparently on its way to experiencing a disruptive neon deflagration; while Woosley, Weaver, and Taam's (1980) 10 $M_\odot$ model loses its outer layers to a series of explosive, off-center, neon-silicon flashes. The ejection energy is too small to correspond to any of the usual supernova types, but the remaining 1.5 $M_\odot$ core eventually burned through to iron and collapsed like the uninterrupted cores of Sec. II.A.7.

The Japanese group (Miyaji *et al.*, 1980; Nomoto, 1981a; Sugimoto and Nomoto, 1980, and references therein) have considered electron-capture supernovae in some detail. They find that the cores of 8 ± 1 to 10 ± 1 $M_\odot$ stars burn carbon peacefully, but that electrons become degenerate in the resulting oxygen core. Electron capture on Ne^{20} and Mg^{24} sets in before oxygen burning, triggering quasidynamical collapse. The onset of an oxygen deflagration is unable to halt the collapse, which was followed up to a density of 10^{11} $\mathrm{g\,cm^{-3}}$, by which point formation of a neutron-rich core and core bounce seemed inevitable. Further calculations are needed to be sure that the outer layers of the star do not fall back and turn the core into a black hole. The authors believe, however, that core bounce and oxygen deflagration should easily eject the hydrogen- and helium-rich layers. The remaining core is less than the maximum stable neutron star mass; thus stars that electron capture should make up a large fraction of the progenitors of Type II supernovae and pulsars. This conclusion is probably safe for $8-12$ $M_\odot$ stars in general, whether or not they are interrupted en route to iron core formation and for either mode of interruption.

7. Formation of degenerate iron cores in $15-100$ $M_\odot$ stars

The remaining class of massive stars is, perhaps, the most thoroughly studied, models having been followed to

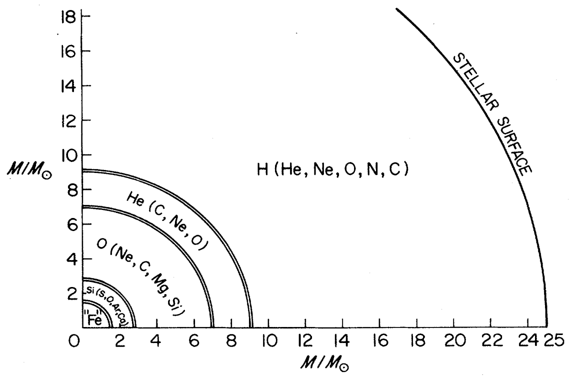

FIG. 3. Interior structure of Population I, 25 $M_\odot$ star just before onset of core collapse. Data from Woosley and Weaver, 1982a. Fe represents assorted iron-peak elements (including neutron-rich ones), Ca^{48}, Ti^{50}, $Fe^{54,56,58}$, Ni^{66}. Other zones are labeled with their dominant constituents, less abundant ones appearing in parentheses. Thin shells between the zones indicate regions where the material of the zone above is burning to form that of the zone below.

within sight of the final disaster for a wide range of core masses, several compositions, and considerable variety of input physics and computational techniques (Rakavy, Shaviv, and Zinamon, 1967; Paczyński, 1970; Arnett, 1977a; Sparks and Endal, 1980; Lamb, Iben, and Howard, 1976; Nomoto *et al.*, 1979a; Woosley and Weaver, 1982b; and many others).

In the absence of major mass loss, these stars carry out the "natural" sequence of nuclear reactions of Sec. A without catastrophic interruption, each new reaction igniting at the center and feeding on the ashes of its predecessors, which continue to occur further out in the star, until a sort of onion structure has been built up around a core of iron-peak elements (Fig. 3).

The evolution of these massive stars is always much faster than that of smaller ones (Table I), because fuel supply scales only as M, while fuel consumption (luminosity) scales more like M^3 (Eddington, 1926). Their evolution becomes rapid even by human standards once the central temperature reaches 10^9 K and the neutrino luminosity (which is not limited by radiation pressure effects on the star) greatly exceeds the photon luminosity.

Different core masses, initial compositions, nuclear reaction rates, and prescriptions for handling semiconvection, etc., result in the same overall structure, but different relative and total amounts of the assorted reaction products. Such variations matter mostly for nucleosynthesis calculations (Sec. VII). In addition, the lower-mass (and lower-initial-Z) stars are, on average, denser, which may affect the ability of core bounce to eject the envelope (Sec. IV.B.2).

Quasihydrostatic evolution continues until the iron core mass approaches the Chandrasekhar limit. Various stars that escaped out the bottom of Sec. II.A.4, 5, and 6 and also manage to build up $1.2-1.5\ M_\odot$ iron cores rejoin evolutionary history at this point.

Nuclear binding is at a maximum near Fe^{56}; thus these cores are not capable of further exoergic reactions, and some form of collapse is unavoidable. Whether they end up as black holes or as neutron stars, eventually they must become neutronized by inverse beta decays ($e+p \rightarrow n+\nu_e$, in or out of nuclei). Indeed some neutronization occurs, so that the dominant species near the center are things like Ca^{48}, Ni^{56}, Cr^{54}, and Ti^{50} (Weaver and Woosley, 1980), but electron capture is not the cause of the initial collapse. Rather, as the central temperature rises above 3×10^9 K, photons begin to break up the nuclei into alpha particles and free n's and p's (Burbidge *et al.*, 1957). The resultant cooling removes pressure support at the center, and the core begins collapsing on a

TABLE I. Central temperatures, central densities, and time scales for Population I stars of initial masses 25 $M_\odot$ and 1 $M_\odot$ at various evolutionary phases. Data for 25 $M_\odot$ from Weaver and Woosley (1980) and for 1 $M_\odot$ from Iben (1974), and references therein.

Phase	T_c (25) (keV)	T_c (1) (keV)	ρ_c (25) (g cm^{-3})	ρ_c (1) (g cm^{-3})	Time (25) (years)	Time (1) (years)
H burning						
core	5	2.5	5	100	2×10^6	10^{10}
shell		2.5→10		$10^3\rightarrow10^5$		10^9
He burning						
core	20	10	700	4×10^4	5×10^5	10^8
shell		10		$4\times10^4\rightarrow10^6$		5×10^7
C burning	80		2×10^5		60	
Ne burning	150		4×10^6		1	
O burning	200		10^7		0.5	
Si burning	350		3×10^7		0.01	
Collapse	600		3×10^9		10^{-6}	

dynamical time scale. We will leave it in this precarious condition until Sec. IV.B.

8. Effects of rotation and magnetic fields

Real stars, even in isolation, are not perfectly spherical. Rotation and magnetic fields distort their shapes and provide nonisotropic pressures within. Evolutionary studies of such stars are very much less numerous and less complete than for spherically symmetric stars. Rotation and magnetic fields appear to have rather similar effects (Tutukov and Ruben, 1974). Much of the early work was discussed at the 1974 Liege Colloquium (Ledoux, 1974); and, more recently, de Loore (1980) has reviewed the subject for the massive stars that largely concern us here. Endal and Sofia's (1979) calculations are the most complete ones published so far, but extend up only to 10 $M_{\odot}$. Some of their C-O cores evolve into bar shapes that may collapse and burn quickly, extending the carbon detonation process to slightly higher masses in stars with interior rotation at close to the maximum possible value. Stothers (1980) has addressed more massive stars with both rotation and magnetic fields, but has not carried them very far from the main sequence.

It would obviously be very interesting to see the results of more calculations of these types for assorted masses and assumptions about angular momentum and field distribution and redistribution; but they may not be very necessary for understanding the main features of supernova progenitors. White dwarfs and isolated neutron stars both tend to be very slow rotators, even shortly after birth (Greenstein *et al.*, 1977; Hardorp, 1974). They are not very readily braked after formation (Brecher and Chanmugam, 1978), thus strengthening the case made by Hardorp (1974) for more or less continuous angular momentum exchange between core and envelope during stellar evolution.

Similarly, most white dwarfs have weak surface fields (Angel, Landstreet, and Borra, 1978), and even the 10^{12} G fields deduced for many neutron stars are far short of what the stars could sustain.

If, as this suggests, rotation and magnetic fields are relatively small perturbations in normal star structure, their most important effect may be interaction to produce mixing (Gross, 1978) with attendant consequences for nucleosynthesis.

Perhaps we should regard distortions from spherical symmetry as reserve guns in our theoretical arsenal, to be loaded and fired only if discrepancies between observations and the simpler calculations appear. Or, as Woltjer (1967) said in another connection, "the larger one's ignorance, the stronger the magnetic field."

B. Binary stars

Half to 90% of all stars in the solar neighborhood are in pairs or multiple systems (Abt and Levy, 1976, 1978). Nevertheless, discussions of stellar and galactic evolution nearly always treat binaries as a minor correction to be tacked onto the end of the main discussion. This is not quite so wicked as it sounds. First, the fraction of stars in pairs close enough for the stars to affect each other's evolution is somewhat smaller, perhaps $\frac{1}{4}-\frac{1}{3}$. Second, for many purposes (including ours here), many of the effects of a close companion are legitimately looked at as corrections, in the sense that they make a star act like one of smaller or larger initial mass, lose mass faster than it otherwise would, and so forth. And finally, one nearly always has to understand the simplest version of any problem before there is much hope of disentangling more complex versions.

Thus the following sections address presupernova evolution of binary systems as modifications to the evolution of the components considered as single stars. The standard reviews of binary evolution are Paczyński (1971b), Thomas (1977), and de Loore (1981), the last emphasizing the effects of mass loss. Eggleton, Mitton, and Whelan (1976) and Plavec, Popper, and Ulrich (1980) contain reports on a number of current research projects.

"Primary" in this discussion will always mean the star that was initially the more massive, no matter what happens to it later.

1. Evolution of the primary

The primary first becomes aware that it is not alone (in the standard, co-rotating, etc., model) when it fills its inner Lagrangian surface or Roche lobe and starts transferring mass across to the lobe of the secondary (Fig. 4). When this happens already at or very near zero age, the system becomes a contact binary, with the stars sharing a common envelope. They eventually merge, or at least evolve to mass ratios $\lesssim 0.2$ in less than the main se-

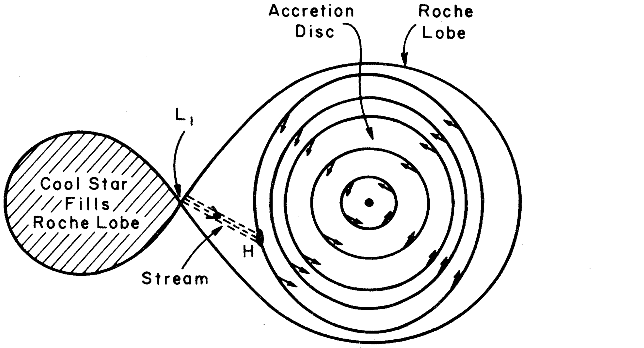

FIG. 4. Idealization of typical cataclysmic binary. A relatively cool (main sequence or giant) star fills its Roche lobe, so that gas is free to stream from L_1 (the first Lagrangian point) toward the hot white dwarf (the dot at the middle of the right-hand lobe). This gas has too much angular momentum to fall straight onto the star, and thus spirals into a disk, from which it gradually accretes onto the star via paths like those indicated by the small arrows. A hot spot, H, is formed where the stream collides with the disk. The white dwarf may eventually accrete enough material to exceed the Chandrasekhar mass limit, and so collapse or explode, presumably as a Type I Supernova.

quence lifetimes of the stars for low-mass (Webbink, 1979a) and some intermediate-mass (Sugimoto and Miyaji, 1980) systems. The time scale is disputed by an order of magnitude (van't Veer, 1980), but in any case the subsequent evolution must be essentially that of a single star. If the system is so wide that the primary never fills its Roche lobe (orbit periods $\gtrsim 20$ yr), again single-star evolutionary tracks apply.

In between come cases (A), (B), and (C), representing mass transfer (A) during hydrogen core burning, (B) during the red giant (hydrogen shell burning) phase before helium iginiton, and (C) during the asymptotic giant (double shell burning) phase before carbon ignition, the three phases in a star's life when its radius is increasing. Which happens depends on the stars' initial separations, (A) for closest and (C) for widest systems. There are numerous models for each of the three cases and many different pairs of primary and secondary masses in the literature.

In general, mass transfer at first goes rapidly, on a thermal (Kelvin-Helmholtz) time scale, because the primary's Roche lobe shrinks as the mass ratio drops towards one. Once the mass ratio is reversed, the lobe grows again, and transfer continues more slowly, on a nuclear time scale, until the primary reaches an evolutionary stage in which its surface shrinks away from the Roche lobe. It is likely that much mass and angular momentum are lost completely to the system during this phase (De Grève and Vanbeveren, 1980), but the qualitative evolution is much the same for mass-losing and mass-conserving cases.

We can be sure that angular momentum loss has occurred because evolved systems sometimes contain white dwarfs and neutron stars massive enough that they must have grown inside giants larger in radius then the present separation of the stars. Such systems include most of the cataclysmic binaries (novae, dwarf novae, etc.) and many x-ray binaries. Evidently, the initial system was wider, and at some point the primary enveloped both cores in a common envelope (Paczyński, 1976, 1979a; Ostriker, 1976; Taam, Bodenheimer, and Ostriker, 1978) to which angular momentum is transferred from the orbiting stars, so that they move together while the envelope is spun off. No observed system has ever been convincingly shown to be in a common envelope phase (they should look about like ordinary giants or supergiants, but more rapidly rotating like the FK Comae variables). The products seem to be common, though, including planetary nebulae with binary nuclei, where we presumably are seeing both stars and the expelled common envelope.

By the time the first mass transfer phase ends, the primary star can easily have been stripped down almost to its hydrogen-exhausted core, producing a Wolf-Rayet binary (Paczyński, 1967) or other sort of helium star (van der Linden, 1980). Thus its late phases resemble those of an initially less massive star. Primaries of $1-3\ M_\odot$ give rise to helium white dwarfs (Paczyński, 1971b), those up to about $8\ M_\odot$ to C-O ones (Webbink, 1979b), and those of $\sim 8-12\ M_\odot$ probably to degenerate dwarfs made of O, Ne, and Si (Nomoto *et al.*, 1979b).

Still more massive stars leave cores massive enough ($\gtrsim 4\ M_\odot$) to proceed via electron capture or photodisintegration of iron to neutron star densities. Understandably, the minimum main sequence mass for which this can happen will depend on the initial separation of the system, etc., and is even more uncertain than for single stars. That it does not happen we are guaranteed by the presence of neutron stars in the bright x-ray binaries. De Loore and De Grève (1976) and van den Heuvel (1976) found that a primary mass of at least $12-15\ M_\odot$ was needed, even if no matter leaves the system. The limit will be still higher when systematic loss of mass and angular momentum is included (Flannery, 1977). The chief difficulties are getting enough systems into the right state for long enough to account for the observed number of high-mass x-ray binaries (like Cen X-3 and Vela X-1; Ziołkowski, 1977) and getting any at all into the state of the low-mass x-ray binaries (like Her X-1 and Sco X-1; van den Heuvel, 1977).

Neutron star formation in this context need not be terribly spectacular if most of the diffuse hydrogen-helium envelope of a normal supergiant has been eaten away by mass transfer and loss to the system. First, a standard Type II light curve won't happen without an extended envelope. Second, mass ejection is likely to be too small to make a conspicuous supernova remnant or to give the system a large recoil velocity. Finally, since the primary (by the time it collapses) is the less massive star, no amount of symmetric mass loss from it can unbind the system. Thus the newborn neutron star will be bathed in a wind from its companion, preventing the propagation of low-frequency radio waves, so we won't even see a pulsar. About half the observed runaway OB stars are likely to be systems of this type (Stone, 1982). Some will evolve into x-ray binaries, and so finally become conspicuous.

Black holes must also be a possible end point of primary evolution. In Cyg X-1, our one good example, the black hole is so massive ($\gtrsim 6\ M_\odot$) that it could not have been "grown" by accretion, even at many times the Eddington rate, onto a neutron star within the lifetime of the system. It is not implausible that black holes come from the most massive primaries ($\gtrsim 100\ M_\odot$), but this is not really known to be so.

2. Evolution of the secondary

The secondary's first job is to accept mass transferred through the first Lagrangian point (Fig. 4) as fast as the primary wants to get rid of it. As the smaller star will have the longer thermal (adjustment) time scale, it cannot possibly, even in principle, succeed. Since Benson (1970) first showed this (and promptly gave up astronomy), a number of calculations have confirmed his basic result—the secondary expands to fill its Roche lobe, too, and the system comes into contact after only $0.1-0.3\ M_\odot$ has been transferred (Neo *et al.*, 1977; Flannery and Ulrich, 1977; Flannery, 1977; Kippenhahn and Meyer-Hofmeister, 1977; Webbink, 1980). Shu and Lubow (1981) disagree. On the basis of calculations of accretion on pre-main-sequence stars (Stahler, Shu, and Taam, 1980), they conclude that the thermal time scale of the outer layers of the mass-gaining star is probably short enough to allow the accreting gas to cool and settle down as it is transferred. The discovery (Plavec, 1980) of a class of binaries in which rapid mass transfer has hidden the receiver in a massive thick disk suggests that there is still a problem to be solved.

None of the published models has so far bridged the gap from disk or contact configuration to one where the more evolved, but now less massive, primary continues to transfer gas on a nuclear time scale to a more-or-less normal looking main sequence primary. But real stars solve the problem somehow, as the latter state is the rather common one of Algol-type binaries. For our purposes, there is no harm in picking up the evolutionary story again at that point.

Once the primary shrinks away from its Roche lobe, stopping mass transfer, the secondary is left to its own devices. Normally, it will still be on the main sequence when the primary has become a white dwarf, neutron star, or black hole, simply because of the steep dependence of stellar lifetimes on mass (cf. de Loore, 1980, Table 5). The system experiences a quiescent period, during which it need not look much different from an isolated star of the secondary's new mass. This can be long enough for a white dwarf primary to cool well below its $\sim 10^8$ K formation temperature and even to undergo chemical differentiation and freezing (Canal *et al.*, 1980a, 1980b). The wind from a massive secondary impinging on a neutron star primary during this phase can already be enough to produce some classes of x-ray sources.

Eventually, the evolving secondary will expand to fill its Roche lobe and, in turn, transfer material back onto the compact primary. For at least some transfer rates, the systems with white dwarfs appear as cataclysmic variables (Robinson, 1976) and those with neutron stars and black holes as x-ray sources (Tananbaum and Hutchings, 1975; Lamb, 1975). Rapid transfer can again lead to a common envelope phase and angular momentum loss, so that the two stars complete their evolution very close together, (Paczyński, 1979a, 1979b) like the 18-min-period binary white dwarf AM CVn and the best-known binary pulsar, 1913 + 16 (Hulse and Taylor, 1975).

What happens next will depend on whether the primaries keep the matter they accrete. The black holes necessarily do and gradually increase in mass at a rate of perhaps $10^{-6-7}\ M_\odot\,\mathrm{yr}^{-1}$ (for 5% efficiency in x-ray production and the maximum luminosity allowed by radiation pressure). Neutron stars also have deep enough potential wells that gas once accreted cannot be lost again. Their masses too will increase and may be driven above the maximum that is stable (whatever it is: Gao *et al.*, 1981), resulting in further collapse. Because a neutron star is only about a factor of 3 larger than its Schwarzschild radius, such a collapse will not release much energy and need not be at all a spectacular event.

Mass retention by white dwarfs is more complex. Those systems that explode as novae must accrete at least $10^{-4-5}\ M_\odot$ of hydrogen to do it, but need burn much less ($10^{-7-8}\ M_\odot$) to make the observed events (Gallagher and Starrfield, 1978). In fact, in order to turn off the explosion, the unburned hydrogen must be cooled by expansion and expulsion from the star. The reaction products can remain. But if the white dwarf keeps only about 1% of what is transferred to it, then the average donor will be able to increase the white dwarf's mass by only 0.1 $M_\odot$ or less, hardly enough to trigger interesting structural changes except in a very few borderline cases.

The accretion that gives rise to these explosive configurations normally occurs in a disk, and except perhaps in the recurrent novae, at rates $\lesssim 10^{-9}\ M_\odot\,\mathrm{yr}^{-1}$. For spherical accretion and higher rates (e.g., $10^{-8}-10^{-5}\ M_\odot\,\mathrm{yr}^{-1}$), a complex assortment of hydrogen and helium shell flashes ensues (Paczyński and Żytkow, 1978; Nomoto, Narai, and Sugimoto, 1979; Taam, 1980a, 1980b). These flashes are rather like the ones that occur during double shell burning in single stars and do not necessarily expel any gas. We probably see some systems in this second mass transfer phase. For very large transfer rates, the infalling matter builds up to a red-giant-type envelope. Somewhat smaller transfer rates seem to produce two of the subclasses of symbiotic stars (Paczyński and Rudak, 1979); and where both components are of low mass, the systems may appear among the nova-like variables and binary OB subdwarfs, though not among the dwarf novae, according to Papaloizou, Pringle, and MacDonald, (1982; responding to a model proposed by Starrfield, Truran, and Sparks, 1981).

Thus, in the absence of nova explosions, the white dwarf will gradually increase its central density and (owing to heating by the flashes) often also its central temperature. This cannot continue indefinitely. On the one hand, if the central density reaches $10^{10}\ \mathrm{g\,cc}^{-1}$ before anything else happens, the core will not be disrupted by any sort of explosions, and a neutron star can result (Barkat, Buchler, and Wheeler, 1971; Bruenn, 1972; Chechetkin *et al.*, 1980). This appears to require either chemical fractionation (Canal, Isern, and Labay 1980a, 1980b) or neglect of shell-flash heating (Ergma and Tutukov, 1976) in a C-O white dwarf, or electron capture in an O-Ne-Si one (Miyaji *et al.*, 1980). On the other hand, ignition at lower density, arising either at the center or in a detonation/deflagration wave propagating from one of the shell flashes, typically disrupts the star (Nomoto, 1982a, 1982b; but see Sec. IV.D. for a dissenting view).

The ignition temperature, density (core mass), and mode will depend on whether the white dwarf was made of He or C-O, on its initial mass, on how much it cooled before accretion began, and on the accretion rate (Sugimoto and Nomoto, 1980). Disruption of the star and expulsion of several tenths of a solar mass or more of iron-peak elements are likely in all cases. As the result should resemble a Type I supernova, we will leave the primaries smoldering away until Sec. IV.A.

3. Last things

Finally the secondary will complete its evolution, ending in a white dwarf, degenerate ignition disruption, a neutron star, or a black hole, depending on the mass it had after the first transfer phase and the amount lost in the second transfer phase (and whatever besides mass matters!). As the secondary is now likely to be the more massive star, it can unbind the system via a symmetric supernova explosion (with or without compact remnant). This perhaps accounts for the rarity of binary ratio pulsars in comparison to the number of neutron stars in x-ray-emitting binaries.

Failing such disruptions, systems can remain as bound but detached pairs of compact objects for very long times. Once the secondary's planetary nebula or pulsar emission fades, these will be remarkably inconspicuous. Nevertheless, a few binary white dwarfs have measured orbits (e.g., G107-70 with $P=20.5$ yr; Christy *et al.*, 1980), and others are probably hiding among white dwarfs with composite spectra. Not surprisingly, nonpulsar double neutron stars and double black holes remain thus far unidentified.

Binaries with two compact objects can continue to lose angular momentum via magnetized winds and must lose it via gravitational radiation. If a common envelope phase has left a system with an orbit period of a fraction of a day or less, the stars will merge in less than a Hubble time. A black hole capturing a white dwarf or neutron star this way squirts out much of the mass along its rotation axis—the "tube of toothpaste" effect. Lattimer and Schramm (1974) have suggested that the highly processed material thus expelled from neutron stars could contribute significantly to nucleosynthesis; one such event each 2000 years could, for instance, make all the neutron-rich isotopes heavier than iron that we see. If two white dwarfs, each of more than half the Chandrasekhar mass, coalesce, the results may be spectacular and could look like some sort of hydrogen-deficient supernova.

Even after binaries have broken up or coalesced to single white dwarfs, neutron stars, or black holes, interesting things can still happen to the stars (Dyson, 1979). But none of them are likely to be supernovae, and the stars depart at last from our narrative.

III. OBSERVATIONS

A. Rates, types, and parent populations

1. Frequency of supernova

Supernovae are rare. There has not, for instance, been one spotted in our galaxy at least since 1680 (Ashworth, 1979). Just how frequently they do occur, and how this depends on galaxy type, mass, luminosity, composition, or whatever, matters both for constraining parent populations and for deciding how much each event must contribute toward nucleosynthesis, cosmic rays, and pulsar production. Determination of realistic supernova rates is greatly complicated by the incompleteness (moderate to gross, depending on who you believe) of all existing surveys. In addition, real variations of rate with galaxy type and luminosity often make subsamples too small for reliable statistical analysis; and real differences between galaxies of the same Hubble type and luminosity probably exceed the statistical uncertainties. The difficulty of the task has not prevented repeated efforts at supernova rate determination.

Baade and Zwicky (1934a, 1934b, 1934c) initially suggested a rate of about one per thousand years in large galaxies, on the basis of about a dozen events known to them. As the 18-in. Schmidt survey got under way, Zwicky (1938c, 1942) revised this upward, first to 1/612 yr, then to 1/359 yr. And there he dug in his toes and would yield no further, on the grounds that the difficulty of putting later surveys all onto any one system of magnitudes, completeness, etc., prevented any improvement of the statistics, even after another 100 supernovae had been found (Zwicky, 1974). Meanwhile, Shklovskii (1960a) had noted that the five or so historical supernovae seen in a rather small part of the Milky Way over the past thousand years must imply an overall rate of one per 30–60 yr, and that other galaxies, in which more than one supernova had been spotted since 1900,

TABLE II. Supernova frequency per 100 years per $10^{10}\ L_{\odot}$ as a function of galaxy type. Data from Tammann (in NATO81).

Type	Total number of events in sample	SN rate	SN I rate	SN II rate
E	13	0.22	0.22	0.0
SO	6	0.12	0.12	0.0
SOa, Sa	9	0.28	0.28	0.0
Sab, Sb	38	0.69	0.37	0.32
Sbc, Sc, Scd, Sd	93	1.38	0.77	0.61
Sdm, Sm, Im	11	1.02	0.83	0.19
IO	7	a	a	a
Milky Way				
As Sb-Sbc		1.03	0.57	0.46
Historical events	7	1.62	0.92	0.69

[a] Unknown, due to corrections for internal absorption.

must have comparably high rates. Kukarkin (1965) found rates as high as 1/15 yr for multiple-event galaxies and an average of 1/35 yr for Type I's alone. The discrepancy is not quite as large as it sounds. Zwicky always insisted on treating all galaxies with $M_{pg} \leq -15$ (for $H_0 = 100\ \mathrm{km\,sec^{-1}\,Mpc^{-1}}$) as equal; and it is clear that, as far as supernova production goes, some galaxies are more equal than others. In addition, he chose not to allow for any incompleteness based on systematic missing of relatively faint events ($M_{pg} = -11$ to -14) or of events in galaxies seen edge-on.

Recent determinations of the supernova rate (Tammann, 1974, 1981, and references therein) come rather close to the Shklovskii number for the Milky Way, but normally scale the rate per unit luminosity of the parent galaxy and find different rates for different galaxy types, as shown in Table II (from Tammann, 1981). The rates are divided between Type I and Type II on the basis of the relatively few events of known type in each class of galaxy. Other types, even if they are physically distinct, are too rare to affect the numbers at present levels of precision.

Features of the table that sound like they ought to be explained include: (a) the restriction of Type II's to galaxies showing strong spiral structure; (b) the reduced rate of SN II's in the most gas-rich galaxies (Sdm-Im, the latter meaning irregulars like the Small Magellanic Cloud), which is not of enormous statistical significance, but puzzling, if true; (c) the roughly equal rates of SN I's and SN II's in galaxy types where both occur; and (d) the increase in both total rate and rate of Type I's along the sequence from elliptical (E) and lenticular (SO) galaxies to spiral (S) and irregular (I) ones. This sequence corresponds to one of increasing predominance of disk structure and Population I (young) objects, like gas and massive stars. But as these are completely absent in many E galaxies, SN I's cannot arise exclusively in extreme Population I objects. No rate is given for the amorphous IO galaxies, because their internal absorption is so large and poorly known that it cannot be corrected for. One of them (NGC 5253) has had two supernovae, both of Type I, and at least the SN I rate is probably high (Thompson, 1981).

Fluctuations from one galaxy to another larger than implied by the statistical uncertainties of Table II are almost certain to be expected. The five Sc galaxies in which three or more supernovae have been spotted since 1900 (NGC 3184, 4303, 4231, 5236, and 6946 for which 1980*k* made five) are just relatively nearby, face-on systems in which most events that happened have been seen and are not really out of statistics. But galaxies with active nuclei supported by bursts of star formation (like NGC 7714) clearly should be, as the predicted SN II rate from massive stars is about one per year (Weedman *et al.*, 1981). Interacting galaxies may also have higher-than-average supernova rates (Smirnov and Tsvetkov, 1981). No anomalously low rates have been seen or predicted. They cannot be excluded, either, and one event in the Local Group in the past century (SN 1885*a* in Andromeda) is distinctly at the bottom of the expected range.

For our own Milky Way, we expect (Tammann, 1981) 40 events per millenium (22 I's and 18 II's), if the galaxy is normal for its type (Sb-Sbc) and disk luminosity ($M_B = -21$). This is in quite good accord with the value determined from observed events over the past 10^3 yr. About seven historical supernovae (1006, 1054 = Crab Nebula, 1181 = 3C58, 1572 = Tycho, 1604 = Kepler, 1680 = Cas A, and either 1408 = CTB 80 or MSH 11−54 = not seen owing to extreme southern declination) all occurred within a pie-shaped sector of the galaxy, about 50° across as seen from the center, with the sun on the median line. Even this sector requires some correction (a 20% increase according to Tammann) for events missed inside galactocentric distance 5 kpc and outside 15 kpc. Thus the disk as a whole should have had 63 supernovae per millenium, 36 I's and 27 II's, if we assign 1054, 1181, and Cas A to Type II and the rest to Type I (on the not-very-secure basis of evidence drawn from remnant structures, light curves, deduced maximum brightnesses, and locations in the galaxy). Clearly these numbers are quite uncertain, the more so as some of the types and SN/SNR associations are debatable (Chevalier, 1976, on Cas A and van den Bergh, 1981, on SN 1480, for instance). The straightforward average of the rate determined historically and that from external galaxies is $50/10^3$ yr, or one SN each 20 yr.

The galactic supernova rate is slightly constrained by several other things we think we know. Considerations of nucleosynthesis, cosmic-ray production, and gamma-ray background fluxes appear in Secs. VI and VII. Here we might note:

(a) No radio supernova as bright as 1970*g*, 1979*c*, or 1980*k* (all Type II's) has been caught in any survey of the Milky Way. As the received flux would have exceeded that from Cas A by factors of 10−300, probably there has been none, at least in the last 20−30 yr (Weiler *et al.*, 1981). Comparable constraints from x-ray observations are less stringent, as the survey period is shorter, though an object like 1980*k*, with $L = 2\times10^{39}\ \mathrm{erg\,sec^{-1}}$ in the 0.4−4-keV band (Canizares, Kriss, and Feigelson, 1982) would have been one of the brightest sources in the sky had it happened anywhere in the Milky Way and not been heavily obscured. The bright radio and x-ray emission apparently lasts a couple of years.

(b) The pulsar birthrate, after many rises and falls, has settled down to about one per 30 yr (Lyne, in NATO81; Manchester, 1982), suitable allowance being made for beaming and other selection effects. The nearness of this to the galactic supernova rate is probably somewhat fortuitous. On the one hand, theory suggests several ways of making neutron stars in nearly "silent" supernovae, when bare cores collapse (Sugimoto and Nomoto, 1980; Chevalier, 1981e).

And, on the other hand, it is virtually certain that not all the historically recorded supernovae produced pulsars, beaming or no beaming, as the remnants do not all show evidence for continuous energy input. SN 1006, 1572, and 1604 did not even make neutron stars, if we understand at all how they cool (Nomoto and Tsuruta, 1981). 3C 58 and CTB 80 (SN 1181 and 1408?) do, however, show compact, synchrotron-spectrum, x-ray sources (Helfand, in NATO81), which may represent pulsars aimed away from us.

(c) The rate of formation of radio-emitting supernova remnants in the Milky Way is about 1/80 yr (Caswell and Lerche, 1979). This should be closely related to the supernova rate—something has to be blown out to make SN light curves and spectra come out right, and gas expelled at high enough energy to make a remnant can't help but radiate. The catch is that remnants remain visible only so long as they are either being fed by a pulsar or are sweeping up interstellar gas of reasonable density. Thus remnants of events occurring far from galactic plane or in other low-density regions (Higdon and Lingenfelter, 1980) disappear quickly from view. This shows up in characteristic scale heights of events versus remnants, and the lower remnant-formation rate becomes explicable. It is of some interest that the rate of formation of remnants in the Magellanic Clouds is about equal to the expected supernova rate there (Long, Helfand, and Grabelsky, 1981), suggesting that the interstellar medium in them is dense enough to support a remnant anywhere a supernova goes off. M31 (Andromeda) shows a SN/SNR rate discrepancy in the same direction as the Milky Way, while M33 has, if anything, more remnants than one per supernova (reflecting statistical uncertainties in the rates and errrors in the SNR age determinations, presumably), according to Dennefeld and Kunth (1981). The correlation between SNR's and pulsars is also highly imperfect. This is partially observational selection—most pulsars are old and nearby (or they wouldn't be bright enough for us to see), while most SNR's are young and far away (as we survey the entire galaxy). This is really a statement about the different rates at which the two kinds of emission die away with time. But some short-period (young?) pulsars are conspicuously remnantless (including PSR 1913 + 16, the best-known binary), and some nearby remnants (the historical ones and others) seem to be pulsarless. No SNR is known for sure to have a nonpulsar neutron star in it, but there are several possible and probable associations between remnants and compact radio or x-ray sources (Helfand, in NATO81; Becker, Helfand, and Szymkowiak, 1981; Fahlman and Gregory, 1981; Bovkoon and Zhouck, 1981). On the other hand, W50 is perhaps more the product of SS433 than of an initial supernova explosion (Shklovskii, 1981a). And some other compact radio source in or near SNR's (Ryle *et al.*, 1978) are apparently chance superpositions (Seaquist and Gilmore, 1982; van Gorkom *et al.*, 1982; Higgs *et al.*, 1981; Sieber, Salter, and Mayer, 1981). Finally, there is modest evidence that it is systematically Type II supernovae that make both pulsars and SNR's with filled centers (plerions or Crab-like remnants; Panagia and Weiler, 1980; Chevalier, 1980). These correlations are not universally accepted (cf. Sec. IV.D).

Thus, although radio and x-ray observations of supernovae, remnants, and pulsars in principle constrain the SN rate determined optically, we cannot at the moment say much more than that there seem to be enough supernovae to account for all the things that are supposed to be made by them!

2. Classification of supernovae

There are two kinds of supernovae, Type I and Type II, distinguished by the absence or presence of hydrogen lines in their spectra near maximum light. Type II's occur among Population I stars, and Type I's occur among Population II stars (broadly interpreted). This confusion of nomenclature is a result of historical accident, not deliberate malevolence. The rest of this section and the one that follows are devoted to the longstanding debate on whether or not it is necessary to say anything more on the subject.

Classification of a supernova as Type I or Type II is usually easily achieved by looking for the hydrogen lines on one well-exposed spectrogram taken near maximum light (see Figs. 6 and 7 in Sec. III.B below). Many of the objects for which this has been done also had their apparent magnitudes measured at many times. The resulting light curves (Figs. 8 and 10 in Sec. III.C below) are, on average, different for the two types. This fact is not very useful for classification purposes, for if nobody took a spectrum (because the object was very faint, or because it was discovered on old plate material long after it had faded from visibility, or because the available observing time was clouded out, or whatever), chances are nobody did enough photometry to yield a classifiable light curve either. The chief exception lies in the pre-telescopic Milky Way supernova events, for which there have been many attempts to reconstruct useful light curves from the historical descriptions ("yellow and as big as a mat," "as bright as Jupiter but red," "visible by day like Venus," and so forth). These are critically discussed by Clark and Stephenson (1977). Classification on this basis is clearly not of very high reliability. SN 1054, for instance, has evolved from Type I (Minkowski, 1964) to neither (Minkowski, 1971) to Type II (Chevalier, 1977) within living memory.

Starting from a framework of two clearly distinct types, two sorts of modification are possible—fewer types or more. Tammann (1977b) has outlined the case for the underlying similarity of all supernovae. It includes objects with intermediate or unclassifiable spectra, at least one with a Type II spectrum and a Type I light curve, the overlap of luminosities between the two classes, and the underlying physical similarity implied by the spectra (Fairall, 1972, 1974; Arp, 1961; Kirshner *et al.*, 1973a; and other references in Tammann, 1977b). It is my guess that these similarities and overlaps mean that in both cases a lot of energy is in a hurry to get out through a lot of atoms, so that the sources of the energy and the initial states of the atoms do not matter as much as they would in less violent circumstances.

Proliferation of types can be achieved in two ways—adding new classes or dividing up the existing ones. Zwicky (1965) advocated three additional, physically distinct, but rare classes. His Type III (protoype 1961*f* in NGC 4304) had a II-ish spectrum (and is so classed by Oke and Searle, 1974) and a light curve with an unusually broad maximum and slow decline. Type IV (prototype 1961*f* in NGC 3003) had a I-ish spectrum, though with faint Hγ emission, and a light curve with stepped decline. The prototype V, 1961*v* in NGC 1058 (1961 seems to have been a good year for new kinds of supernovae), was recorded on sporadic, chance plates at about 18^m for more than 20 yr before rising about 6^m to a doubled-peaked maximum luminosity well within the normal supernova range. It then declined some 10^m over the next nine years, looking nebulous in 1968 and 1970 (Branch and Greenstein, 1971). The spectrum was of Type II, showing an ejection velocity near 2000 km sec^{-1}, the presence of both hydrogen and helium, but with an He/H abundance ratio about four times solar, and an ejected mass of 0.3 $M_\odot$ plus whatever neutral gas was also present (Branch and Greenstein, 1971). This all sounds remarkably reminiscent of something that might evolve into a Crab Nebula, presumably accounting for Zwicky's occasional remark (which I have not located anywhere in print) that SN 1054 was a Type V. He included also Eta Carinae in this class. About three more events have been assigned to each of Types III, IV, and V by one author or another (cf. Sargent, Searle, and Kowal, 1974; Barbon, Ciatti, and Rosino, 1979). The claim that Zwicky defined yet another three types, VI–VIII, with no examples at all (Sciatti, 1965) is a foul calumny.

In addition, Chevalier (1976) has proposed that the event giving rise to Cas A may have been of a third, rare type, coming from a massive star that had lost its hydrogen-rich envolope, thus accounting for the relative faintness of the event and the composition of the remnant. Jura and Morris (1981) suggest that Betelgeuse (a massive star with a high mass-loss rate and a circumstellar shell containing gas that has been processed through the C-N-O cycle) may eventually produce a remnant like Cas A. Imshennik and Nadyozhin (1982) believe that Crab-like remnants are the product of another rare type, neither I nor II in the usual sense.

The proliferative alternative to distinct new types is subdivision of existing ones. Barbon, Ciatti, and Rosino (1973) appear to have been the first to suggest that Type I light curves differed by more than the observational errors in a way that implied subtyping, as "fast" and "slow" in rate of decline from maximum brightness. They regarded the subtypes as distinct and found correlations with ejection speed ("fast" decline=low ejection velocity), parent galaxy type ("fast" underrepresented in E galaxies, "slow" in irregulars), colors, and maximum luminosities ("fast"=bright).

The possibility of distinct subtypes of SN I's is attractive as we look ahead to perhaps modeling them with two rather different kinds of progenitors (degenerate cores formed in close binaries or in intermediate-mass single stars). Unfortunately, although subsequent work has confirmed real variations in decline rate and their correlations with expansion velocity (Pskovskii, 1977; Branch, 1981a), it has also tended to smear the subtypes into a continuum (Barbon, 1980, demurs). Pskovskii explained the direction of the velocity-decline correlation as the tendency of a rapidly expanding photosphere to cancel out part of the fading that would otherwise have been seen. Unfortunately, the next level of sophistication in modeling (Chevalier, 1980) predicts a correlation of the right magnitude (25% in velocity for a 50% difference in time scale) but in the opposite direction to that observed.

These models also show a correlation of maximum luminosity with decline rate, in the sense that fast SN I's should be about half a magnitude brighter than slow ones. A correlation in the opposite direction, with the slower events the brighter ones, shows up in the models by Nomoto (1982b) in which both helium and carbon detonate. The real correlation must be weak, as "fast=bright" (Barbon, Ciatti, and Rosino, 1973), "fast=faint" (Pskovskii, 1977; Branch, 1981a), and "no discernable difference" (Barbon, Cappaciolli, and Ciatti, 1975; Tammann, in NATO81) have all been claimed at about the half-magnitude level.

Type II supernovae are also amenable to subdivision. Pskovskii (1978) suggested a continuum of light curve types, based again on rate of luminosity decline, rapid decline being correlated with small expansion velocity. He attributes this, as for the Type I's, to the effects of a slowly or rapidly expanding photosphere, but (also as for the Type I's) models (Falk and Arnett, 1977) yield velocity-rate correlations in the opposite sense to that seen. Pskovskii found no significant difference in maximum brightness associated with decline rate. Barbon, Ciatti, and Rosino (1979), on the other hand, proposed two distinct subtypes, based on whether or not the declining part of the light curve shows a plateau. Their plateau SN II's tend to be Pskovskii's slow ones and their linear-decline SN II's his fast ones, but the correlation is not perfect. Barbon, Ciatti, and Rosino (1979) do not report luminosity, color, or velocity differences associated with their subtypes. But Branch *et al.* (1981) suggest that linearly declining light curves may occur among the lowest-mass stars capable of making SN II's ($8-10\ M_\odot$).

In summary, the division into Type I and Type II results in samples that are more uniform in light curve, spectrum, and luminosity (Tammann, in NATO81) than the total population of supernovae. Additional uniformity can be achieved by tossing out some of the weirder events. There is no obvious physical way to choose between labeling the rejects "I peculiar" and "II peculiar" and assigning them new classes, III, IV, V, etc. The remaining subsamples still show variations larger than observational errors in all the properties one can think of, some of the properties being correlated in ways that are not easily modeled. Under these circumstances, it is not surprising that scatter can be reduced by subtyping, but the available data do not enable us to decide whether the subtypes are distinct statistically (let alone physically) or part of one or more continua.

3. Parent populations (It's a wise supernova that knows its own father)

No supernova (apart from the Type V in NGC 1058) has ever been caught more than a few days or a few magnitudes before its peak luminosity. We cannot, therefore, say anything very direct about what the progenitor stars look like. The most interesting upper limit comes from SN 1970g, for which Kristian (1976) found a preoutburst brightness of at most $M \sim -6$, corresponding to a mass $\lesssim 35\ M_{\odot}$. Various indirect pieces of evidence do, however, somewhat constrain the identities of the exploding stars.

Type II supernovae arise within Population I. This, at least, has not been disputed in recent years. The evidence is: (a) that they occur only in Hubble types with dominant young components, at a frequency that increases with blueness of the galaxy (Oemler and Tinsley, 1979), though their low rate in the latest types remains puzzling; (b) that, within these galaxies, they happen mostly in the spiral arms (Maza and van den Bergh, 1976); and (c) that their distribution in galaxies is generally like that of the neutral hydrogen (Tammann, 1977a).

The restriction to spiral arms requires an association with the most massive, short-lived stars. The implied lower mass limit depends on details of gas speed and pattern speed that must vary considerably from one galaxy to another, but is surely $\gtrsim 4\ M_{\odot}$ (Moore, 1973). Moore's suggestion that SN II's were further confined, to the leading edges of spiral arms, would have required progenitor masses $\gtrsim 35\ M_{\odot}$ and has mercifully (since such stars are very rare) proven to be a false alarm (Maza and van den Bergh, 1976).

The scale height, z, distribution (distances away from the galactic plane) of SN II's and their remnants does not contradict the presumption of massive progenitors. Supernova remnants cannot be separated by type once they are old enough for their structure to be dominated by interactions with the interstellar medium; but the whole class has a scale height (~ 60 pc; Clark and Caswell, 1976) comparable to that of the interstellar medium and largely determined by it. Pulsars, on the other hand, have a scale height (300−400 pc) much larger than that of massive stars, but they are themselves high-velocity objects, and their distribution is consistent with birth in the galactic plane (Lyne, 1981), where Population I is concentrated. Their high velocities could be acquired from either asymmetric supernova explosions or asymmetric radiation after they form. Notice that 400 pc is still smaller than the widths of spiral arms, so that the relatively large pulsar scale height does not contradict their association with arms (Harding, 1981).

For the SN II events themselves, information on scale heights is rather scanty. Four extragalactic events in edge-on galaxies yield $\langle z \rangle \leq 1000$ pc (Tammann, 1977b). The two putative Type II's in the Milky Way, SN 1054 and 1181, have distances from the plane of about 200 and 400 pc. Tammann (in NATO81) attributes them to runaway OB progenitors. These constitute nearly half of all O stars (but many fewer of the B's) and are probably mostly runaway binaries with collapsed primaries (Stone, 1981, 1982), as an asymmetric supernova explosion in a binary can produce a recoiling pair more readily than it can unbind the system, since it is the less massive star that explodes (van den Heuvel, 1976), and the companion is not badly damaged (Fryxel and Arnett, 1981).

One additional constraint on the masses of SN II parents comes from the observed rate—there have to be enough progenitors to make the events we see! The constraint is not a perfectly clean one, as the SN II rate comes only from external galaxies, and the Initial Mass Function (number of stars born per unit time per unit mass interval) can be measured only in the solar neighborhood. Luckily, calculations of galaxy evolution suggest that a "universal" IMF is a good first approximation (Tinsley, 1980b). Nevertheless, even local determinations of the IMF differ by a factor of about 3 at the upper end (Lequeux, 1979; Miller and Scalo, 1979). Thus, even if a star's fate is a unique function of its mass, Tammann's (in NATO81) estimate of the local SN II rate tells us only that all stars more massive than $5.6-9.6\ M_{\odot}$ (or $3.7-13\ M_{\odot}$ if a factor of 2 uncertainty in the rate is admitted) must become supernovae. If rotation, duplicity, or other properties besides mass help determine a star's eventual fate, then the lower mass cut becomes even more uncertain. It is, anyhow, apparently in the general ballpark suggested for the minimum mass that can form a neutron star by the evolutionary processes outlined in Secs. II.A.6 and 7.

Type I supernovae, on the other hand, are not readily associated with a unique parent population or mass range. Some data suggest young progenitors. Their rate as a function of galaxy type increases monotonically with prominence of gas and young objects (cf. Table II) and with blueness (i.e., current star-formation rate) of the parent galaxy, at least for spirals (Oemler and Tinsley, 1979) and members of rich clusters (Caldwell and Oemler, 1981). In addition, the SN I's occurring in spirals are largely confined to the disks, though not to the arms, and have a scale height $\lesssim 700$ pc (Maza and van den Bergh, 1976; Tammann, 1977b), possibly as small as 100 pc (Tsvetkov, 1982). Finally, Gunn, Stryker, and Tinsley (1981) find that synthetic spectra providing a good match to observations of ellipticals include a hot stellar population, which could be star formation at the rate required to make SN I's from young progenitors. These considerations collectively imply ancestral masses in excess of $2\ M_{\odot}$ (Tinsley and Oemler, 1980). Because there are many more little stars than big ones, either some rather rare phenomenon in $2-6\ M_{\odot}$ stars or some narrow mass range ($3.7-4.0\ M_{\odot}$ or whatever you like) could provide the observed SN I rates.

Other data imply older progenitors. SN I's unquestionably occur in elliptical galaxies. These are not, on average, any bluer than the general run of E's; and the radial distribution of supernovae in them is roughly the same as the average light distribution (Maza and van den Bergh, 1976; Tammann, 1977b; Oemler and Tinsley, 1979). This last point is important because gas and excess blue light, plausible signatures of star formation, when they occur in elliptical galaxies are generally confined to the nuclear regions (see also Bertola, Cappacioli, and Oke, 1982). In addition, in galaxies that have both neutral hydrogen and SN I's, the two are not well correlated in position (Tammann, 1977a). Next, the SN I 1980*i* occurred about 50 kpc from the center of the nearest galaxy (Smith, 1981), well away from likely regions of recent star formation. And finally, the seven supernovae recorded in our galaxy in the past 10^3 yr have an average scale height near 200 pc, which cannot be attributed to motions after the events occurred! This second set of considerations implies progenitor masses less than 1.5 $M_\odot$. As such stars are even commoner than $2-6$ $M_\odot$ ones, SN I's arising among them could be the product of some still rarer evolutionary history, presumably involving mass transfer onto a white dwarf along the lines discussed in Sec. II.B.2. For progenitors of this sort, the Type I supernova rate would probe not the total number of stars in the right mass range (largest inevitably in halo and elliptical populations), but the fraction in the right sort of binary. Binaries of any sort are rare in the halo of our own galaxy. Should this be the case for other spheroidal star distributions, the relatively low elliptical SN I rate would be fully accounted for (cf. Shklovskii, 1981b).

Given the contradictory bits of evidence on SN I populations, an attractive compromise (meaning an arrangement that annoys both sides equally) would be to postulate two classes of SN I progenitors—a subset of the single stars of $\sim 4-8$ $M_\odot$, presumably exploding via traditional carbon detonation (Sec. II.A.5), and a subset of the ~ 1 $M_\odot$ white dwarfs formed in close binaries, exploding via degenerate helium or carbon burning as a result of mass accumulated from their companions (Sec. II.B.2). Judicious mixes of the two subsets, the proportions varying with galaxy type, could probably be made to agree with the full range of observed correlations and noncorrelations. Independent evidence for two classes of SN I includes the "fast" and "slow" light curves found by Barbon, Ciatti, and Rosino (1973; Barbon, 1980), to be associated with different parent galaxy types, and the possible variation in SN I luminosity at maximum light as a function of galaxy type (Tammann, 1977b; disowned by Tammann, 1981, but see Arnett, 1982). The differences remain interesting even if the two classes are really slices out of a continuum of properties (Sec. III.A.2 above).

A few supernova remnants offer hints of what their progenitor masses may have been, though it must again be emphasized that their types are uncertain, even when the event was seen. The Crab Nebula's unusual combination of pulsar, excess helium, and normal-to-deficient heavy elements suggests, in combination with evolutionary models, a main sequence mass near 9 $M_\odot$ (Nomoto, in NATO81; Davidson *et al.*, 1982). A small group of very young remnants, discussed by Chevalier (1981a) and including Cas A and MSH $11-54$ in the Milky Way, N 132D in the Large Magellanic Cloud, and an unnamed remnant in NGC 4449, have spectra (optical and for Cas A also x-ray) showing large excesses of O, and in some cases Ne and oxygen-burning products (Ar, Si, etc.), strongly suggesting that they came from stars that had reached at least this far in the natural chain of nulcear reactions (Sec. II.A). Such abundance anomalies appear to be inhomogeneous through the remnants (Chevalier and Kirschner, 1979), which complicates relating them to a precise ancestral star. But Dopita (in NATO81) suggests progenitor masses of $6-10$ $M_\odot$ for the LMC remnants that show very strong oxygen lines in the spectra of some of their filaments.

The x-ray spectra of the Tycho and Kepler remnants also reveal enhancements of oxygen and its burning products, though not of the iron-peak elements made in explosive carbon burning (Becker *et al.*, 1980a, 1980b). We can be reasonably confident that these effects are real, as systematic surveys of about a dozen older remnants yield normal-to-low abundances of the same heavy elements (Szymkowiak, in NATO81), presumably reflecting their domination by swept-up interstellar matter with some of the metals hidden in dust.

Perhaps the most interesting hint from the galactic supernova remnants is the masses implied by their thermal continuum x-ray emission. Nearly all are large. For old remnants, like Pup A, the $50-100$ $M_\odot$ derived must be largely swept-up interstellar gas (Winkler, in NATO81). This cannot be so for more recent events—in 300 yr, expansion at 10 000 km sec^{-1} picks up $2.5n_H$ $M_\odot$, where n_H is the local gas density per cm^3. Tycho (at $z=98$ pc), Kepler (at $z=474$ pc), SN 1006 (at $z=376$ pc), and Cas A (at $z=103$ pc) are unlikely to have gone off in regions with n_H even as large as one. The 15 $M_\odot$ found for Cas A (Canizares, Fabian, and Seward, separately in NATO81; Brecher and Wasserman 1980), the $5-15$ $M_\odot$ for 1006 (Pye *et al.*, 1981), the 15 $M_\odot$ for Tycho (Seward), and the 7 $M_\odot$ for Kepler (White, in NATO81) should, therefore, be mostly supernova ejecta. This presents a modest problem for Cas A—there is no nearby OB association from which so massive a star seems likely to have come (though you can go a kiloparsec in 10^7 yr at a runaway velocity of 100 km sec^{-1}). And the type of 1006 is not really known. But the problem for Kepler and Tycho sounds dire. They are universally advertised as having been of Type I, which we just finished saying arises in a relatively old, low-mass population. Mercifully, the estimated masses drop enormously (e.g., factors of 5) if the SNR's are not made mostly of hydrogen and/or helium—and they should not be in the carbon (etc.) deflagration models of SN I's (Sec. IV.C). A composition dominated by iron, as predicted by these models, is not inconsistent with the lack of iron lines in

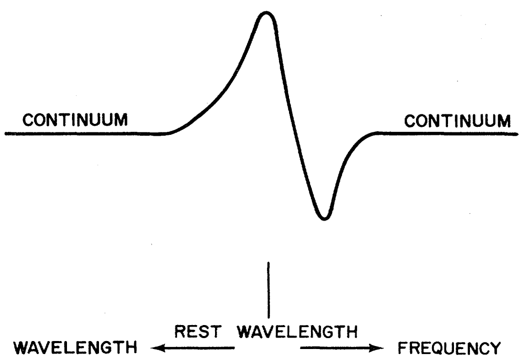

FIG. 5. Idealized P Cygni line profile, representing gas flowing outward from a hot photosphere. Gas between the observer and the photosphere produces the blue-shifted absorption. Gas along other lines of sight produces emission centered near the photospheric rest wavelength and extending redward to the maximum expansion velocity.

the spectrum of the 1006 SNR (Fabian, Stewart, and Brinkman, 1982).

B. Spectra and their interpretation

1. Features common to both types

A typical supernova spectrum near maximum light consists of a continuum badly cut up by emission and absorption lines. The continuum carries most of the energy for at least the first month (Type I) to year (Type II). The photospheric temperature obtained by fitting a blackbody to the continuum gradually declines from $\sim 10\,000-12\,000$ K at maximum light to 5000−7000 K a few weeks after. Many of the conspicuous narrow absorption lines, particularly in the ultraviolet, are interstellar. Most of the intrinsic lines show broad P Cygni profiles (Fig. 5). Such a profile is a signature of an expanding gas cloud that does not totally absorb the photons from a continuum produced inside it. Emission near the rest wavelength comes from gas that is not between us and the photosphere, and blue-shifted absorption from gas that is. The absorption velocity (roughly that of the photosphere) drops from 10 000−15 000 $\mathrm{km\,sec^{-1}}$ near maximum light to 5000−8000 $\mathrm{km\,sec^{-1}}$ a few weeks later. The larger numbers typically belong to the Type I's. The drop does not represent real deceleration of the gas. Rather, our line of sight is penetrating to deeper layers (in mass coordinate) as the gas expands, and these are moving more slowly than the outer ones. Lines that have been identified in both types include Ca II *H* and *K*, the Ca II infrared triplet, the Mg I *b* band, and, probably, Na *D*. The photospheric radii are $\sim(1-5)\times 10^{15}$ cm, concordant values coming from the product of velocity times time and from $L = 4\pi R^2 \sigma T^4$. The photosphere first grows with time (though not as fast as the initial velocity would predict) and then shrinks, again because we see further in as time goes on. The data supporting these generalizations are discussed by Kirshner *et al.* (1973a), Searle (1974), Oke and Searle (1974), Kirshner and Oke (1975), Mustel and Chugai (1975), Kirshner (1980, and in NATO81), and Branch (1980a, 1980b, and in NATO81).

Most of this could have been said about Type II's several decades ago. The successful interpretation of Type I spectra has come only within the past dozen years, following two major advances. These are the replacement of photographic by photoelectric observing techniques, permitting coverage of a wider wavelength range with better spectral resolution and greater dynamic range, and the adoption of spectrum synthesis techniques by the modelers. The following sections address differences between Type I and Type II spectra and their interpretation.

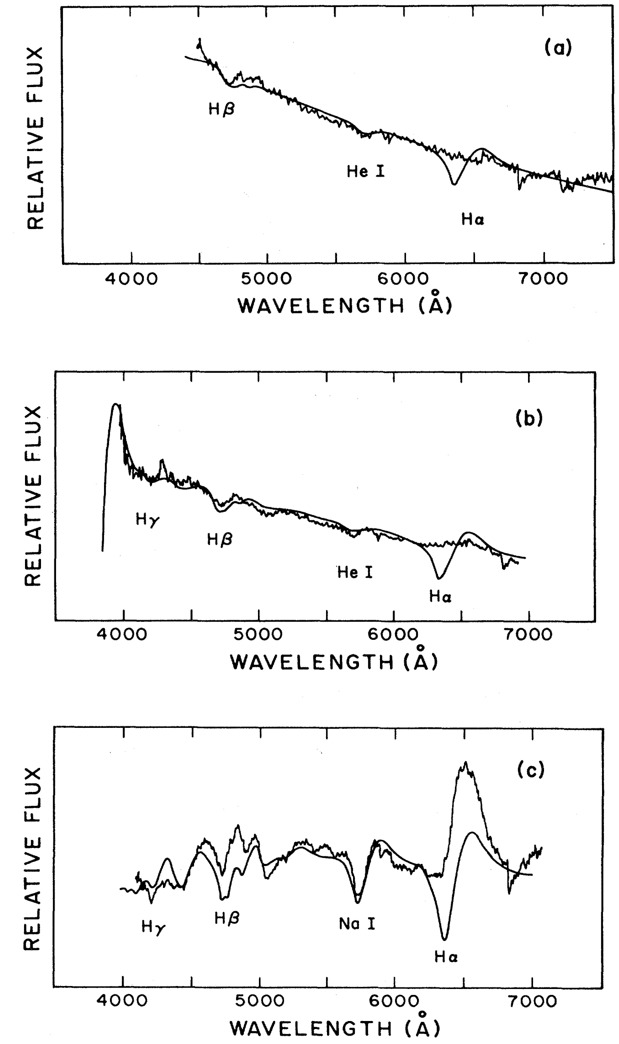

FIG. 6. Observed spectra (the wigglier lines) and synthesized fits (the smoother lines) for the Type II SN 1979c in M 100: (a) at maximum light, (b) six days thereafter, and (c) 36 days after maximum. The flux scale is linear in units of flux per unit wavelength, and the wavelength scale is in the rest frame of M 100. Unlabeled features in the synthetic spectrum are due to Fe II. From Branch *et al.* (1981).

2. Type II spectra

Figure 6 from Branch *et al.* (1981) shows spectra and synthesized fits for the Type II SN 1979*c* at maximum light and about a month later. The aspects usually regarded as important are the presence of hydrogen lines and the relative weakness of all lines, reflecting a large ratio of continuum opacity (scattering by electrons from hydrogen) to line opacity. Similar-looking spectra and fits exist for earlier Type II's (Oke and Searle, 1974; Patchett and Branch, 1972; etc.).

The synthesized spectra are not wildly good fits, owing perhaps to the excitation of Hα being collisional rather than resonant scattering (Branch *et al.*, 1981). The basics are probably right, however, as independent workers get similar results. For instance, the temperatures, radii, and velocities deduced from spectra of SN 1979*c* have been used to get Baade-Wesselink distances to the object by three groups. Panagia *et al.* (1980) find 24 Mpc, Branch *et al.* (1981) 23 Mpc, and Kirshner (in NATO81) 22 Mpc.

All these calculations have, however, neglected the possibilities of significant continuum opacity (Wagoner, in NATO81; Sec. VIII.B) and of a flat density profile at the photosphere (Chevalier, private communication, 1982), either of which could greatly change the derived luminosities etc.

Abundances cannot be derived unambiguously from the spectra until the excitation and other conditions in the envelopes are better understood, but no obvious inconsistency arises if normal solar or interstellar medium abundances are assumed (Kirshner and Kwan, 1975). The mass in the line-forming region need be only a few tenths of a solar mass (Searle, 1974); but maintaining an optically thick continuum, given the rapid expansion and the year or more over which it is seen, requires ejected masses of at least $\sim 5\ M_\odot$ (Panagia *et al.*, 1980), strengthening the tie of Type II events to the most massive Population I stars.

Type II spectra charge with time in a way that varies a good deal from one event to another (Oke and Searle, 1974), but is apparently attributable to changes in just temperature, density, and velocities, not composition of the radiating gas. Eventually, we must see down into processed regions of the star, since excesses of oxygen and its burning products show up in young remnants, but there are not many data points more than a few months past maximum light. The ultraviolet spectrum is very rich. Both the continuum and the lines are probably produced by interaction between the expanding supernova shell and circumstellar material lost earlier by the evolving star (Panagia *et al.*, 1980; Chevalier, in NATO81), but no synthesis fits have yet been attempted.

3. Type I spectra

Figure 7 (from Branch, in NATO81) shows spectra and synthesized fits for the 1981 Type I supernova in NGC 4536, at maximum light and 17 days thereafter.

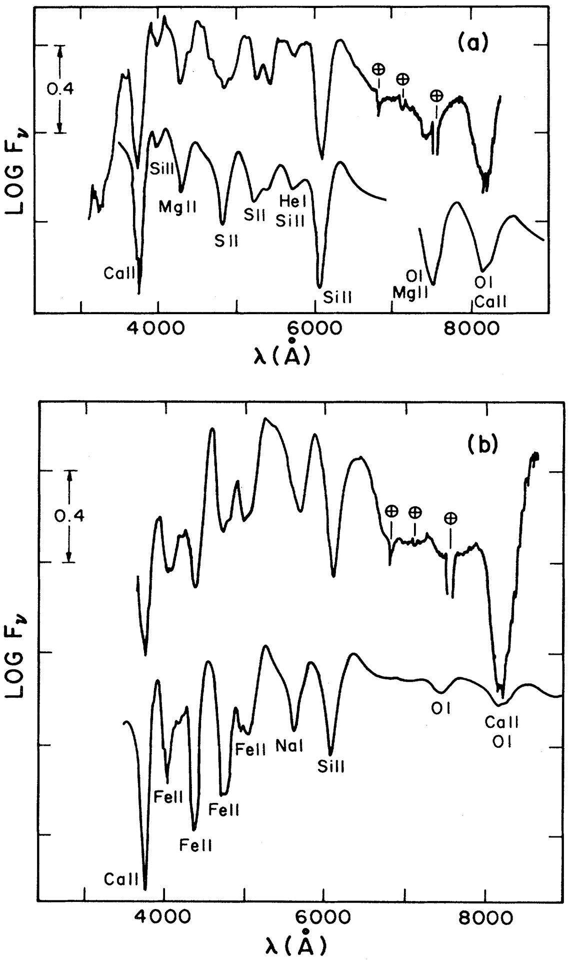

FIG. 7. Observed spectra (upper lines) and synthesized fits (lower lines) for the Type I SN 1981 in NGC 4536: (a) at maximum light, and (b) 17 days postmaximum. The two fits, respectively, have $T_m = 17\,000$ K and 8000 K; $V_m = 12\,000$ km sec and 11 000 km sec; and $A_v = 0.3$ and 0.1. Terrestrial lines are indicated in the observed spectra. From Branch (in NATO81).

The aspects usually regarded as important are the total absence of hydrogen lines and the relative strength of all lines, reflecting a low ratio of continuum opacity (scattering by free electrons which would come mostly from hydrogen in normal gas) to line opacity. Similar-looking spectra and fits exist for earlier SN I's (Kirshner *et al.*, 1973a; Branch and Patchett, 1973; etc.), the very first going back to Whipple and Payne-Gaposchkin (1941), who, although they included only emission lines, concluded that hydrogen was probably depleted and iron enhanced. The continuum drops below blackbody values in the ultraviolet (first noted by Minkowski, 1939, for the SN I in IC 4182), as a result of opacity sources not properly included in the fits (probably blends of Fe II, etc., features; Kurucz, 1981). The line shapes are well fit by gas expanding with velocity proportional to radius (Sobolev, 1981).

What abundances are implied by these spectra? A simple inventory of the elements present at maximum light (He, O, Mg, Si, S, Ca, but no H) shows that both solar composition and pure carbon detonation products are wrong. Solar ratios of heavy elements in local thermodynamic equilibrium (LTE) with enormously diminished hydrogen ($[\mathrm{H/Si}] \lesssim -3$) provide one possible fit (Branch, in NATO81; Branch *et al.*, 1982), the weakness of the helium lines being then explained by excitation effects. Other quite different fits are surely possible at the present state of our knowledge of conditions in the envelopes. But the weakness of hydrogen, at least, is a real abundance effect. SN 1972*e*, the most thoroughly analyzed Type I to date, developed a weak line near λ6500 a few weeks past maximum light. Kirshner and Oke (1975) and Assousa *et al.* (1976) attributed it to Hα. A hydrogen mass of at most $0.1-0.3\ M_\odot$ is implied, and $[\mathrm{H/Fe}] \sim -1.3$ (Kirshner and Oke, 1975, and Friedjung, 1975, on SN 1972*e*; Wheeler, in NATO81, on the March 1981 Type I in NGC 4536). Hydrogen is still more deficient if that line is really due to Fe II (Branch and Tull, 1979).

The total mass required in the envelope is very sensitive to model assumptions. It need be large ($\gtrsim 2\ M_\odot$) only if the continuum persists for a long time and there is no energy input after the initial event (Lasher, Karp, and Chan, 1977; Falk, 1980). The former becomes doubtful after $40-50$ days (Branch, 1980a), and the latter is surely wrong in models that invoke either fluorescence (Sartori, Chiu, and Morrison, 1974) or radioactive decay (discussed in Sec. III.C.3). The observed emission at any given time could easily be produced by a few tenths of a solar mass, if there is not much gas with velocities smaller than those seen (Branch, in NATO81). Of that total mass, at most half is helium and the rest heavy elements, according to Axelrod's (in NATO81) analysis of Type I spectra taken more than 100 days after maximum light.

The time evolution of SN I spectra is very similar for most events, so that a single spectrogram often suffices to identify evolutionary stage and time since light maximum uniquely (Oke and Searle, 1974). But the changes cannot be attributed to temperature and velocity variations alone. By about a year after maximum light, products of the supernova explosion became detectable in spectra of 1972*e* (which closely resembled the prototype SN I, 1937*c*). Not only do the spectra imply excess iron (Kirshner and Oke, 1975), of order $0.5\ M_\odot$ (Meyerott, 1980b), but the non-LTE excitation conditions are best explained by energy supplied from radioactive decay of Co^{56} and Ni^{56} (Meyerott, 1980a; Axelrod, 1980). Lines from the cobalt itself were probably weakly present, and the subsequent spectral evolution is consistent with the cobalt's being gradually transformed into iron (Axelrod, in NATO81).

This sounds almost too good to be true; and indeed unconfined rejoicing would be premature. The models that best match observed light curves produce higher temperatures and stronger forbidden lines than the spectra show (Colgate and Petschek, 1980). In addition, the features that Axelrod (1980, and in NATO81) attributes to Co is Branch's (1980a, and in NATO81) Na *D* line. And, more generally, extrapolations backward in time of the fits to the late spectra and forward in time of the fits to the maximum-light spectra do not match up very well (Meyerott, 1980b). Branch and Axelrod (separately in NATO81) plan to work together on bridging this particular gap.

C. Light curves and their interpretation

1. Features common to both types

Supernovae get very bright very fast, at least the last few magnitudes of the rise to a peak luminosity of $M_B = -18 \pm 2.5$ occurring in a couple of weeks. They then fade away more slowly, at rates of $0.01-0.1$ magnitude day^{-1}, and disappear in at most $2-3$ yr, having radiated $\gtrsim 10^{49-50}$ erg in optical phonons. At least some also radiate significantly in other wavelengths. The total energy requirement, including what goes into the expanding shell, is $\gtrsim 10^{51}$ erg. These numbers have deliberately been made vague enough to cover both some peculiar supernovae and a range of values for Hubble's constant, $50-100$ km sec^{-1} Mpc^{-1}.

Supernova colors change in a fairly regular way as the objects fade. The $B-V$ color index reddens gradually from ~ 0.0 at maximum light to $\sim +1.0$ a month or so later, then flattens out (Type II) or turns over (Type I). $U-B$ also reddens monotonically by about a magnitude (-1 to 0 in Type II; 0 to $+1$ in Type I) in the same period, then changes more slowly (Type II) or flattens out (Type I). Because the continua look thermal early on, the fitted luminosities are probably good estimates of the total photon fluxes from the events. After the first 40 days, blackbodies no longer provide a good fit to the colors, reflecting the increasing dominance of line emission and (in Type I's) uv deficiency. Observed fluxes then set only lower limits to the total luminosities (Barbon, Ciatti, and Rosino, 1973, 1979; Ardeberg and de Groot, 1977; Panagia *et al.*, 1980; Wyckoff and Wehinger, 1977; Kirshner and Kwan, 1974; Kirshner, in NATO81).

The declining branch of the light curve normally changes slope at least once in each type; and the ranges of slope overlap. Thus fragmentary photometric data can frequently be fitted by a "standard curve" for either type, particularly if the time of maximum light and the distance and reddening of the parent galaxy are not well known (Wegner, 1979). This ambiguity largely disappears if well-calibrated data are available for a month or more near maximum light (Ciatti, 1978), though under these circumstances, spectra are quite likely also to have been taken.

Supernova light curves have been plausibly modeled with an instantaneous energy input at the base of an extended ($\gtrsim 10^{14}$ cm) envelope of $\gtrsim 2\ M_\odot$. Models with gradual energy input are also possible and are probably required for the slowest-decaying Type II's and for all

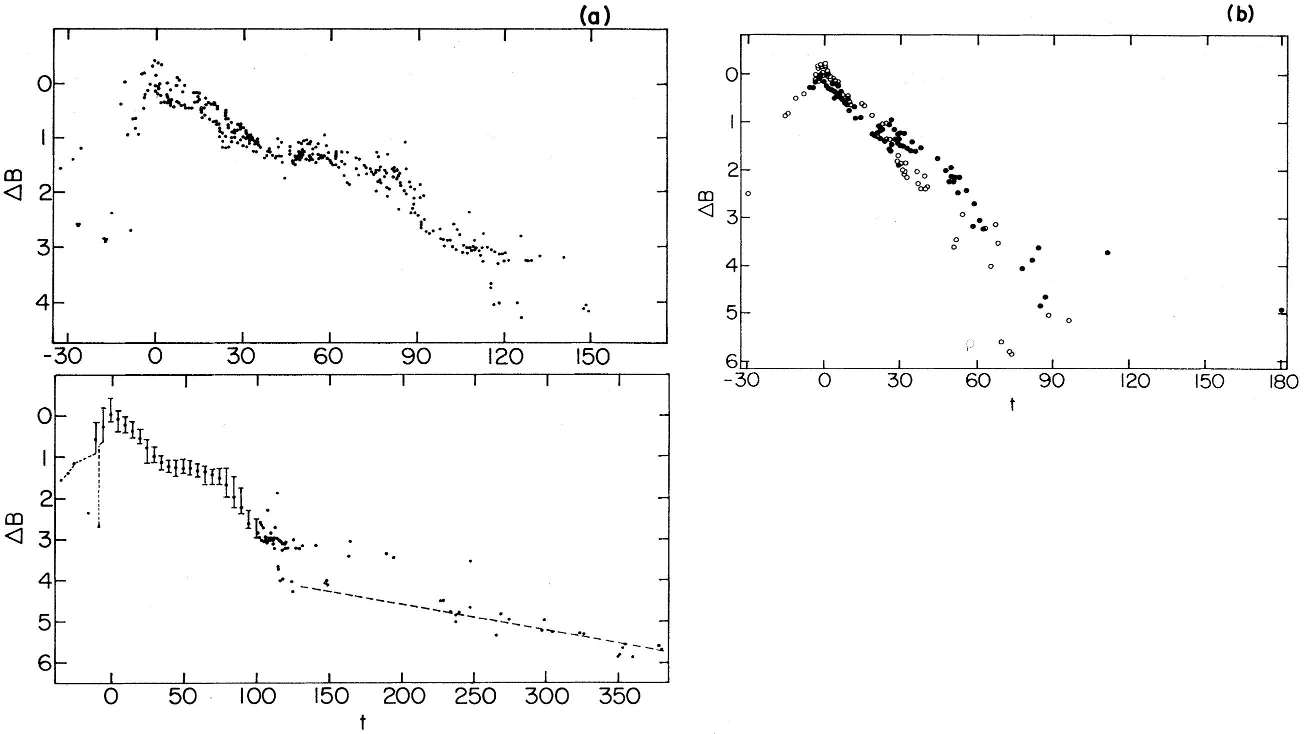

FIG. 8. Composite blue light curves of Type II supernovae: (a) 15 events showing plateaus in the declining branch (and data for one event beyond 150 days), and (b) 6 events with almost linear declines. Time is in days from maximum light; brightness in blue magnitudes, adjusted to make peaks of all events coincide. From Barbon, Ciatti, and Rosino (1979).

Type I's if the envelope is initially compact ($\lesssim 10^{13}$ cm) and/or less massive ($\lesssim 1\ M_\odot$). The sources of continuing energy most often invoked are radioactive decay of $0.1-1.0\ M_\odot$ of Ni^{56} and a central pulsar with initial period $\lesssim 10$ msec. Chevalier (1981b) provides a useful and comprehensive overview of the techniques and results of these various kinds of hydrodynamic models of supernova light curves.

2. Type II light curves

Figure 8 (from Barbon, Ciatti, and Rosino, 1979) shows the range of vaguely normal Type II light curves. Others (some older and photographically, rather than photoelectrically, derived) are given by Shklovskii (1968) in Cosmovici (1974) and Schramm (1977), etc. The two main types, with and without plateau, may be correlated with spectroscopic differences (Panagia *et al.*, 1980). There is no marked correlation of subtype or of peculiarities with parent galaxy, the very strange 1961*v* (Zwicky's prototype V) having, for instance, been followed in NGC 1058 by the very average Type II SN 1969*l*.

Very few Type II's have either been caught much before maximum light or followed for more than a few months thereafter. The former is sometimes attributed to very short rise times, though the sparse existing data do not really require this for most events. The latter is largely bad luck. Significant features seem to be the rather sharp peak in most light curves and the 30–60 day plateau interrupting the decline in about $\frac{2}{3}$ of them.

The peak luminosity of Type II supernovae is apparently quite variable, two recent determinations (Barbon, Ciatti, and Rosino, 1979; Tammann, in NATO81) yielding dispersions of 1.0 and $1\overset{m}{.}4$ about a mean of $M_B=-19$ ($H_0=50$ km sec^{-1}Mpc^{-1}) after assorted corrections were made. Derived luminosities depend both on choice of distance scale and on corrections for reddening and absorption. Some nearby parent galaxies have distances known from secondary or tertiary indicators (de Vaucouleurs, 1979a, and other papers in that series). For a few others, the Baade-Wesselink method has yielded a distance for the supernova itself (e.g., Branch *et al.*, 1981 on SN 1979*c*). For the rest, our knowledge of the distance comes from the recession velocity of the parent galaxy, some value of Hubble's constant, and the assumption that even at the rather moderate distances often involved, Hubble expansion dominates peculiar velocities. This may well not be so, particularly in the direction of the Virgo Cluster (de Vaucouleurs, 1979b). We will here assume that all is well, and normalize to an isotropic Hubble constant so that the mean peak luminosity is $\overline{M}_B=-19+5\log(H_0/50)$.

The absorption correction cannot be expressed so simply. Reddening within our own galaxy is reasonably well known; but Type II parent galaxies are all spirals or irregulars which, being dusty, introduce absorption of their own. We don't usually know whether a given supernova event has gone off behind, within, or before the plane of its galaxy. Thus the primary handle on absorption there has been the color of the supernova itself. When observed colors are fitted to standard observed or calculated curves, the implied values of absorption can range from a few tenths to 4—5 magnitudes in B (Schurmann, Arnett, and Falk, 1979). Correcting for them if anything increases the dispersion of M_B at peak luminosity (Barbon, Ciatti, and Rosino, 1979; Tammann, in NATO81). Where high spectral resolution or ultraviolet data are available, absorption can be derived from the intensity of Ca II of λ2200 absorption features. This has, so far, been done for 1979*c* and 1980*k*. Additional cases should much increase the reliability of SN II peak brightnesses. Properties of infrared emission from grains heated by the supernovae may also help pin down absorption (Pearce, private communication, 1982).

Models intended to fit and interpret Type II supernova light curves abound (Grasberg, Imshennik, and Nadyozhin, 1971; Chevalier, 1976; Falk and Arnett, 1977; Weaver and Woosley, 1980; etc.). Most start by dumping $\sim 10^{51}$ erg at the bottom of an extended envelope. The energy moves outward as a shock wave, heating and accelerating gas as it goes. As the shock wave reaches the surface, the gas there begins to expand and radiate. The models end with predicted curves of bolometric luminosity, photospheric radius, and photospheric velocity versus time. Conversion of those to quantities given by the observations is not entirely trivial. A range of curves results from varying the initial energy and the mass and radius of the extended envelope. The fits near maximum light are good enough to make possible a rational preference of one set of input parameters to another (Fig. 9).

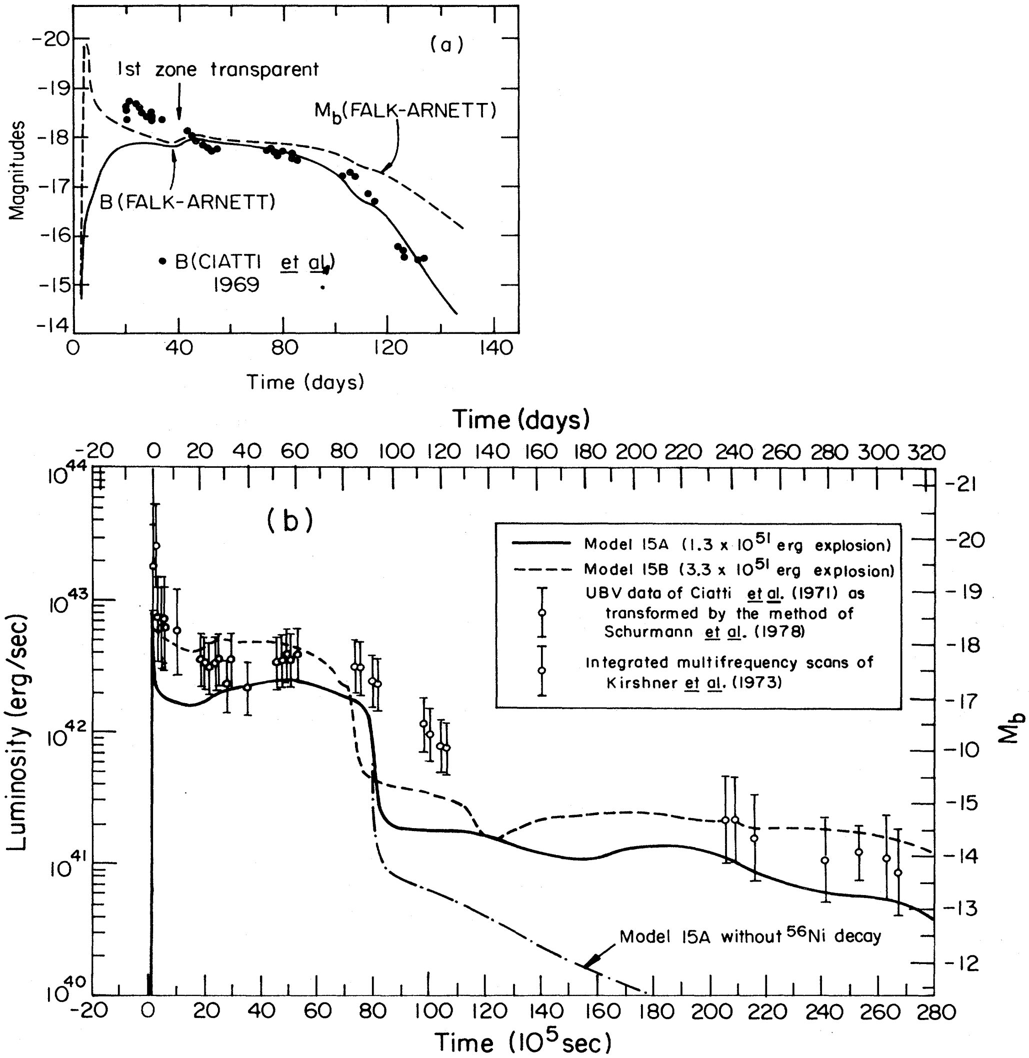

FIG. 9. Model fits to SN II light curves: (a) from Arnett (1977b) and (b) from Weaver and Woosley (1980). The observed points in both cases are for SN 1969l. The three Weaver and Woosley models differ in initial input energy and in whether or not additional continuous energy from Ni^{56} decay is included. Such modeling has clearly reached the stage where, not only are the fits reasonably good, but some are significantly better than others.

The rise time is always very short, increasing brightness resulting directly from the expansion of the photosphere. The plateau on the declining branch of the light curve occurs as the expanding envelope cools and hydrogen recombination sets in, keeping the photosphere at a nearly constant radius and temperature for some time, while the gas moves outward through it. Light curves without such a plateau may occur for the smallest envelope masses that make Type II's (Branch *et al.*, 1981), though none of the current models actually shows this linear-decline behavior (Falk and Arnett, 1977).

The total light radiated is about 1% of what was put in to begin with. The rest remains as kinetic energy of the expanding envelope, which must eventually interact with circumstellar material shed by the evolving progenitor star and/or the general interstellar medium. The result is further heating and radiation that will be discussed below and in Sec. VI.F.

These "instantaneous energy input" models make at least one definite prediction: as the shock emerges, the envelope surface is heated to some 10^5 K. Thus, 20 days before maximum light, there should occur (Klein and Chevalier, 1978) a $\sim 10^{45}$ erg burst of ultraviolet and soft x-ray photons, lasting about 10^3 sec, and detectable from as far away as 10 Mpc. Nothing of the sort was seen in a search of HEAO-1 data, but the data and the predictions are both uncertain enough that there is no real contradiction (Klein *et al.*, 1979; Lasher, Karp, and Chan 1977).

Most of the models have been stopped after $60-100$ days, when recombination in the envelope was essentially complete and, as a result, the luminosity was dropping rapidly. If the steller mantle is included in the model, then a reverse shock in it produces a layer of dense gas that can continue to give a photosphere after 100 days (Chevalier, 1976; Weaver and Woosley, 1980). SN 1969*l*, one of the few for which there are data beyond 150 days, dropped off even more slowly than predicted by the models with mantles. Weaver and Woosley blame the extended light curves on continuing energy input from Ni^{56} synthesized explosively as the shock wave enters the base of the envelope. Other concomitantly produced radionuclides make much smaller contributions on varying time scales. Existing data do not tell us whether such long-tailed light curves are common or rare among SN II's, though 1979*c* still had $L \sim 10^{42}$ erg $\sec^{-1}$ (mostly in the infrared) 15 months after maximum light (Chevalier, in NATO81). The models could accommodate either, since whether radioactive energy goes into radiation or into envelope acceleration depends on where the photosphere is relative to the newly made Ni^{56} and Co^{56} for the first few of their 6 and 77 day half-lives.

Other models for Type II light curves invoke continuous energy input throughout the life of the event. Ostriker and Gunn (1971) attributed both envelope expansion and radiation to energy supplied by a central pulsar. The light curves that result (Bodenheimer and Ostriker, 1974) are not much like observed ones. Gaffet (1977) found more promising light curves on the assumption that the pulsar produced only the radiation, by heating an envelope whose dynamics had already been established in an initial explosion.

At least one Type II supernova has now been seen in each of the bands, x-ray, ultraviolet, infrared, and radio (Canizares, Kriss, and Feigelson, 1982; Panagia *et al.*, 1980; Dwek *et al.*, 1981; Weiler *et al.*, 1981; Benvenuti, in NATO81; and Chevalier, in NATO81). The luminosities are all much smaller than the optical one, apart from infrared well after peak brightness.

The ultraviolet data seem to present the fewest difficulties of interpretation. The uv emission fades on the same sort of time scale as the optical; the line velocities are smaller than the optical ones (for 1979*c*); and the continua (for 1979*c* and 1980*k*, which showed no uv lines) are well fit by two-photon emission (Panagia *et al.*, 1980; Benvenuti, in NATO81). These points indicate emission from a low-density gas outside the photosphere. A likely source is circumsteller gas ionized and radiatively accelerated by ultraviolet photons from the hot photosphere (Chevalier, 1981c). A mass of $10^{-2}\ M_\odot$ suffices for 1979*c* and $\lesssim 10^{-3}\ M_\odot$ for 1980*k* (Panagia, in NAT081).

Radio emission at a peak level $\sim 10^{37}$ erg $\sec^{-1}$ was detected in 1970*g*, 1979*c*, and 1980*k*, the latter two with the Very Large Array (Weiler *et al.*, 1981). The radio light curves at 6 and 20 cm somewhat resemble the optical ones, with rapid rises and more gradual fading, interrupted by plateaus. But the rises occur later, the 6-cm emission being first detected a month (1980*k*) to a year (1979*c*) after optical maximum, and longer wavelengths still later. Linear polarization was less than 1% in 1979*c*. The brightness temperature strongly suggests nonthermal emission, while the rapid turn-on, its frequency dependence, and the subsequent spectral evolution are suggestive of decreasing free-free absorption in ionized gas around the source. The masses required are $10^{-2}\ M_\odot$ and $10^{-4}\ M_\odot$ for 1979*c* and 1980*k*, respectively (Weiler *et al.*, 1981). The resemblance to the uv masses may not be an accident if, as Chevalier (1981c) suggests, the radio emission comes from the inner part of, and is partially absorbed by, the same ionized circumsteller shell that makes the uv. This model predicts that the radio emission should turn off very rapidly as the heating shock runs out of circumsteller matter to heat (Chevalier, in NATO81). An alternative model (Pacini and Salvati, 1981) attributes the radio radiation to newly born pulsars, but getting their radiation out through several solar masses of ionized envelope would seem to be insuperably difficult. Turn-off in this model would be more gradual but still occur in the $2-4$ yr required by the disappearance of 1970*g*. Finally, the radio emission of older supernovae remnants is not a continuation of this process, whatever it is. Branch (in NATO81) notes that radio upper limits on six supernovae that went off in NGC 5253 and 5231 between 1895 and 1968 imply fluxes well below an interpolation between the 1979 and 1980 events and CAS A.

1980*k* is the first supernova to turn up as an x-ray source less than 300 yr after the event (Canizares, Kriss, and Feigelson, 1982, and in NATO81). It was radiating 2×10^{39} erg sec^{-1} 35 days after maximum light (first Einstein observation), and about half as much 50 days (second Einstein observation), after which increasing difficulties with scheduling and the eventual demise of Einstein prevented further observations. 1979*c*, which reached light maximum in April, was not seen either then or in December, but the limits are well above the 1980*k* detection (it is further away and the data come from Copernicus), and it ought, anyhow, to have peaked between those times (Panagia, in NATO81). Given the sparsity of data and the small amount of energy involved, it is not surprising that a rich field of models is currently in the running. Suggestions include light echoes of the x-ray burst that marks shock emergence from the envelope, inverse Compton scattering of optical photons by radio synchrotron electrons, and thermal emission from a shock-heated circumstellar shell (Canizares, Kriss, and Feigelson, 1982; Chevalier, in NATO81; Panagia, in NATO81). For the last model, the difference between 1979*c* and 1980*k* would be straightforward—more or less the same amount of energy going into $10^{-4}\ M_{\odot}$ and $10^{-2}\ M_{\odot}$ makes x-ray and uv temperatures, respectively. No further constraining data are likely to appear until the next generation of x-ray satellites.

The infrared (e.g., $2-20\ \mu$) luminosity is not entirely negligible in the supernova energy balance. Although $L(\text{ir})/L(\text{opt})=1/40$ at maximum light for 1979*c*, the ir decayed much more slowly (time scale 200 days vs 20 days; Merrill, 1980) and was still some 10^{42} erg sec^{-1} 15 months after maximum light. Thus the integrated ir output was about a quarter of the total. The two likely infrared contributors are newly formed grains in the expanding supernova envelope (Chevalier, 1981c) and previously existing circumstellar grains heated by the outburst to give a light echo (Shklovskii, 1968, p. 17; Bode and Evans, 1980). Dwek *et al.* (1981), after studying the infrared from SN 1980*k*, conclude that one cannot yet exclude either sort of model, but the light echo is the more likely, particularly as the required circumstellar shell is much like the one required to interpret the radio and ultraviolet data (Chevalier, 1981c; 1982, private communication).

In summary, Type II supernova light curves, like Type II spectra, fit reasonably well with what the theorists tell us ought to be there. Any process that can deposit about 10^{51} erg at the base of an envelope with $R\sim10^{14}$ cm and $M\sim4-30\ M_{\odot}$ will do.

3. Type I light curves

Figure 10 shows a collection of Type I light curves (from Barbon, Ciatti, and Rosino, 1973) subdivided by rate of decline into "fast" and "slow" subtypes. Correlations of these subtypes with other observable properties of the events were addressed in Sec. III.A.2. Additional light curves are to be found in Shklovskii (1968), Cosmovici (1974), Danziger and Renzini (1978), Ciatti (1980), and assorted other conference proceedings. All authors agree that the Type I light curves are considerably more homogeneous than the Type II's, at least near maximum light.

A few Type I's have been caught $3-4$ magnitudes before maximum or followed for more than a year thereafter, though we cannot be sure that the very early and very late parts of the light curves are as homogeneous as the middle. Significant features seem to be the smooth, rapid rise; the rather broad peak and sharp decline; and the change of slope about 30 days post-maximum, leading to a long exponential tail, with an average half-life of 56 days or so. The weakness of Type I's in all nonoptical bands where they have been looked at or for (Kirshner *et al.*, 1973b; Weiler *et al.*, in NATO 81; Benvenuti, in NATO81) suggests that the optical light curves really do represent most of the electromagnetic energy near maximum light, though infrared emission may dominate after a year or two (Axelrod, 1980).

The peak luminosity of Type I supernovae has proven remarkably constant (both with time and from one object to another) at $M_B=-19.7$ to $-20.1+5\log(H_0/50)$ (Kowal, 1968; Tammann, in NATO81), with dispersions of $0.4-0\overset{m}{.}8$. The lower dispersion results from considering only events in elliptical galaxies, where reddening and absorption are essentially absent. It can probably be completely accounted for by observational errors and uncertainties in the distances to the parent galaxies (for which there are the same difficulties as for the Types II's mentioned above). Semi-independent evidence that SN I's are genuine standard candles comes from plotting M_B vs galaxy redshift (Tammann, in NATO81). Such a plot shows the constant slope (plus scatter) expected for a homogeneous population, rather than the changing slope that would indicate we were picking out only the brighter members of a variable population at the largest distances. Application of these explosive candles to cosmological problems is addressed briefly in Sec. VIII. Branch (in NATO81) has sounded a note of warning that, although the dispersion in Type I M_B's looks small, it may be concealing real correlations of total brightness with decline rate and velocity of the parent galaxy. These imply a total range of about 2^m in M_B and selection effects against faint events at large distances (see also Arnett, 1982). Infrared light curves may eventually equal or surpass the optical ones as standard candles because of their more complex shape and smaller vulnerability to absorption effects (Elias *et al.*, 1981).

Models intended to reproduce and interpret Type I light curves are of three basic types: those that dump all or most of the energy at the bottom of an extended envelope to start with and let a shock carry it out (Lasher, 1975, 1980; Sobolev, 1979; Falk, 1980); those that release all or most of the energy gradually via pulsar emission (Nadyozhin and Utrobin, 1977) or radioactive decay (Colgate and McKee, 1969; Arnett, 1979; Axelrod, 1980; Colgate, Petschek, and Kriese, 1980); and those that do some of each (Weaver, Axelrod, and Woosley, 1980;

Woosley, Weaver, and Taam, 1980; Chevalier, 1981d; Imshennik, Nadyozhin, and Utrobin, 1981; Arnett, 1982). Models in the third class generally derive the instantaneous energy from detonation or deflagration of $\sim 1\ M_\odot$ of carbon (etc.) and the continuous input from radioactive Ni^{56} synthesized in the same burning episode. The general conclusion is that the early part of the light curve can be matched with either instantaneous or con-

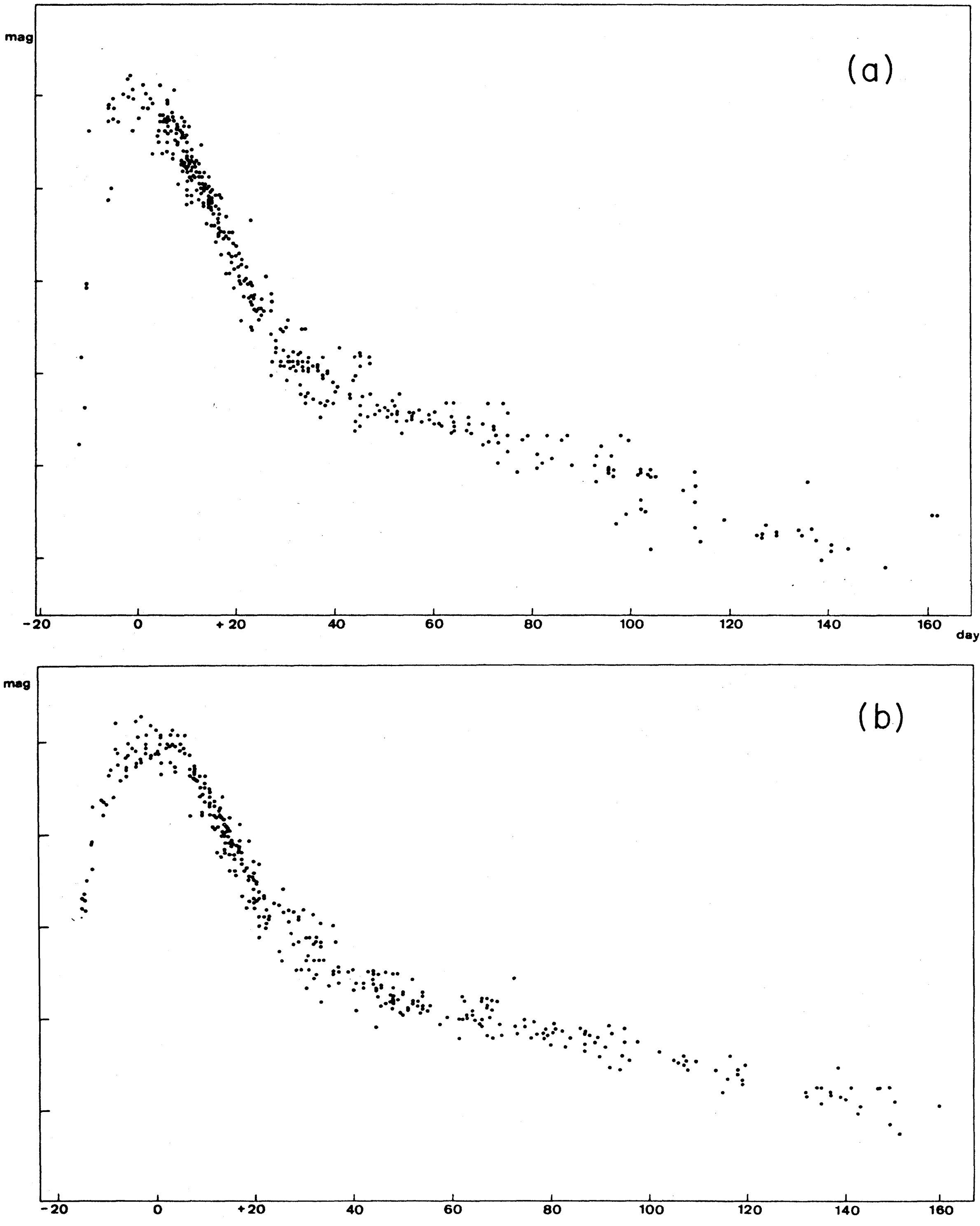

FIG. 10. Composite blue light curves of Type I supernovae: (a) 11 events of the "fast" decline subtype, and (b) 15 events of the "slow" decline subtype. Time is in days from maximum light; brightness in blue magnitudes, adjusted to make peaks of all events coincide. From Barbon, Ciatti, and Rosino (1973).

tinuous input, but the post-40-day exponential tail only with a continuing energy source. In all cases, the observed light curve is determined by a complex balance between energy generation and energy transport (opacities) in the expanding envelope.

What becomes of the initial (deflagration) energy impulse depends on the size of the pre-fireworks star. A compact envelope (and/or star) must be pushed out of the way, turning the shock largely into bulk kinetic energy before it reaches the surface, so that we do not see it directly. A shock in an initially extended envelope reaches the surface (as in Type II's) still with appreciable energy, sending forth a precursor burst of uv and soft x-rays; and the expanding gas which it has heated radiates the light seen near maximum. The two cases cannot be directly distinguished by observation, as the photospheric radius has already grown to $\sim 10^{15}$ cm at the earliest time any SN I has been caught (5 days before maximum light for SN 1975*a*, Kirshner, Arp, and Dunlop, 1976). As maximum light lags the initial energy deposition by $10-15$ days in either class of model, we are not surprised. Less directly, the fact that SN 1572 apparently went off in a neutral region of interstellar gas says that it did not have the precursor pulse associated with extended envelope structure (Chevalier, Kirshner, and Raymond, 1980). Panagia (1980), on the other hand, suggests that the uv data on 1979*c* do imply a soft x-ray precursor, and Dopita (in NATO81) has identified three probable SN I remnants in the Magellanic Clouds, for which a comparison of neutral and total gas density may indicate that there were precursor bursts and so extended envelopes on the progenitors. Other interpretations of the data may be preferable (Helfand 1982, private communication).

Composition of an extended envelope also affects the light curve shape (Lasher, Karp, and Chan, 1977), total absence of hydrogen, in particular, not yielding an acceptable model, though 10% H is ok. The proper attitude to take toward envelope size and composition in a model is probably to decide *a priori* what sort of star one is talking about—a white dwarf in a cataclysmic binary, an isolated Wolf-Rayet star, or whatever (Sec. IV.C)—and then choose envelope properties accordingly.

Continuous energy input from radioactivity has two pieces—gamma rays, appearing promptly after the 6-day half-life decay of Ni^{56} to Co^{56}, and positrons, released on a 77-day half-life as Co^{56} decays to Fe^{56}. The former deposit energy in the envelope (by repeated scatterings) only until it becomes optically thin to them. Their energy deposition and escape dominate the rapidly declining part of the light curve in models with initially compact envelope. The positrons continue to deposit energy until production ceases and they are all annihilated, after many half-lives, and are responsible for the long exponential tail of Type I light curves. In some models, the calculated decline is slower than the observed one unless appreciable flux comes out in infrared lines (Chevalier, 1981d; 1982, private communication) or near-zero magnetic fields allow the relativistic positrons to escape from the envelope on a time scale rather shorter than the production half-life (Colgate, Petschek, and Kriese, 1980; Weaver, Axelrod, and Woosley, 1980).

The most detailed published light curves are for cases of initially compact envelopes and the two forms of radioactive input. Figure 11 shows successful fits of this type to various observed light curves (from Weaver, Axelrod, and Woosley, 1980; Chevalier, 1981e). There are a number of adjustable parameters, including the zeros of magnitude and time for the observations (as individual distances are not very well known, and the initial stages of rising light have never been seen). Within the models, the amount and composition of material burned explosively, the burning temperature and density (which determine product composition), and the mass and size of an overlying envelope can all be chosen within wide ranges permitted by the nature of the exploding stars. Apart from gross envelope size, the things that matter most are the amount of Ni^{56} and the total mass over which its energy (nuclear binding and, later, radioactive decay) has to be spread. These provide plenty of freedom to match the range of decline speeds, etc., discussed by Pskovskii 1977; Sec. III.A.2 above), and even the odd-sounding correlation of rapid decline with slow ejection speed described by Branch (in NATO81), via a correlation of small total mass with small burned mass (Wheeler, in NATO81).

Unfortunately, although the amount of Ni^{56} made is the single most important quantity in the models, reasonably successful fits have been obtained with amounts varying by more than a factor of 5, from 0.25 to 1.4 $M_{\odot}$ (cf. Arnett, 1979, 1982; Colgate, Petschek, and Kriese, 1980; Axelrod, 1980; Weaver, Axelrod, and Woosley, 1980; Imshennik, Nadyozhin, and Utrobin, 1981; Chevalier, 1981e). Why the large spread? Partly, it is the distance scale. $L_{\max}$, and so, crudely, the number of atoms that must decay to make it, varies as $1/H_0^2$. The other main variable is the average ejection speed of the envelope. This is not the same as the observed photospheric velocity, as there is surely a distribution through the envelope, and which bits we see at which times depends on details of envelope opacity (density distribution, composition, etc.) which are not uniquely known. There is a factor of 4 in mass attributable to the distance scale, and another factor of 4 from ejection speed, though the two are not entirely independent when the additional requirement of matching the light curve shape is added [Axelrod, 1980, Eq. (6.20)]. The result is a 6:1 range in mass of Ni^{56} needed.

We mind about the total Ni^{56} because it severely constrains: (a) how many different kinds of stars are allowed as progenitors; (b) whether there will be enough non-Ni^{56} core mass left to make a neutron star, thus helping with the pulsar birthrate; and (c) how many such events the galaxy can tolerate without drowning in iron.

For all three, less is distinctly more: Arnett's (1979) and Colgate, Petschek, and Kriese's ~ 0.25 $M_{\odot}$ are much less constricting than Imshennik, Nadyozhin, and Utrobin's, Weaver, Axelrod, and Woosley's, and

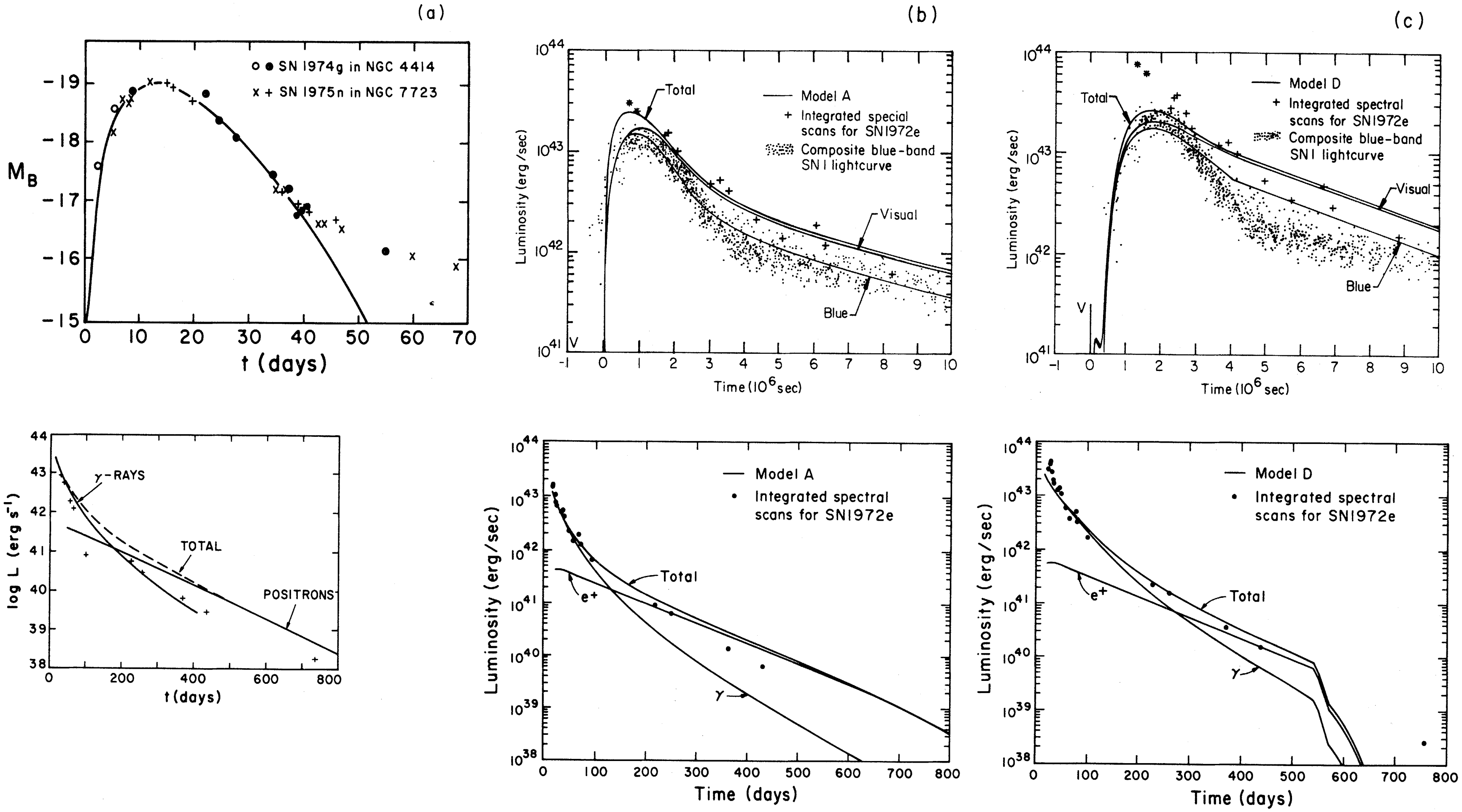

FIG. 11. Model fits to SN I light curves: (a) from Chevalier (1981d), (b) and (c) from Weaver, Axelrod, and Woosley (1980). Both the broad maximum phase and exponential decline phases are shown. The two Weaver *et al.* models differ in total star mass, in mass of Ni^{56} made, and in initial envelope size. The Ni^{56} decay contributions via gamma-ray production and positron production are shown separately for the last time light curves. Again it is interesting both that reasonably good fits are obtainable and that some are better than others.

Chevalier's 1.0−1.4 $M_\odot$. Tinsley (1980a) for instance, noted that galactic evolution calculations would be happiest with $\lesssim 0.2\ M_\odot$ of Fe per event, though she could not absolutely rule out even a Chandrasekhar 1.4 $M_\odot$ of iron from each SN I.

Lots of iron from SN I's presents one more problem: we see no evidence for it in the x-ray spectra of SN 1006, SN 1572, and SN 1604. The iron might satisfactorily be hidden either by keeping it cool (Fabian, in NATO81, and Fabian, Stewart, and Brinkman, 1982, on 1006) or by swamping it with swept-up interstellar gas. Chevalier (1981e) suggests as much as $\gtrsim 8\ M_\odot$ for 1572. The latter explanation has the additional virtue of accounting for the large total masses found from x-ray observations of these young remnants (end of Sec. III.A.3 above), as well as justifying the composition assumptions that went into their derivation.

Finally, one would worry a good deal less about the largish masses of Ni^{56} needed in some models if there were genuinely two or more populations of SN I's, differing in ejection velocity, progenitor mass, and parent population (if not in maximum brightness). This would provide enough stray factors of 2 in the various calculations to make everything fit. The evidence for such separable classes is, unfortunately, rather tenuous (Dallaporta, 1973; Sec. III.A.2 above). I am, nevertheless, inclinded to believe in them.

In summary, Type I light curves,like Type I spectra, are quite well fit by current models. But for both, one is a bit surprised at the extremity of the composition required.

IV. MODELS

A. Features common to both types

At first glance both types of superonovae seem remarkably easy to make. All we need for a Type II is a kindly genie willing to deposit $\gtrsim 10^{51}$ erg at the base of a $\gtrsim 5\ M_\odot$ envelope of solar composition and supergiant structure, and the inevitable heating, expansion, and photon leakage will give us respectable fits to the light curves, spectra, and remnants of observed events. And, if the same genie will be good enough to put $\sim 1\ M_\odot$ of Ni^{56} into the portion of the hydrogen-poor star that is being disrupted by detonation or deflagration, while shielding it from immediate view with $\sim 0.1\ M_\odot$ of unprocessed material, then the system will naturally evolve so as to match our observations of Type I supernovae (cf. Arnett, in NATO81).

In both cases, the genies have proven either uncooperative or inept. The Type II genie has plenty of energy at his disposal (the binding energy of a neutron star), but has difficulty getting it into the form of a sufficiently powerful outgoing shock wave. And the Type I genie has been so busy running from one kind of star to another looking for the best place to put his nickel that he hasn't quite finished the job in any of them.

The preceding remarks presuppose a one-to-one correlation between the dichotomies neutron star versus deflagration and hydrogen versus no hydrogen. The correlation holds for most, but not all, of the evolutionary end points reach in Sec. II. The exceptions are: (1) Miyaji *et al.*'s (1980) O-Ne-Mg cores which can collapse to neutron stars via electron capture, whether they are made from single, hydrogen-covered stars or from binary white dwarfs with, at most, a very thin accreted H layer; (2) traditional, Arnett (1969)-type carbon detonation in single stars, which, if it happens at all, does not care whether a hydrogen envelope is still around or not; and (3) iron core collapse in a (single or binary) star that has lost all its hydrogen layers.

Pretending that anything that makes a neutron star is unambiguously a Type II will slightly simplify the organization of the next two sections, which explore some of the details and difficulties of models intended to help the genies with their tasks. Recent reviews of the problems include Sugimoto and Nomoto (1980), Mazurek and Wheeler (1980), Chevalier (1981b), Lattimer (1981), Wheeler (1981a, and in NATO81), and Woosley and Weaver (1982a).

A striking feature of NATO81 was the extent to which the several groups working on supernova models agreed both about the main features of what must be going on and about the nature and relative importance of the remaining problems. The implication is that, if we are all going the same direction, it must be forward; and our understanding of the supernova phenomenon may finally have advanced significantly beyond that achieved by Baade and Zwicky (1934a, 1934b, 1934c), Burbidge *et al.* (1957, B^2FH), and Hoyle and Fowler (1960).

The next two sections have been written on the assumption that, indeed, the overall schemes are right and, therefore, detailed agreements and disagreements between models and between models and observations are worth looking at. The history of astronomy suggests, however, that cautious distrust of such general agreement might be wise. The reviews by Shklovskii (1981c) and Imshennik and Nadyozhin (1982) reach very different conclusions (see also Sec. IV.D).

B. Models of Type II supernovae

Single stars in excess of $7\pm 3\ M_\odot$ eventually develop nondegenerate carbon-oxygen cores larger than the Chandrasekhar mass (Secs. II.A.6 and 7), as do binary components with main sequence masses (initial or acquired through transfer) $\gtrsim 15\ M_\odot$ (Secs. II.B.1 and 3; Webbink, 1979b). Nuclear burning proceeds in them until the core evolves a Chandrasekhar mass of degenerate iron. At this point, the photon temperature is $\sim 8\times 10^9$ K (Weaver, Zimmerman, and Woosley, 1978) and the degeneracy energy of the electrons is comparable with the neutron-proton mass difference, permitting photodisintegration of the iron and electron captures to take place. These erode pressure support within the core, which begins a rapid collapse to neutron star densities (or beyond), releasing $\gtrsim 10\%$ of mc^2, much as envisaged by Baade and Zwicky (1934a, 1934b, 1934c).

Once the collapse starts, it goes much faster than either of the processes that triggered it, photodisintegration being inhibited by the populating of excited states of the nuclei (Lamb *et al.*, 1978; Bethe *et al.*, 1979) and electron capture by neutrino trapping (Mazurek, 1974, 1976; Sato, 1975) and neutron shell blocking (Fuller, 1982). Luckily the details of these complex processes do not matter much for the hydrodynamics of the core collapse, which is essentially homologous (Lattimer, 1981; Hillebrandt, in NATO81).

But in order for the collapse to make a Type II supernova, about 1% of the available energy must be deposited at the base of an extended, hydrogen-rich (supergiant) envelope. This in turn requires two things—the existence of an appropriate envelope and a suitable energy transport mechanism. Most massive single stars probably still have such an envelope when their cores become unstable, even after extensive mass loss during hydrogen and helium burning (de Loore, 1980). The binaries typically do not, and so presumably give rise to silent supernovae. Extended helium envelopes are also possible, at least for a narrow range of core masses (Paczyński, 1971a), but explosions inside them would look more like SN I's than SN II's.

Two proposed transport mechanisms are still alive and kicking, though neither has yet proven entirely satisfactory. Colgate and Johnson (1960; Colgate, Grasberger, and White, 1961) suggested the collapsing core would bounce at high density (due to adiabatic compression and the hardening of the equation of state at nuclear densities), generating an outgoing shock wave capable of ejecting the envelope. Shortly therafter, Colgate and White (1966; Colgate, 1968) proposed alternatively that neutrinos made by electron capture would deposit much of their energy and momentum at the base of the envelope, thus ejecting it (Schwartz, 1967).

1. Neutrino transport supernovae

The neutrino transport mechanism was promptly criticized as inadequate (Arnett, 1967, 1968), but seemed to draw a new lease on life with the inclusion of neutral-current effects (Freedman, 1974). Neutral-current coherent scattering by large nuclei increased the stellar opacity to neutrinos and so seemed to help them deposit useful energy (Wilson, *et al.*, 1974; Bruenn, 1974). Later treatments, however, showed that, because the collapsing core was made mostly of heavy nuclei, the effect was in fact to trap the neutrinos in the core, from which they could escape only on a time scale longer than that of the collapse (Mazurek, 1976; Tubbs, 1978). And, with the longer time scale and corresponding lower neutrino luminosity, the outward force due to neutrino radiation pressure never exceeded that of gravity, so no ejection. The surface within which the neutrinos are trapped is often called the neutrinosphere (by analog with photosphere), meaning that the optical depth above it is unity. It occurs at a density near 5×10^{10} g cc^{-1} (Bethe, in NATO81).

But all was not lost. Epstein (1979) noted that the trapped configuration was, in effect, a light fluid (the degenerate neutrinos) supporting a heavier one (the baryons of the overlying outer core and mantle) and so ought to be subject to Rayleigh-Taylor instabilities, and, because of the gradient in lepton-to-baryon ratio, to convection as well. Colgate (1978) suggested that, given these instabilities, even small amounts of rotation would trigger convective overturn of the entire core. The first models including these effects (Bruenn, Buchler, and Livio, 1979; Livio, Buchler, and Colgate, 1980) showed that, if convective overturn occurs, coupling hydrostatic core, shocked mantle, and neutrinosphere, then the neutrino transport rate is indeed large enough to produce ejection. In the absence of overturn, however, the convection serves largely to smooth out the lepton-to-baryon ratio, and so is self-limiting (Wilson, 1980).

A second generation of spherically symmetric models (Smarr *et al.*, 1981; Lattimer and Mazurek, 1981), with more detailed equations of state, etc., indicates that convection is confined to the mantle region (the zone $\sim 0.7-1.1\ M_\odot$ from the center), coupling to neither the inner core nor the outer, transparent regions. Thus there is no overturn, and neutrino transport should not contribute significantly to ejection. Colgate *et al.* did not present a competing model at NATO81, but the last word on this has surely not been heard. In particular, viscous dissipation and the effects of material motion on neutrino transport have probably not yet been included with sufficient accuracy (van den Horn and van Weert, 1982; Bruenn and Ballester, 1981).

Intriguingly, the first generation of two-dimensional, rapidly rotating models (Müller and Hillebrandt, 1981) shows circulating flows that transport neutrino energy from the hydrostatic core to the zones behind the shock front at a rate of about 10^{51} erg msec^{-1}, much as in the case of convective overturn. Such a neutrino flow should be just as effective in producing ejection as the one generated more violently by overturn.

2. Core bounce supernovae

While the neutrinos were arguing, the shock generated by core bounce has been working its way out through the mantle. Let's see how it's getting along. Recent relevant numerical models include those calculated by Wilson (1980), Mazurek, Cooperstein, and Kahana (1980), Lichtenstadt, Sack, and Bludman (1980), Hillebrandt and Müller (1981), Van Riper (1981), Arnett (1981), and Hillebrandt (1981). Bethe *et al.* (1980, and in NATO81) and Brown, Bethe, and Baym (1981, and in NATO81) have given important analytical discussion of the dominant effects. And Hillebrandt (in NATO81) provides a useful overview of the similarities and differences among the several calculations. All agree that a shock forms. A rather lengthy (but still somewhat simplified) description of the mechanism follows.

Shortly (a few msec) after the core begins to collapse, the central region adjusts itself so that it is collapsing homologously (velocity proportional to radius). This is possible only as far out as where the required velocity becomes equal to the sound speed. The outer core is in quasi-free-fall ($v \sim \frac{1}{3}$ free-fall velocity, owing to partial pressure support by relativistic leptons). The "last good homology" occurs as the very center of the star reaches nuclear density and begins to decelerate (because the nuclei finally break up and degenerate neutron pressure stiffens the equation of state to $\Gamma \sim \frac{5}{3}$).

The amount of mass within the homologous core at this instant will prove to be exceedingly important for the later evolution. Values from 0.5 to 1.0 $M_\odot$ have been found, as a function largely of Y_e, the number of electrons per nucleon in the homologous region. Large Y_e's yield large cores. Thus, if the inhibition of electron capture by trapping and shell effects keeps Y_e up around $0.36-0.38$ (Brown, in NATO81) from its initial value of ~ 0.41 (Weaver, Zimmerman, and Woosley, 1978; Arnett, 1980), the homologous core mass will be $0.6-0.8$ $M_\odot$ (Hillebrandt, in NATO81).

Because the core is homologous, it all reaches high density practically at once. As a result of the large infall kinetic energy, the collapsing core overshoots nuclear density (by about 50%), then bounces back, sending a pressure shock into the quasi-free-fall mantle. This is the shock that will eventually work its way back out through the mantle and neutrinosphere, ejecting the envelope (or not, as the case may be). Successful ejection requires $\gtrsim 10^{51}$ erg at the base of the envelope, and thus depends on the initial shock energy and on the processes that augment and deplete it en route. It now seems likely that the bounce is critically damped; the core rebounds once and stops. Hence the existence of the nuclear-density core ceases to matter, except as a hard surface against which infalling mantle can splat and as a source of neutrinos that can diffuse out (both adding energy to the shock).

The shock is initially a stationary, accretion one. It begins propagating outward (in spatial coordinate) only after $\sim 0.1-0.2$ $M_\odot$ has fallen through, adding energy and raising the shock speed above that of the infall (Brown *et al.*, 1981). The shock energy at this time is about 6×10^{51} $(Y_e/0.37)^2$ erg. This energy is larger when bounce occurs at higher densities. Thus a relatively soft equation of state favors ejection—but it must not be so soft that the homologous core collapses to a black hole before the bounce happens!

The propagating shock gains energy from kinetic energy of the infalling material and from neutrinos diffusing out of the core up to the shock front. It loses energy via neutrino production (pairs and electron capture) and dissociation of nuclei to nucleons in the matter it transverses. The numbers involved are $\sim 10^{51}$ erg for each. The amount of material that has to be dissociated is, therefore, clearly very important. That is why a large homologous core mass and small total iron core mass (thus less stuff outside the initial shock) favor an explosion. This dependence on initial core mass and on amount of dissociation required seems to imply that the O-Ne-Mg cores studied by Miyagi *et al.* (1980) have a particularly good chance of making a bounce that ejects. Such cores have not been followed far enough to be sure of this, but Nomoto (in NATO81) suggests this scenario particularly for SN 1054.

The shock retains the energy of the neutrinos in it only until it reaches the neutrinosphere, where they can stream out and electron capture, etc., proceed uninhibited. Thus the location of the neutrinosphere also matters.

Published (or nearly so) calculations for Fe cores disagree on whether the shock reaches the envelope with useful energy, stalls into an accretion shock, or dies. The differences in results correlate well with differences in input physics and modeling techniques (Hillebrandt, in NATO81). The several groups involved were generally in agreement at NATO81 about how the various processes should be handled. But no one had as yet done a numerical calculation using the best prescription for each.

Brown and Bethe (in NATO81) were quite sure the shock would get out. If so, the basic problem of making SN II's has been solved. If you share their optimism, feel free to skip to the next section.

Woosley, Hillebrandt, and Arnett (in NATO81) and Wilson (1982) were less sanguine. Arnett (reported by Bethe, 1982) has also found a class of models in which the shock has negative total energy before it ever reaches the envelope, and so surely doesn't get out. But even if this pessimism is justified, all is not lost. Various two-dimensional effects of magnetic fields and rotation (Müller and Hillebrandt, 1979, 1981; Hillebrandt and Müller, 1981) all tend to provide extra outward pressure and help the shock one way or another (qualitatively this is not very surprising). These may also be most effective in relatively low-mass cores, hence in stars of initial mass, e.g., $8-15$ $M_\odot$.

The numerical calculations from which the above conclusions derive all used explicit-time-step hydrodynamic codes. This limits them to considering only the first few tens of milliseconds of the collapse and associated phenomena. Very many time steps (and marks worth of computing time) would otherwise be required. Two kinds of later processes may, however, be interesting for the ejection problem. First, the proto-neutron star must get rid of its excess leptons via diffusion to the neutrinosphere. Burrows, Mazurek, and Lattimer (1981) find that this takes about half a second and deposits some 10^{52} erg in the mantle. This could possibly push a stalled accretion shock enough to get it going again and produce ejection.

Second, if core bounce falls and a black hole forms from the homologous core and infalling mantle, material from further out will be trying to get into it at close to the free-fall rate. This is considerably higher than the Eddington rate for which the force of radiation pressure due to accretion luminosity equals the force of gravity. Rotation, magnetic fields, and nuclear burning of Si, Ne-Mg, and C-O layers also all tend to push outward.

Woosley and Weaver (1982a and in NATO81) suggest that a black hole, as a result, can scarcely swallow a whole red giant without burping extensively. If so, then massive stars might eject the products of their nuclear reactions without necessarily leaving a neutron star remnant. The ejection process may not look much like a Type II supernova, but this doesn't matter, as the stars massive enough to contribute much nucleonsynthesis are very rare. A plausible combination of events is, therefore, one $8-15\ M_\odot$ going off by core bounce every $30-50$ years (yielding pulsar, SN II, modest amounts of excess helium, as in the Crab Nebula, and perhaps some C-N-O nuclei) and one $\gtrsim 25\ M_\odot$ star going off every few centuries (yielding most of the traditional nucleosynthesis).

C. Models of Type I supernovae

1. Single stars

Three classes of single stars evolve potentially explosive cores containing roughly a Chandrasekhar mass of degenenerate carbon and oxygen (Sec. II.A; Mazurek and Wheeler, 1980). They (and their potential disasters) are $\sim 4-8\ M_\odot$ (carbon detonation/deflagration) and $8-10\ M_\odot$ (oxygen deflagration) normal main sequence stars whose hydrogen-rich envelopes have gone with the stellar winds, and $1.4-4\ M_\odot$ (carbon and oxygen ignition) helium stars produced by (abnormal) total mixing during hydrogen shell burning. All three cases have been modeled, in one sense. That is, Weaver, Axelrod, and Woosley (1980) or Wheeler and Sutherland (1981) have shown that, if the cores are half or more incinerated to Ni^{56} (and adjacent nuclides, in nuclear statistical equilibrium) inside a plausible range of helium envelope masses ($0-0.5\ M_\odot$) and sizes ($10^{11}-10^{13}$ cm), the product looks like an SN I.

The details of the burning turn out to matter hardly at all, only the previously mentioned (Sec. III.C.3) parameters of total mass, Ni^{56} mass, and envelope mass/size being important. Thus these calculations can be decoupled from the preceding stellar evolution for all purposes except the vital one of deciding if the explosion actually occurs.

There is some doubt for all three cases. Gradual shrinkage in recent years of the carbon-detonation mass range was noted in Sec. II.A.5. It may well have shrunk to zero. The O-Ne-Mg core of Weaver, Axelrod, and Woosley's (1980) $9\ M_\odot$ star may blow up at neon ignition, but a slightly more massive core neutronized and collapsed for Miyaji *et al.* (1980). Even the exploded one made just barely enough Ni^{56} ($\sim 0.3\ M_\odot$) for a Type I. And, finally, although assorted helium stars belonging to the third class seem to have been observed (R CrB variables, etc.), no evolutionary tracks have made them, casting doubts upon their existence.

It is perhaps slightly ominous that satisfactory models result not only from cores that seem likely to blow up, but also from artificial explosions of configurations that one is quite sure are, in reality, stable (C-O core masses well below the Chandrasekhar limit, for example—Wheeler in NATO81).[1] The single-star models have, however, the virtues: (a) of accommodating easily a range of envelope masses and sizes (useful for adjusting the peak of the light curve in brightness, duration, and ejection velocity, as well as for hiding the Ni-Co-Fe early on); and (b) of falling in the main sequence mass range suggested by the arguments of Oemler and Tinsley (1979). I should like to allow at least a few carbon deflagrations and helium stars, but to send the oxygen cores back to Sec. B to make SN II's.

One other path will surely produce an unstable configuration, likely to explode of collapse. The Chandrasekhar limiting mass for stable white dwarfs is slightly larger for hot, rotating stars than for cold, static ones. Thus there is a narrow mass range over which degenerate dwarfs can form, but find themselves suddenly unstable as they lose heat and/or angular momentum (Finzi and Wolf, 1967; Ostriker, 1971). The relevant mass range is, however, so exceedingly narrow that such stars can be responsible for at most a small fraction of observed SN I's (Shklovskii, 1978). The advantage of this mechanism is that the temperature and rotation rate may take a very long time to decline to the unstable range, allowing for events among the oldest stars. Schatzman's (1965) suggestion of white dwarfs driven over the Chandrasekhar limit by accretion of interstellar gas has the same time-scale argument in its favor and the same statistical one against it.

2. Binary stars

A wide range of initial masses, mass ratios, and separations yields degenerate dwarfs in binaries close enough for a second phase of mass transfer eventually to occur (Sec. II.B). Models of this type become popular about a decade ago (Wheeler and Hansen, 1971; Truran and Cameron, 1971; Hartwick, 1972; Whelan and Iben, 1973; Mazurek, 1973). The details are not all yet under control, but there is general agreement (see Sec. IV.D for the disagreements) that explosions really will occur for most white dwarfs driven to sufficiently high mass, and that this can occur rather similarly in systems that started out quite different, perhaps accounting for the homogeneity of SN I spectra and light curves. The parameters that matter are the initial mass and composition (He, CO, or O-Ne-Mg) of the white dwarf, the length of time it cools before back transfer begins, and the arrival rate and composition of the accreted gas.

A helium white dwarf must start out with $M < 0.45\ M_\odot$; otherwide it would have gotten hot enough for normal helium-flash ignition before degeneracy set in. The

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[1] As Anne Underhill once said in another connection, there are more models that aren't stars than there are stars that aren't models!

longer the star cools, the more gas must be accreted for adiabatic compression to reheat it to helium-burning temperatures. And, the more material added, the higher the central density at eventual ignition, and the more violent the explosion. Mazurek (1973, 1980) and Nomoto and Sugimoto (1977) have looked at accretion rates from the 10^{-6} $M_\odot\,\mathrm{yr}^{-1}$ maximum permitted by radiation pressure when hydrogen burns steadily in the accreted gas down to about 1% of that. They find that any ignition occurring past $M=0.67$ $M_\odot$ will process the entire star to iron-peak elements and completely disrupt it. Such a disruption does not look much like a Type I supernova. There is no unprocessed envelope left to hide the new Ni, and helium burning releases so many ergs per gram that ejection is too rapid. Earlier ignition, at $M<0.6$ $M_\odot$, can leave an unprocessed mantle, though the amount of Ni^{56} made is then only just barely enough (~ 0.3 $M_\odot$) to fit SN I light curves.

There exist real systems with helium white dwarfs (or at least white dwarf masses $\lesssim 0.45$ $M_\odot$). But most, apparently, do not end explosively. Either they are formed only in very close systems, so that reverse transfer sets in quickly, resulting in a mild helium flash, or they generally do not build up to the fatal 0.67 $M_\odot$ in a Hubble time. Observed mass transfer rates in cataclysmic binaries are usually larger than 0.3 $M_\odot$ per Hubble time, but explosive burning of accreted hydrogen can make the mass retention rate arbitrarily small. Hydrogen accretion on helium white dwarfs has not historically been regarded as a promising nova mechanism, thus the burning has been taken as steady *a priori* in the models calculated so far. The question of what becomes of helium white dwarfs in close binaries deserves further attention, even if they don't make Type I supernovae (cf. Vogt *et al.*, 1981).

Carbon-oxygen white dwarfs in close binary systems begin life at a point within the range $0.45-1.4$ $M_\odot$ that depends (monotonically but not linearly) on main sequence mass and on when the first phase of mass transfer happened. The average for single white dwarfs is about 0.75 $M_\odot$, with rather small dispersion, but the (generally rather poorly) measured binary values cover the permitted range more or less uniformly. Accretion of hydrogen and/or helium back onto the white dwarfs from an evolving secondary is the most widely studied of explosive binary processes. Again, initial mass, cooling time, and accretion rate all matter.

Fujimoto and Sugimoto (1980, 1981), Woosley, Weaver, and Taam (1980), Taam (1980a, 1980b), and Nomoto (1981a, 1982a, 1982b) have explored overlapping regions of the likely parameter space: $M=0.5-1.4$ $M_\odot$; $\dot{M}=10^{-10}-10^{-6}$ $M_\odot\,\mathrm{yr}^{-1}$; and $T_c=(1-5)\times 10^7$ K, representing cooling over $10^{8\pm 0.5}$ yr. These groups disagree only on minor points, and the discrepancies are qualitatively understood (Nomoto, 1982a). The smallest accretion rates probably lead to hydrogen shell flashes, which expel the unburned hydrogen: about 99.9% of it must leave to turn off the flash on the time scale of observed novae. Thus accretion rates of $10^{-10}-10^{-9}$ $M_\odot\,\mathrm{yr}^{-1}$ can apparently lead to SN I's only if the companion has lost its hydrogen-rich envelope and is transferring nearly pure helium, which accumulates and flashes periodically without blowoff. Such systems could easily exist, though I know of no clear observed examples.

Very low accretion rates allow C-N-O to diffuse downward out of the accumulating gas, so that hydrogen can burn peacefully by the *pp* chain (Starrfield, Truran, and Sparks, 1981). The permitted rate is, however, so slow that the time required to reach the Chandrasekhar mass will equal or exceed a Hubble time, and these systems cannot correspond to observed dwarf novae (Papaloizou, Pringle, and MacDonald, 1982; Paczyński, 1982).

Intermediate accretion rates produce steady hydrogen burning (Paczyński and Rudak, 1979), but the helium accumulates and flashes from time to time. Near-Eddington rates yield steady burning of both H and He until the carbon ignites (on or off center). It is not clear whether we see any systems accreting at these larger rates. The largest regenerate a red giant envelope around the white dwarf, so that it becomes indistinguishable from other evolved stars; intermediate accretion rates may occur among some symbiotic stars (Paczyński and Rudak, 1979) and OB subdwarfs.

Helium flashes do not expel the surface layers in a novalike fashion. Growth to the Chandrasekhar limiting mass is, therefore, inevitable. Carbon ignition is virtually always fatal. In addition, the strongest helium shell flashes, which occur as the mass reaches 1.4 $M_\odot$ via accretion rates of $(1-40)\times 10^{-9}$ $M_\odot\,\mathrm{yr}^{-1}$, trigger an outgoing deflagration wave in the helium envelope and an ingoing one in the carbon-oxygen core. These burn most of the star and disrupt all of it. Thus accretion on a C-O white dwarf always produced explosive burning and (almost always) complete disruption in these models. Incineration is not, however, always total. Several of Nomoto's (1980) models made $0.2-0.3$ $M_\odot$ of intermediate elements (O, Ne, Si, Ca, etc.), $0.2-1.0$ $M_\odot$ of Ni^{56}, and left $0.2-1.0$ $M_\odot$ of unburned C-O and/or He. This is particularly encouraging in connection with the relative normalcy of the abundances of intermediate elements found by Branch (in NATO81) from SN I spectra near maximum light.

Most of these explosions leave no compact remnant. A narrow range of initial masses and transfer rates (around 1.08 $M_\odot$ and 3×10^{-10} $M_\odot\,\mathrm{yr}^{-1}$; Nomoto, 1980) may, however, flash the entire accumulated helium mantle, while leaving the initial C-O core bound. About 0.3 $M_\odot$ of Ni^{56} is blown off, with an energy of $\sim 10^{51}$ erg (average ejection speed 1.7×10^9 $\mathrm{cm\,sec}^{-1}$), making a not-intolerably-feeble supernova. The remnant of SN 1006 has a partially degenerate OB subdwarf (log $g=6.7$) within its confines (Schweizer and Middleditch, 1980; Simon, Hunger, and Kudritzki, 1981) which is, however, too faint to be a remnant of this scenario so recently (Savedoff and Van Horn, 1982). No neutron stars remain, in good agreement with the absence of point x-ray sources in the remnants of SN 1006, 1572, and 1604 (Becker, Helfand, and Szymkowiak, 1982; Seward, in NATO81; Helfand, in NATO81), while some are found in Crab-like remnants. The place of the Tycho point radio surface, for which existence seems to be the only predicate (Gull and Pooley, 1980; van den Bergh and Morbey, 1981), in this picture is not clear.

Neutron stars do result from the accreting C-O white dwarfs studied by Ergma and Tutukov (1976; Ergma, 1979) and Ivanova, Imshennik, and Utrobin (1978). In fact, so total are the collapses that there is unlikely to be a detectable supernova event or even a shock to make an SNR. These stars thus join the accreting O-Ne-Mg white dwarfs of Miyaji *et al.* (1980) in making "silent" supernovae. Such systems provide some freedom for matching birthrates of x-ray binaries and, perhaps, pulsars, without affecting supernova statistics. Sugimoto and Nomoto (1980) believe that the calculations that yield neutron stars from accreting white dwarfs differ significantly in their treatment of electron screening and heat transport from the calculations that yield disruption starting with similar initial conditions.

For carbon-oxygen white dwarfs that begin accreting only after $\gtrsim 10^9$ yr of isolation and cooling, evolution may be interestingly different. Below about 6×10^7 K, at white dwarf densities, the core wants to begin crystallizing (Salpeter, 1961; Mestel and Ruderman, 1967; cf. Wigner, 1934, and Fuchs and Wills, 1935). But carbon and oxygen can freeze together only in a eutectic ratio 2:1 (Stevenson, 1980). Thus, in a standard C=O mix, freezing begins with a flurry of oxygen snow flakes falling toward the center. Canal *et al.* (1980a, 1980b; 1981, 1982) have followed this process and find that a complete separation of O from C and partial neutronization of the O at $\rho\sim10^{10}$ g cc^{-1} normally occur before carbon can ignite, if the star is cool enough when accretion begins. Inevitably, then, at least the oxygen half of the core collapses to neutron star densities. The stars have not yet been properly modeled past this point, but Canal *et al.* think it likely that, in at least some cases, much of the carbon will deflagrate and the products be expelled. The result would be a $0.6-0.7\ M_\odot$ neutron star at the center of a Type I supernova, consisting of $0.6-0.7\ M_\odot$ of Ni^{56}, plus whatever accreted gas had not yet been processed to carbon. As Canal *et al.* began with a white dwarf just below the Chandrasekhar limit, their unprocessed gas fraction is only $10^{-2}\ M_\odot$. It could be usefully larger for smaller starting masses.

Sparks and Stecher (1974) have suggested another variation of the standard scheme, in which two degenerate cores (a white dwarf and the center of a red giant) come together through common envelope binary evolution. If each had $\gtrsim$ half a Chandrasekhar mass, a merger product would be subject to either collapse or detonation. The authors mention only neutron star formation as a possible outcome. But the collision energy is $\sim2\times10^{49}$ erg, so that detonation or even mechanical disruption of the cores seems equally likely. The messiness of a proper calculation would be second only to that of the events themselves.

Of the several sites and scenarios discussed, mass transfer onto a C-O white dwarf in a binary system would win an election for "most beautiful model." It would be interesting to estimate from (almost) first principles what the SN I rate ought to be by identifying the range of close binary evolutionary tracks (e.g., Webbink, 1979b) that lead to the right white dwarf masses and mass transfer rates, and thereby deciding how many explosive systems ought to exist from known (sort of) distribution functions of stellar mass, binary mass ratio, and binary separation at age zero.

There was at NATO81 a general feeling that our understanding of Type I supernovae is in pretty good shape: analysis of the spectra and light curves leads to a picture of the explosion reasonably close to what the theorists can produce. And there are several plausible astrophysical sites for the events. Thus, perhaps, everything is at last more or less under control. It is also true that groups who have published discordant analyses and models in recent years were largely unrepresented at the meeting, particularly those working in Israel and the USSR.

D. Dissenting views

The preceding sections have, among other things, indicated evidence for correlations of the form:

Type I: lowish-mass progenitor; nuclear (detonation/deflagration) energy source; no compact remnant; continuous energy input from radioactive decay important for light curve and envelope kinetics.

Type II: massive progenitor; gravitational (collapse) energy source with transport by shock wave; compact (neutron star) remnant; continous energy input relatively unimportant for light curve and envelope kinetics.

Assorted weaknesses in the arguments have been noted within the discussion. In addition, some of the calculators of supernova models disagree completely with one or more of the suggested correlations and have presented alternative ones, reviewed by Shklovskii (1981c) and Imshennik and Nadyozhin (1982).[2] The points at issue include the following:

(1) What becomes of the collapsing core of a massive star? Nadyozhin (1977, 1978) has followed collapses of "iron-oxygen" stars of 2 and 10 $M_\odot$ and finds that core bounce, neutrino deposition, and explosive oxygen burning all fail to eject the envelope, contrary to the conclusions of Sec. IV.B.2. In particular, the energy of the shock wave generated by hydrodynamic bounce is almost entirely carried away by neutrinos.

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[2] I am indebted to D. K. Nadyozhin for a copy of the latter in advance of translation and publication.

(2) What becomes of a deflagrating core? Ivanova, Imschennik, and Chechetkin (1974, 1977, 1978) and Chechetkin *et al.* (1980) have considered both accreting C-O white dwarfs in binary systems and degenerate C-O cores of $3.5-8\ M_\odot$ single stars. Contrary to the conclusions of Secs. II.A.5 and IV.C.1 and 2, they find that detonation and deflagration are frequently postponed until the central density is high enough that the star need not be completely disrupted. Within the mass range considered, the larger stars disrupt completely, with enough kinetic energy to power a typical supernova, while the lower masses are only partly disrupted, leaving a collapsed remnant. The envelope expelled is low in both mass and kinetic energy (10^{49-50} erg; Chechetkin *et al.*, 1980) and, in order to make a typical supernova, will need additional energy input—more than can come from radioactivity.

(3) Which SN Type is which? The preceding paragraph implies that supernovae arising from relatively massive stars, the Type II's, will not leave neutron stars, while the ones coming from lower masses, the Types I's, may. If so, then these neutron stars must cool more rapidly than conventional models predict—for instance, via pion condensation (Yakovlev and Urpin, 1981) or quark cores (Iwamoto, 1980; Burrows, 1980)—to avoid conflict with observed upper limits to x-rays coming from the surfaces of neutron stars in the Kepler and Tycho remnants (Nomoto and Tsuruta, 1981). Alternatively, Imshennik and Nadyozhin (1982) propose that Crab-like remnants with neutron stars may be the products of some rarer, third type of supernova event.

(4) What expels the envelope? If neither core collapse nor deflagration (without disruption) puts enough energy into the envelope to expel it, then there must be some other process that does. Otherwise, neither the statistics of supernovae nor the ratios of products of nucleosynthesis are likely to come out right. Bisnovatyi-Kogan (1971; Bisnovatyi-Kogan, Popov, and Samochkin 1976; Ardelyan, Bisnovatyi-Kogan, and Popov, 1979) has treated, in a one-dimensional calculation with cylindrical symmetry, the transfer of the rotational energy of a newly formed neutron star via a magnetic field to a surrounding envelope, and finds this to be the relevant ejection mechanism in many cases.

Notes added in proof

1. Accidental deletion of a paragraph in Sec. IV.A resulted in failure to credit the pioneering work of Borst (1950) on radioactive decay as an energy source for supernovae and that of Pankey (1962) who seems to have been the first to suggest Ni^{56} as a suitable substance to decay.

2. A recent determination of the white-dwarf-supernova mass cut (Sec. II.A.3) yielded $5\ M_\odot$ from examination of white dwarfs (or their absence) in a number of young, open clusters (B. Anthony-Twarog, Astrophys. J. **245**, 255, 1982).

3. A new limit on the mass of one Type II supernova progenitor (Sec. III.A.3) comes from a photograph of NGC 6946 taken about six weeks before the 1980 supernova therein. The absence of a visible star at the SN position yields $M_\odot$ 18 $M_\odot$ (L. A. Thompson, Astrophys. J. **257**, L67, 1982).

4. The chances of a shock wave resulting from core bounce being able to expel the envelope of a massive star to make an SN II (Sec. IV.B.2) continue to drop. Bowers and Wilson (1982, Astrophys. J., in press) report that, in effect, the more carefully they treat the relevant physics, the feebler the shock looks.

INTERMISSION

The preceding four sections have brought supernovae from their beginnings in the hearts of massive stars and the minds of Baade and Zwicky to the instant of explosion and radiation. Four additional sections, to appear later in this journal, will address the aftermath of supernovae (remnants; production of cosmic rays and gamma rays; nucleosynthesis and galactic evolution) and the future of supernova research.

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The NATO Advanced Study Institute of Supernovae was the first such meeting in many years not enlivened by the presence of Beatrice M. Tinsley. I should like to dedicate this review respectfully and affectionately to her memory.

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REFERENCES

Abt, H. A. and S. G. Levy, 1976, Astrophys. J. Suppl. Ser. **30**, 273.

Abt, H. A. and S. G. Levy, 1978, Astrophys. J. Suppl. Ser. **36**, 241.

Andriesse, C. D., B. D. Donn, and R. Viotti, 1978, Mon. Not. R. Astron. Soc. **185**, 771.

Angel, J. R. P., J. D. Landstreet, and E. F. Borra, 1978, preprint, cited by J. Angel, Annu. Rev. Astron. Astrophys. **16**, 487.

Ardeberg, A., and M. de Groot, 1974, in *Supernovae and Their Remnants,* edited by C. B. Cosmovici (Reidel, Dordrecht), p. 103.

Ardelyan, N. V., G. S. Bisnovatyi-Kogan, and Yu. P. Popov, 1979, Sov. Astron. AJ **23**, 705.

Arnett, W. D., 1967, Can. J. Phys. **45**, 1621.

Arnett, W. D., 1968, Astrophys. J. **153**, 341.

Arnett, W. D., 1969, Astrophys. Space Sci. **5**, 180.

Arnett, W. D., 1973, in *Explosive Nucleonsynthesis,* edited by D. Schramm and W. D. Arnett (University of Texas, Austin), p. 236.

Arnett, W. D., 1977a, Astrophys. J. Suppl. Ser. **35**, 145.

Arnett, W. D., 1977b, Ann. N.Y. Acad. Sci. **302**, 91 (8th Texas Symposium).

Arnett, W. D., 1979, Astrophys. J. **230**, L37.

Arnett, W. D., 1980, Ann. N.Y. Acad. Sci. **336**, 366 (9th Texas Symposium).

Arnett, W. D., 1981, in NATO81; and in preparation.

Arnett, W. D., 1982, Astrophys. J. **253**, 785.

Arp, H. C., 1961, Astrophys. J. **132**, 883.

Ashworth, W., 1979, Bull. Am. Astron. Soc. **11**, 660.

Assousa, G. E., C. J. Patterson, V. C. Rubin, and W. K. Ford, 1976, Publ. Astron. Soc. Pac. **88**, 828.

Axelrod, T. S., 1980, Ph.D. thesis (University of California, Santa Cruz; Report No. UCRL 52994) and in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 80.

Axelrod, T. S., 1981, in NATO81.

Baade, W., 1936, Publ. Astron. Soc. Pac. **48**, 226.

Baade, W., 1938, Astrophys. J. **88**, 285.

Baade, W., 1942, Astrophys. J. **96**, 188.

Baade, W., 1943, Astrophys. J. **97**, 119.

Baade, W., 1945, Astrophys. J. **102**, 309.

Baade, W., G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, and W. A. Fowler, 1956, Publ. Astron. Soc. Pac **68**, 296.

Baade, W., and F. Zwicky, 1934a, Proc. Natl. Acad. Sci. USA **20**, 254.

Baade, W., and F. Zwicky, 1934b, Proc. Natl. Acad. Sci. USA **20**, 259.

Baade, W., and F. Zwicky, 1934c, Phys. Rev. **45**, 138.

Baade, W., and F. Zwicky, 1934d, Phys. Rev. **46**, 76.

Baade, W., and F. Zwicky, 1938, Astrophys. J. **88**, 411.

Baldwin, J. E., and D. O. Edge, 1957, Observatory **77**, 139.

Barbon, R., 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 16.

Barbon, R., M. Capaccioli, and F. Ciatti, 1975, Astron. Astrophys. **44**, 267.

Barbon, R., F. Ciatti, and L. Rosino, 1973, Astron. Astrophys. **25**, 241.

Barbon, R., F. Ciatti, and L. Rosino, 1979, Astron. Astrophys. **72**, 287.

Barkat, Z., 1977, in *Supernovae,* edited by D. N. Schramm (Reidel, Dordrecht), p. 131.

Barkat, Z., J. R. Buchler, and J. C. Wheeler, 1971, Astrophys. Lett. **6**, 8.

Barkat, Z., G. Rakavy, and N. Sack, 1967, Phys. Rev. Lett. **18**, 379.

Barkat, Z., Y. Reiss, and G. Rakavy, 1974, Astrophys. J. **193**, L21.

Barnothy, J., and M. Forro, 1936, Nature **138**, 344.

Batten, A. H., J. M. Fletcher, and P. J. Mann, 1978, Publ. Dom. Astrophys. Obs., Victoria, B.C. **15**, 121.

Becker, R. H., E. A. Boldt, S. S. Holt, P. J. Serlemitsos, and N. E. White, 1980a, Astrophys. J. **235**, L5.

Becker, R. H., E. A. Boldt, S. S. Holt, P. J. Serlemitsos, and N. E. White, 1980b, Astrophys. J. **237**, L77.

Becker, R. H., D. S. Helfand, and A. E. Szymkowiak, 1982, Astrophys. J. **255**, 557.

Becker, S. A., and I. Iben, 1980, Astrophys. J. **237**, 111.

Benson, R. S., 1970, Ph.D. thesis (University of California, Berkeley).

Benvenuti, P., 1981, in NATO81.

Bertaud, M., 1941, Astronomie **55**, 73, and 103.

Bertola, F., M. Capaccioli, and J. B. Oke, 1982, Astrophys. J. **254**, 494.

Bethe, H. A., in NATO81.

Bethe, H. A., 1982, Seminar at California Institute of Technology, February, 1982.

Bethe, H. A., J. Applegate, and G. E. Brown, 1980, Astrophys. J. **241**, 343.

Bethe, H. A., G. E. Brown, J. Applegate, and J. M. Lattimer, 1979, Nucl. Phys. A **324**, 487.

Bisnovatyi-Kogan, G. S., 1971, Sov. Astron. AJ **14**, 652.

Bisnovatyi-Kogan, G. S., Yu. P. Popov, and A. A. Samochkin, 1976, Astrophys. Space Sci. **41**, 321.

Bode, M. F., and A. Evans, 1980, Mon. Not. R. Astron. Soc. **193**, 21p.

Bodenheimer, P., and J. P. Ostriker, 1974, Astrophys. J. **191**, 465.

Bohannan, B., and P. Conti, 1976, Astrophys. J. **204**, 797.

Bondi, H., 1964, Proc. R. Soc. London Ser. A **281**, 39.

Boozer, A. H., P. C. Joss, and E. E. Salpeter, 1973, Astrophys. J. **181**, 393.

Borst, L. B., 1950, Phys. Rev. **78**, 807.

Bovkoon, V. P., and I. N. Zhouck, 1981, Astrophys. Space Sci. **79**, 181.

Brancazio, P. J., and A. G. W. Cameron, 1969, *Supernovae and Their Remnants* (Gordon and Breach, New York).

Branch, D., 1980a, in *Supernovae Spectra,* edited by R. E. Meyerott and G. H. Gillespie (AIP Conference Proceedings No. 63), p. 39.

Branch, D., 1980b, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 66.

Branch, D., 1981a, Astrophys. J. **248**, 1076.

Branch, D., 1981b, in NATO81.

Branch, D., R. Buta, S. W. Falk, M. L. McCall, P. G. Sutherland, A. K. Uomoto, J. C. Wheeler, and B. J. Wills, 1982, Astrophy. J. **252**, L61.

Branch, D., S. W. Falk, M. L. McCall, P. Rybski, A. K. Uomoto, and B. J. Willis, 1981, Astrophys. J. **244**, 780.

Branch, D., and J. L. Greenstein, 1971, Astrophys. J. **167**, 89.

Branch, D., and B. Patchett, 1973, Mon. Not. R. Astron. Soc. **161**, 71.

Branch, D., and R. G. Tull, 1979, Astron. J. **84**, 1837.

Brecher, K., and G. Chanmugam, 1978, Astrophys. J. **221**, 696.

Brecher, K., and I. Wasserman, 1980, Astrophys. J. **240**, L105.

Brown, G. E., 1981, in NATO81.

Brown, G. E., H. A. Bethe, and G. Baym, 1981, Nordita preprint 81/17.

Bruenn, S. W., 1972, Astrophys. J. Suppl. Ser. **24**, 283.

Bruenn, S. W., 1974, Ann. N.Y. Acad. Sci. **262**, 80 (7th Texas Symposium).

Bruenn, S. W., and J. L. Ballester, 1981, Astrophys. Space Sci. **78**, 247.

Bruenn, S. W., J. R. Buchler, and M. Livio, 1979, Astrophys. J. **234**, L183.

Buchler, J. R., and T. J. Mazurek, 1975, Mem. Soc. R. Sci. Liege Collect. **8**, 435.

Burbidge, E. M., G. R. Burbidge, W. A. Fowler, and F. Hoyle, 1957, Rev. Mod. Phys. **29**, 547 (B^2FH).

Burrows, A., 1980, Phys. Rev. Lett. **44**, 1640.

Burrows, A., T. J. Mazurek, and J. M. Lattimer, 1981, Astrophys. J. **251**, 325.

Caldwell, C. N., and A. Oemler, 1981, Astron. J. **86**, 1424.

Cameron, A. G. W., 1960, Mem. Soc. R. Sci. Liege, Ser. 15, Vol. III, p. 163.

Canal, R., J. Isern, and J. Labay, 1980a, Space Sci. Rev. **27**, 595.

Canal, R., J. Isern, and J. Labay, 1980b, Astrophys. J. **241**, L33.

Canal, R., J. Isern, and J. Labay, 1981, in NATO81.

Canal, R., J. Isern, and J. Labay, 1982, Nature **196**, 225.

Canizares, C. R., 1981, in NATO81.

Canizares, C. R., G. A. Kriss, and E. E. Feigelson, 1982, Astrophys. J. **253**, L17.

Carr, B., 1981, in NATO81.

Cassinelli, J. P., J. S. Mathis, and B. Savage, 1981, Science **212**, 149.

Caswell, J. L., and I. Lerche, 1979, Mon. Not. R. Astron. Soc. **187**, 201.

Chechetkin, V. M., S. S. Gershtein, V. S. Imshennik, L. N. Ivanova, and M. Yu. Khlopov, 1980, Astrophys. Space Sci. **67**, 61.

Checketkin, V. M., V. S. Imshennik, L. N. Ivanova, and D. K. Nadyoshin, 1977, in *Supernovae,* edited by D. N. Schramm (Reidel, Dordrecht), p. 159.

Chevalier, R. A., 1976, Astrophys. J. **207**, 872; **208**, 826.

Chevalier, R. A., 1977, in *Supernovae,* edited by D. N. Schramm (Reidel, Dordrecht), p. 53.

Chevalier, R. A., 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 53.

Chevalier, R. A., 1981a, Adv. Space Res. **1**, 71.

Chevalier, R. A., 1981b, Fundam. Cos. Phys. **7**, 1.

Chevalier, R. A., 1981c, Astrophys. J. **251**, 259.

Chevalier, R. A., 1981d, Astrophys. J. **246**, 267.

Chevalier, R. A., 1981e, in *Pulsars,* IAU Symposium No. 95, edited by W. Sieber and R. Wielebinski (Reidel, Dordrecht), p. 403.

Chevalier, R. A., 1981f, in NATO81.

Chevalier, R. A., 1982, private communication.

Chevalier, R. A., and R. P. Kirshner, 1979, Astrophys. J. **233**, 154.

Chevalier, R. A., R. P. Kirshner, and J. C. Raymond, 1980, Astrophys. J. **235**, 186.

Christy, J. S., R. S. Harrington, C. L. Dahn, and K. Aa. Strand, 1980, Bull. Am. Astron. Soc. **12**, 454.

Ciatti, F., 1978, Mem. Soc. Astron. Ital. **49**, 343.

Ciatti, F., 1980, in *Variability in Stars and Galaxies* (5th European Regional Meeting), edited by P. Ledoux (Institute d'Astrophysique, Liège), p. F1.1.

Ciatti, F. *et al.*, 1971, Mem. Soc. Astron. Ital. **42**, 163.

Clark, D. H., and J. L. Caswell, 1976, Mon. Not. R. Astron. Soc. **174**, 267.

Clark, D. H., and F. R. Stephenson, 1977, *The Historical Supernovae* (Pergamon, New York/London).

Clark, D. H., and F. R. Stephenson, 1981, in NATO81.

Cocke, W. J., M. J., Disney, and D. J. Taylor, 1969, Nature **221**, 525.

Cohen, J. G., 1980, in *Star Clusters,* IAU Symp. No. 85, edited by J. Hesser (Reidel, Dordrecht), p. 385.

Cole, P. W., and R. G. Deupree, 1980, Astrophys. J. **239**, 284.

Cole, P. W., and R. G. Deupree, 1981, Astrophys. J. **247**, 607.

Colgate, S. A., 1968, Astrophys. J. **153**, 335.

Colgate, S. A., 1978, Mem. Soc. Astron. Ital. **49**, 399.

Colgate, S. A., W. H. Grasberger, and R. H. White, 1961, Astron. J. **66**, 280.

Colgate, S. A., and M. L. Johnson, 1960, Phys. Rev. Lett. **5**, 235.

Colgate, S. A., and C. McKee, 1969, Astrophys. J. **157**, 623.

Colgate, S. A., and A. G. Petschek, 1980, Astrophys. J. **236**, L115 and in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 42.

Colgate, S. A., A. G. Petschek, and J. T. Kriese, 1980, Astrophys. J. **237**, L81.

Colgate, S. A., and R. H. White, 1966, Astrophys. J. **143**, 626.

Cosmovici, C. B., Ed., 1974, *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45 (Reidel, Dordrecht).

Curtis, H. D., 1921, Bull. Natl. Res. Council (U.S.) **2**, part 3, p. 171 (the Curtis-Shapley debates).

Dallaporta, N., 1973, Astron. Astrophys. **29**, 393.

Danziger, J., and A. Renzini, Eds., 1978, *Supernovae and Supernova Remnants,* Mem. Soc. Astron. Ital. **49**, Nos. 2 and 3.

Davidson, K., 1979, Astrophys. J. **228**, 179.

Davidson, K. *et al.*, 1982, Astrophys. J. **253**, 696.

Davies, R. D., and F. G. Smith, Eds., 1971, *The Crab Nebula,* IAU Symposium No. 46 (Reidel, Dordrecht).

De Grève, J. P., and D. Vanbeveren, 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich (Reidel, Dordrecht), p. 103.

de Loore, C., 1980, Space Sci. Rev. **26**, 113.

de Loore, C., 1981, in *Effects of Mass Loss on Stellar Evolution,* IAU Colliquium No. 59, edited by C. Chiosi and R. Salio (Reidel, Dordrecht), p. 405.

de Loore, C., and J. P. De Grève, 1976, in *Structure and Evolution of Close Binaries,* IAU Symposium No. 73, edited by P. P. Eggleton, S. M. Mitton, and J. A. J. Whelan (Reidel, Dordrecht), p. 27.

Dennefeld, M., and D. Kunth, 1981, Astron. J. **86**, 989.

de Vaucouleurs, G., 1979a, Astrophys. J. **227**, 729.

de Vaucouleurs, G., 1979b, Astrophys. J. **233**, 433.

de Vaucouleurs, G., and R. Buta, 1981, Publ. Astron. Soc. Pac. **93**, 294.

Dombrovsky, W. A., 1954, Doklady, Akad. Nauk USSR **94**, **104**; and **102**, 907.

Dopita, M., 1981, in NATO81.

Dwek, E. *et al.*, 1981, Bull. Am. Astron. Soc. **14**, 795, and work in progress.

Dyson, F. J., 1979, Rev. Mod. Phys. **51**, 447.

Eddington, A. S., 1926, *The Internal Constitution of the Stars*

(Cambridge University, Cambridge, England).

Edmonds, M. G., and B. E. J. Pagel, 1978, Mon. Not. R. Astron. Soc. **185**, 77p.

Eggleton, P. P., S. M. Mitton, and J. A. J. Whelan, Eds., 1976, *Structure and Evolution of Close Binaries,* IAU Symposium No. 73 (Reidel, Dordrecht).

Elias, J. H., J. A. Frogel, J. A. Hackwell, and S. E. Persson, 1981, Astrophys. J. **251**, L13.

Endal, A. S., and S. Sofia, 1979, Astrophys. J. **232**, 531.

Epstein, R. I., 1979, Mon. Not. R. Astron. Soc. **188**, 305.

Ergma, E. V., 1979, in *White Dwarfs and Variable Degenerate Stars,* IAU Colloquium No. 53, edited by H. Van Horn and V. Weidemann (University of Rochester, Rochester), p. 48.

Ergma, E. V., and A. V. Tutukov, 1976, Acta Astron. **26**, 69.

Fabian, A. C., 1981, in NATO81.

Fabian, A. C., G. C. Stewart, and W. Brinkman, 1982, Nature **295**, 508.

Fahlman, G. G., and P. C. Gregory, 1981, Nature **293**, 202.

Fairall, A. P., 1972, Mon. Not. Astron. Soc. So. Africa **31**, 23.

Fairall, A. P., 1974, Mon. Not. Astron. Soc. So. Africa **34**, 94.

Falk, S. W., 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 57.

Falk, S. W., and W. D. Arnett, 1977, Astrophys. J. Sup. **33**, 515.

Finzi, A., and R. A. Wolf, 1967, Astrophys. J. **150**, 115.

Flannery, B., 1977, Ann. N.Y. Acad. Sci. **302**, 36 (8th Texas Symposium).

Flannery, B., and R. Ulrich, 1977, Astrophys. J. **212**, 533.

Fraley, G. S., 1968, Astrophys. Space Sci. **2**, 96.

Freedman, D. A., 1974, Phys. Rev. D **9**, 1389.

Friedjung, M., 1975, Astron. Astrophys. **44**, 431.

Fryxel, B., and W. D. Arnett, 1981, Astrophys. J. **243**, 994.

Fuchs, K., and H. H. Wills, 1935, Proc. R. Soc. London **151**, 585.

Fujimoto, M. Y., K. Nomoto, and D. Sugimoto, 1976, Astrophys. Space Sci. **45**, 71

Fujimoto, M. Y., and D. Sugimoto, 1980, in *White Dwarfs and Variable Degenerate Stars,* IAU Colloquium No. 53, edited by H. Van Horn and V. Weidemann (University of Rochester, Rochester), p. 285.

Fujimoto, M. Y., and D. Sugimoto, 1982, Astrophys. J. **257**, 291.

Fuller, W. K., 1982, Astrophys. J. **252**, 741.

Gaffet, B., 1977, Astrophys. J. **216**, 565 and 852.

Gallagher, J. S., and S. Starrfield, 1978, Annu. Rev. Astron. Astrophys. **16**, 171.

Gamow, G., and M. Schönberg, 1941, Phys. Rev. **59**, 539.

Gao S.-H., Ge Y.-Z., Y. C. Leung, Li Z.-W., and Liang S.-R., 1981, Astrophys. J **245**, 1110.

Garcia-Munoz, M., G. M. Mason, and J. A. Simpson, 1977, Astrophys. J. **217**, 859.

Garmany, C. D., and P. Massey, 1981, Publ. Astron. Soc. Pac. **93**, 500.

Gold, T., I. Axford, and E. C. Ray, 1965, in *Quasi-Stellar Sources and Gravitational Collapse,* edited by I. Robinson, A. Schild, and E. Schücking (University of Chicago, Chicago), p. 93.

Gordon, C., 1972, Astron. Astrophys. **20**, 79.

Grasberg, E. K., V. S. Imshennik, and D. K. Nadyozhin, 1971, Astrophys. Space Sci. **10**, 28.

Greenstein, J. L., A. Boksenberg, R. Carswell, and K. Shortridge, 1977, Astrophys. J. **212**, 186.

Gross, P. G., 1978, in *The HR Diagram,* IAU Symposium No. 80, edited by A. G. D. Philip and D. S. Hayes (Reidel, Dordrecht), p. 323.

Gull, S. F., and G. G. Pooley, 1980, IAU Circ. 3502.

Gunn, J. E., L. Stryker, and B. M. Tinsley, 1981, Astrophys. J. **249**, 48.

Harding, A., 1981, in *Pulsars,* IAU Symposium No. 95, edited by W. Sieber and R. Wielebinski (Reidel, Dordrecht), p. 439.

Hardorp, J., 1974, Astron. Astrophys. **32**, 133.

Hartwick, F. D. A., 1972, Nature (London) Phys. Sci. **237**, 137.

Helfand, D., 1981, in NATO81.

Helfand, D., 1982, private communication.

Higdon, J. E., and R. E. Lingenfelter, 1980, Astrophys. J. **239**, 867.

Higgs, L. A., R. S. Toger, T. L. Landecker, and J. M. Dickey, 1981, Astron. Astrophys. **103**, 770.

Hillebrandt, W., 1981, in NATO81.

Hillebrandt, W., and E. Müller, 1981, Astron. Astrophys. **103**, 147.

Hoyle, F., 1946, Mon. Not. R. Astron. Soc. **106**, 243.

Hoyle, F., and W. A. Fowler, 1960, Astrophys. J. **132**, 565.

Hubble, E., 1937, Mt. Wilson Annual Report, 1936—37.

Hubble, E., 1941, Publ. Astron. Soc. Pac. **53**, 141.

Hulse, R. A., and J. H. Taylor, 1975, Astrophys. J. **195**, L51.

Humason, M. L., 1936, Publ. Astron. Soc. Pac. **48**, 110.

Humphreys, R. M., and K. Davidson, 1979, Astrophys. J. **232**, 409.

Hutchings, J. B., 1980, Space Sci. Rev. **26**, 331.

Iben, I., 1974, Annu. Rev. Astron. Astrophys. **12**, 215.

Iben, I., 1982, Astrophys. J. **253**, 238.

Ibrahim, A., A. Boury, and A. Noels, 1981, Astron. Astrophys. **103**, 390.

Imshennik, V. S., and D. K. Nadyozhin, 1982, Astrophys. Space Sci. Rev. (Section E of Sov. Sci. Rev.), in press.

Imshennik, V. S., D. K. Nadyozhin, and V. P. Utrobin, 1981, Astrophys. Space Sci. **78**, 105.

Ivanova, L. N., V. S. Imshennik, and V. M. Chechetkin, 1974, Astrophys. Space Sci. **31**, 497.

Ivanova, L. N., V. S. Imshennik, and V. M. Chechetkin, 1977, Sov. Astron. AJ **21**, 197 and 374.

Ivanova, L. N., V. S. Imshennik, and V. M. Chechetkin, 1978, Sov. Astron. AJ **21**, 571.

Iwamoto, N., 1980, Phys. Rev. Lett. **44**, 1637.

Joss, P. C., 1980, Ann. N.Y. Acad. Sci. **336**, 479 (9th Texas Symposium), and in *Fundamental Problems in the Theory of Stellar Evolution,* IAU Symposium No. 93, edited by D. Sugimoto, D. Q. Lamb, and D. N. Schramm (Reidel, Dordrecht), p. 207.

Jura, M., and M. Morris, 1981, Astrophys. J. **251**, 181.

Kippenhahn, R., and E. Meyer-Hofmeister, 1977, Astron. Astrophys. **54**, 542.

Kirshner, R. P., 1980, in *Supernovae Spectra,* edited by R. E. Meyerott and G. H. Gillespie (AIP Conference Proceedings No. 63), p. 39.

Kirshner, R. P., 1981, in NATO81.

Kirschner, R. P., H. C. Arp, and J. R. Dunlop, 1976, Astrophys. J. **207**, 44.

Kirshner, R. P., and J. Kwan, 1974, Astrophys. J. **183**, 27.

Kirshner, R. P., and J. Kwan, 1975, Astrophys. J. **197**, 415.

Kirshner, R. P., and J. B. Oke, 1975, Astrophys. J. **200**, 574.

Kirshner, R. P., J. B. Oke, M. V. Penston, and L. Searle, 1973a, Astrophys. J. **185**, 303.

Kirshner, R. P., E. P. Willner, E. Becklin, and G. Neugebauer, 1973b, Astrophys. J. **180**, L97.

Klein, R. I., and R. A. Chevalier, 1978, Astrophys. J. **223**, L100.

Klein, R. I., R. A. Chevalier, P. Charles, and S. Bowyer, 1979, Astrophys. J. **234**, 566.

Koester, D., and D. Reimers, 1981, Astron. Astrophys. **99**, L8.

Kowal, C. T., 1968, Astron. J. **73**, 1021.

Kowal, C. T., J. Huchra, W. L. W. Sargent, 1976, Publ. Astron. Soc. Pac. **88**, 521.

Kristian, J., 1976, private communication to Tammann (1977b).

Kukarkin, B. V., 1965, Astrofiz. **1**, 245.

Kumar, S., 1963, Astrophys. J. **137**, 1121.

Kurucz, R. L., 1981, remarks at Arcturus Workshop, Cambridge, UK, Mar. 1981.

Lamb, D. Q., J. M. Lattimer, C. J. Pethick, and D. G. Ravenhall, 1978, Phys. Rev. Lett. **41**, 1623.

Lamb, F. K., 1975, Ann. N.Y. Acad. Sci. **262**, 311 (7th Texas Symposium).

Lamb, S. A., I. Iben, and W. M. Howard, 1976, Astrophys. J. **207**, 209.

Lambert, D. L., J. F. Dominy, and S. Silvertsen, 1980, Astrophys. J. **235**, 114.

Lasher, G., 1975, Astrophys. J. **201**, 194.

Lasher, G., 1980, in *Supernovae Spectra,* edited by R. E. Meyerott and G. H. Gillespie (AIP Conference Proceeings No. 63), p. 1.

Lasher, G., A. H. Karp, and K. L. Chan, 1977, in *Supernovae,* edited by D. N. Schramm (Reidel, Dordrecht), p. 13.

Lattimer, J. M., 1981, Annu. Rev. Nucl. Part. Sci. **31**, 337.

Lattimer, J. M., and T. J. Mazurek, 1981, Astrophys. J. **246**, 955.

Lattimer, J. M., and D. N. Schramm, 1974, Astrophys. J. **192**, L145.

Ledoux, P., Ed., 1974, Mem. Soc. R. Sci. Liege Ser. 16, Vol. VIII.

Lequeux, J., 1979, Astron. Astrophys. **80**, 35.

Lichtenstadt, I., N. Sack, and S. A. Bludman, 1980, Astrophys. J. **237**, 903.

Livio, M., J. R. Buchler, and S. A. Colgate, 1980, Astrophys. J. **238**, L139.

Long, K. S., D. J. Helfand, and D. A. Grabelsky, 1981, Astrophys. J. **248**, 925.

Lundmark, K., 1920, Sven. Vetekapsakad. Handlingar 60, No. 8.

Lundmark, K., 1921, Publ. Astron. Soc. Pac. **33**, 234.

Lyne, A. G., 1981, in NATO81.

Maeder, A., 1981, Astron. Astrophys. **92**, 101.

Manchester, R. N., 1982, Ann. N.Y. Acad. Sci. **375**, 414 (10th Texas Symposium).

Maza, J., and S. van den Bergh, 1976, Astrophys. J. **204**, 519.

Mazurek, T. J., 1973, Astrophys. Space Sci. **23**, 365.

Mazurek, T. J., 1974, Nature **252**, 287.

Mazurek, T. J., 1976, Astrophys. J. **207**, L87.

Mazurek, T. J., 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 182.

Mazurek, T. J., J. Cooperstein, and S. Kahana, 1980, in *Proceedings of the DUMAND Workshop* (University of Hawaii, Honolulu).

Mazurek, T. J., and J. C. Wheeler, 1980, Fundam. Cos. Phys. **5**, 193.

Merrill, K. M., 1980, IAU Circular 3444 and private communication to Chevalier (1981c).

Mestel, L., and M. Ruderman, 1967, Mon. Not. R. Astron. Soc. **136**, 27.

Meyerott, R. E., 1980a, Astrophys. J. **239**, 257 and in Meyerott and Gillespie (1980), p. 49.

Meyerott, R. E., 1980b, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 72.

Meyerott, R. E., and G. H. Gillespie, Eds., 1980, *Supernovae Spectra,* AIP Conference Proceedings No. 63.

Milano, L., A. Vittoni, F. Ciatti, A. Mammano, R. Margoni, and G. Strazzulla, 1981, Astron. Astrophys. **100**, 59.

Miller, G. E., and J. M. Scalo, 1979, Astrophys. J. Suppl. **41**, 513.

Minkowski, R., 1939, Astrophys. J. **89**, 156.

Minkowski, R., 1940, Publ. Astron. Soc. Pac. **52**, 206.

Minkowski, R., 1941, Publ. Astron. Soc. Pac. **53**, 224.

Minkowski, R., 1942, Astrophys. J. **96**, 199.

Minkowski, R., 1959, in *Paris Symposium on Radio Astronomy,* IAU Symposium No. 3, edited by R. N. Bracewell (Stanford University), p. 315.

Minkowski, R., 1964, Annu. Rev. Astron. Astrophys. **2**, 247.

Minkowski, R., 1971, in *The Crab Nebula,* IAU Symposium No. 46, edited by R. D. Davies and F. G. Smith (Reidel, Dordrecht), p. 241.

Miyaji, S., K. Nomoto, K. Yokoi, and D. Sugimoto, 1980, Publ. Astron. Soc. Jpn. **32**, 303.

Moore, E., 1973, Publ. Astron. Soc. Pac. **85**, 564.

Müller, E., and W. Hillebrandt, 1979, Astron. Astrophys. **80**, 147.

Müller, E., and W. Hillebrandt, 1981, Astron. Astrophys. **103**, 358.

Murdin, P., and D. H. Clark, 1981, Nature **294**, 543.

Mustel, E. R., 1972, Sov. Astron. AJ **16**, 10.

Mustel, E. R., and N. N. Chugai, 1975, Sov. Astron. AJ **19**, 411.

NATO81. Talks given at the NATO Advanced Study Institute on Supernovae (Institute of Astronomy, Cambridge, UK, July 1981), most of which will appear in the proceedings, *Supernovae,* edited by M. J. Rees and R. J. Stoneham (Reidel, Dordrecht).

Nadyozhin, D. K., 1977, Astrophys. Space Sci. **49**, 399; **51**, 283.

Nadyozhin, D. K., 1978, Astrophys. Space Sci. **53**, 131.

Nadyozhin, D. K., and V. P. Utrobin, 1977, Sov. Astron. AJ **21**, 564.

Neo, S., S. Miyaji, K. Nomoto, and D. Sugimoto, 1977, Publ. Astron. Soc. Jpn. **29**, 249.

Nomoto, K., 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 164.

Nomoto, K., 1981a, in *Fundamental Problems in the Theory of Stellar Evolution,* IAU Symposium No. 93, edited by D. Sugimoto, D. Q. Lamb, and D. N. Schramm (Reidel, Dordrecht), p. 295.

Nomoto, K., 1981b, in NATO81.

Nomoto, K., 1982a, Astrophys. J. **253**, 798.

Nomoto, K., 1982b, Astrophys. J. **257**, 780.

Nomoto, K., Y. Kamiya, K. Yokoi, and S. Miyaji, 1979a, work in progress, cited by Sugimoto and Nomoto, 1980.

Nomoto, K., S. Miyaji, K. Yokoi, and D. Sugimoto, 1979b, in *White Dwarfs and Variable Degenerate Stars,* IAU Colloquium No. 53, edited by H. Van Horn and V. Weidemann (University of Rochester, Rochester), p. 56.

Nomoto, K., K. Narai, and D. Sugimoto, 1979, Publ. Astron. Soc. Jpn. **31**, 287.

Nomoto, K., and D. Sugimoto, 1977, Publ. Astron. Soc. Jpn. **29**, 765.

Nomoto, K., D. Sugimoto, and S. Neo, 1976, Astrophys. Space Sci. **39**, L37.

Nomoto, K., and S. Tsuruta, 1981, Astrophys. J. **250**, L19.

Ober, W. W., M. El Eid, and K. J. Fricke, 1982, in NATO81.

Oemler, A., and B. M. Tinsley, 1979, Astron. J. **84**, 985.

Oke, J. B., and L. Searle, 1974, Annu. Rev. Astron. Astrophys. **12**, 315.

Oppenheimer, J. R., and G. M. Volkoff, 1939, Phys. Rev. **55**, 374.

Ostriker, J. P., 1976, talk at symposium reported in *Structure and Evolution of Close Binaries,* IAU Symposium No. 73, edited by P. P. Eggleton, S. M. Mitton, and J. A. J. Whelan (Reidel, Dordrecht), but not printed there.

Ostriker, J. P., 1971, Annu. Rev. Astron. Astrophys. **9**, 353.

Ostriker, J. P., and J. E. Gunn, 1971, Astrophys. J. **164**, L95.

Ostriker, J. P., D. O. Richstone, and T. X. Thuan, 1974, Astrophys. J. **188**, L87.

Pacini, F., and M. Salvati, 1981, Astrophys. J. **245**, L107.

Paczyński, B., 1967, Acta Astron. **17**, 355.

Paczyński, B., 1970, Acta Astron. **20**, 47.

Paczyński, B., 1971a, Acta Astron. **21**, 1.

Paczyński, B., 1971b, Annu. Rev. Astron. Astrophys. **9**, 183.

Paczyński, B., 1976, in *Structure and Evolution of Close Binaries,* IAU Symposium No. 73, edited by P. P. Eggleton, S. M. Mitton, and J. A. J. Whelan (Reidel, Dordrecht), p. 65.

Paczyński, B., 1979a, in *Highlights of Astronomy* (Reidel, Dordrecht), Vol. 5, p. 27.

Paczyński, B., 1979b, in *X-ray Astronomy,* edited by W. A. Baity and L. E. Petersen (Pergamon, New York/London), p. 251.

Paczyński, B., 1982, seminar at California Institute of Technology, February 1982 (unpublished).

Paczyński, B., and B. Rudak, 1979, Astron. Astrophys. **82**, 349.

Paczyński, B., and A. Żytkow, 1978, Astrophys. J. **222**, 664.

Panagia, N., 1980, in *Proceedings of the 2nd European IUE Conference* (March 1980 Tübingen) ESA SP-157, p. xxviii.

Panagia, N., 1981, in NATO81.

Panagia, N., and K. W. Weiler, 1980, Astron. Astrophys. **82**, 389.

Panagia, N. *et al.*, 1980, Mon. Not. R. Astron. Soc. **192**, 861.

Pankey, T., 1962, Ph.D. thesis, Howard University (Diss. Abst. 23, 4).

Papaloizou, J. C. B., 1973, Mon. Not. R. Astron. Soc. **162**, 169.

Papaloizou, J. C. B., J. Pringle, and J. MacDonald, 1982, Mon. Not. R. Astron. Soc. **198**, 215.

Patchett, B., and D. Branch, 1972, Mon. Not. R. Astron. Soc. **158**, 375.

Payne-Gaposchkin, C. H., 1936a, Astrophys. J. **83**, 245.

Payne-Gaposchkin, C. H., 1936b, Astrophys. J. **83**, 173.

Payne-Gaposchkin, C. H., 1936c, Proc. Nat. Acad. Sci. USA **22**, 332.

Payne-Gaposchkin, C. H., 1957, *The Galactic Novae* (North-Holland, Amsterdam), pp. 258–285.

Pearce, G., 1982, private communication.

Plavec, M., 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich (Reidel, Dordrecht), p. 251.

Plavec, M. J., D. M. Popper, and R. K. Ulrich, Eds., 1980, *Close Binary Systems,* IAU Symposium No. 88 (Reidel, Dordrecht).

Popper, D. M., 1937, Publ. Astron. Soc. Pac. **49**, 283.

Pskovskii, Yu. P., 1969, Sov. Astron. AJ **12**, 750.

Pskovskii, Yu. P., 1977, Sov. Astron. AJ **21**, 675.

Pskovskii, Yu. P., 1978, Sov. Astron. AJ **22**, 200.

Pye, J. P., K. A. Pounds, D. P. Rolf, F. D. Seward, A. Smith, and R. Willingale, 1981, Mon. Not. R. Astron. Soc. **194**, 569.

Rakavy, G., and G. Shaviv, 1967, Astrophys. J. **148**, 803.

Rakavy, G., G. Shaviv, and Z. Zinamon, 1967, Astrophys. J. **150**, 131.

Robinson, E. L., 1976, Annu. Rev. Astron. Astrophys. **14**, 119.

Romanishin, W., and J. R. P. Angel, 1980, Astrophys. J. **235**, 992.

Rose, W. K., 1969, Astrophys. J. **155**, 491.

Rosenbluth, M. N., M. Ruderman, F. Dyson, J. N. Bahcall, J. Shaham, and J. P. Ostriker, 1973, Astrophys. J. **184**, 907.

Ryle, M., J. L. Caswell, G. Hine, and J. Shakeshaft, 1978, Nature **276**, 571.

Saio, H., and J. C. Wheeler, 1980, Astrophys. J. **242**, 1176.

Salpeter, E. E., 1961, Astrophys. J. **134**, 669.

Sargent, W. L. W., L. Searle, and C. T. Kowal, 1974, in *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 33.

Sartori, L., B. C. Chiu, and P. Morrison, 1974, in *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 131.

Sato, K., 1975, Prog. Theor. Phys. **54**, 1325; **53**, 595.

Savedoff, M. P., and H. M. Van Horn, 1982, Astron. Astrophys. **107**, L3.

Schatzman, E., 1949, Ann. Astrophys. **12**, 281.

Schatzman, E., 1965, in *Stellar Structure,* edited by L. H. Aller and D. B. McLaughlin (University of Chicago, Chicago), p. 327.

Schramm, D. N., Ed., 1977, *Supernovae,* Astrophys. Space Sci. Lib. No. 66 (Reidel, Dordrecht).

Schurmann, S., W. D. Arnett, and S. W. Falk, 1979, Astrophys. J. **230**, 11.

Schwartz, R. A., 1967, Ann. Phys. **43**, 42.

Schweizer, F., and J. Middleditch, 1980, Astrophys. J. **241**, 1039.

Sciatti, Hjalmar, 1965, private communication.

Searle, L., 1974, in *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 125.

Seaquist, E. R., and W. S. Gilmore, 1982, Astron. J. **87**, 378.

Seward, F. D., 1981, in NATO81.

Shklovskii, I. S., 1953, Dokl. Akad. Nauk SSSR **91**, 475.

Shklovskii, I. S., 1960a, *Cosmic Radio Waves* (Harvard University, Cambridge, Mass.), p. 282.

Shklovskii, I. S., 1960b, Sov. Astron. AJ **4**, 243.

Shklovskii, I. S., 1968, *Supernovae* (Wiley-Interscience, New York).

Shklovskii, I. S., 1978, Sov. Astron. AJ **22**, 413.

Shklovskii, I. S., 1981a, Sov. Astron. AJ **25**, 315.

Shklovskii, I. S., 1981b, Sov. Astron. AJ **24**, 387.

Shklovskii, I. S., 1981c, Astrophys. Space Phys. Rev. (Section E of Sov. Sci. Rev.) **1**, 177.

Shu, F. H., and S. H. Lubow, 1981, Annu. Rev. Astron. Astrophys. **19**, 277.

Sieber, W., C. J. Salter, and C. J. Mayer, 1981, Astron. Astrophys. **103**, 393.

Simon, K. P., K. Hunger, and R. P. Kudritzki, 1981, Astron. Astrophys. **98**, 211.

Smarr, L., J. R. Wilson, R. T. Barton, and R. L. Bowers, 1981, Astrophys. J. **246**, 515.

Smirnov, M. A., and D. Yu. Tsvetkov, 1981, Sov. Astron. AJ Lett. **7**, 86.

Smith, H. A., 1981, Astron. J. **86**, 998.

Sobolev, A. M., 1981, Sov. Astron. AJ Lett. **7**, 91.

Sobolev, V. V., 1979, Astrofizika **15**, 401.

Souffrin, P., 1960, Mem. Soc. R. Sci. Liege Collect., 5th Ser. **3**, 245.

Sparks, W. M., and A. S. Endal, 1980, Astrophys. J. **237**, 130.

Sparks, W. M., and T. P. Stecher, 1974, Astrophys. J. **188**, 149.

Stahler, B. W., F. H. Shu, and R. E. Taam, 1980, Astrophys. J. **241**, 637; **242**, 226.

Starrfield, S., J. R. Truran, and W. M. Sparks, 1981, Astrophys. J. **243**, L27.

Stevenson, D. J., 1980, J. Phys. (Paris) **41**, Suppl. to No. 3 (Colloq. No. 2), p. C2−53.

Stone, R. C., 1981, Astron. J. **86**, 544.

Stone, R. C., 1982, Astron. J. **87**, 90.

Stothers, R., 1980, Astrophys. J. **242**, 756.

Sugimoto, D., 1971, Prog. Theor. Phys. **45**, 761.

Sugimoto, D., and S. Miyaji, 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich, (Reidel, Dordrecht), p. 133.

Sugimoto, D., and K. Nomoto, 1980, Space Sci. Rev. **25**, 155.

Szymkowiak, A., 1981, in NATO81.

Taam, R. E., 1980a, Astrophys. J. **237**, 142.

Taam, R. E., 1980b, Astrophys. J. **242**, 749.

Taam, R. E., P. Bodenheimer, and J. P. Ostriker, 1978, Astrophys. J. **222**, 269.

Tammann, G., 1974, in *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 155.

Tammann, G., 1977a, Ann. N.Y. Acad. Sci. **302**, 61 (8th Texas Symposium).

Tammann, G., 1977b, in *Supernovae,* Astrophys. Space Sci. Lib. No. 66, edited by D. N. Schramm (Reidel, Dordrecht), p. 95.

Tammann, G., 1981, in NATO81.

Tananbaum, H. D., and J. Hutchings, 1975, Ann. N.Y. Acad. Sci. **262**, 299 (7th Texas Symposium).

Thomas, H.-C., 1977, Annu. Rev. Astron. Astrophys. **15**, 127.

Thompson, L. A., 1981, Publ. Astron. Soc. Pac. **93**, 176.

Tinsley, B. M., 1980a, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 196.

Tinsley, B. M., 1980b, Fundam. Cos. Phys. **5**, 287.

Tinsley, B. M., and A. Oemler, 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 9.

Truran, J., and A. G. W. Cameron, 1971, Astrophys. Space Sci. **14**, 179.

Tsvetkov, D. Yu., 1982, Sov. Astron. AJ Lett. **7**, 254.

Tubbs, D. L., 1978, Astrophys. J. Suppl. **37**, 287.

Tuchman, Y., N. Sack, and Z. Barkat, 1979, Astrophys. J. **234**, 217.

Tutukov, A. V., and G. V. Ruben, 1974, in *Stellar Physics and Evolution,* edited by Yu. L. Frantsman (Akad. Nauk SSSR Moscow), p. 5.

van den Bergh, S., 1971, Astrophys. J. **168**, 38.

van den Bergh, S., 1981, J. Astron. Soc. **22**, 440.

van den Bergh, S., and C. Morbey, 1981, Astron. J. **86**, 206.

van den Heuvel, E. P. J., 1975, Astrophys. J. **196**, L121.

van den Heuvel, E. P. J., 1976, in *Structure and Evolution of Close Binaries,* IAU Symposium No. 73, edited by P. P. Eggleton, S. M. Mitton, and J. A. J. Whelan (Reidel, Dordrecht), p. 35.

van den Heuvel, E. P. J., 1977, Ann. N.Y. Acad. Sci. **302**, 14 (8th Texas Symposium).

van den Horn, L. F., and C. G. van Weert, 1982, Astrophys. J. **251**, L97.

van der Laan, H., 1962, Mon. Not. R. Astron. Soc. **124**, 125 and 179.

van der Linden, Th.J., 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich (Reidel, Dordrecht), p. 109.

van Gorkom, J. H., W. M. Goss, E. R. Seaquist, and W. S. Gilmore, 1982, Mon. Not. R. Astron. Soc. **198**, 757.

Van Horn, H., and V. Weidemann, Eds., 1979, *White Dwarfs and Variable Degenerate Stars,* IAU Colloquium No. 53 (University of Rochester, Rochester).

Van Riper, K. A., 1981, Astrophys. J. **257**, 793.

van't Veer, F., 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich (Reidel, Dordrecht), p. 517.

Vogt, N., R. Schoembs, W. Krzeminski, and H. Pederson, 1981, Astron. Astrophys. **94**, L29.

Wagoner, R., 1981, in NATO81.

Weaver, T. A., T. S. Axelrod, and S. E. Woosley, 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 113.

Weaver, T. A., and S. E. Woosley, 1980, in *Supernovae Spectra,* edited by R. E. Meyerott and G. H. Gillespie (AIP Conference Proceedings No. 63), p. 15, and Ann. N.Y. Acad. Sci. **336**, 335 (9th Texas Symposium).

Weaver, T. A., G. B. Zimmerman, and S. E. Woosley, 1978, Astrophys. J. **225**, 1021.

Webbink, R. F., 1979a, Astrophys. J. **227**, 78.

Webbink, R. F., 1979b, in *White Dwarf and Variable Degenerate Stars,* IAU Colloquium No. 53, edited by H. Van Horn and V. Weidemann (University of Rochester, Rochester), p. 426.

Webbink, R. F., 1980, in *Close Binary Systems,* IAU Symposium No. 88, edited by M. J. Plavec, D. M. Popper, and R. K. Ulrich (Reidel, Dordrecht), p. 122.

Weedman, D. W., R. F. Feldman, V. A. Balzano, L. W. Ramsey, R. A. Sramek, and C.-C. Wu, 1981, Astrophys. J. **248**, 105.

Wegner, G., 1979, Astron. J. **84**, 502.

Weiler, K. W., and N. Panagia, 1978, Astron. Astrophys. **70**, 419.

Weiler, K. W., and N. Panagia, 1980, Astron. Astrophys. **90**, 269.

Weiler, K. W., R. A. Sramek, J. M. van der Hulst, and N. Panagia, 1981, in NATO81.

Wheeler, J. C., 1979, Astrophys. J. **234**, 569.

Wheeler, J. C., Ed., 1980, *Type I Supernovae* (University of Texas, Austin, and MacDonald Observatory).

Wheeler, J. C., 1981, Rep. Prog. Phys. **44**, 88, and in NATO81.

Wheeler, J. C., and C. Hansen, 1971, Astrophys. Space Sci. **11**, 373.

Wheeler, J. C., and P. G. Sutherland, 1981, in Wheeler in NATO81, and work in progress.

Whelan, J. A. J., and I. Iben, 1973, Astrophys. J. **186**, 1007.

Whipple, F., 1939, Proc. Natl. Acad. Sci. USA **25**, 118.

Whipple, F., and C. H. Payne-Gaposchkin, 1941, Proc. Am. Philos. Soc. **84**, 1

White, R., 1981, in NATO81.

Wigner, E. P., 1934, Phys. Rev. **46**, 1002.

Wilson, J. R., 1980, Ann. N.Y. Acad. Sci. **336**, 358 (9th Texas Symposium).

Wilson, J. R., 1982, private communication.

Wilson, J. R., R. Couch, S. Cochran, J. LeBlanc, and Z. Barkat, 1974, Ann. N.Y. Acad. Sci. **262**, 54 (7th Texas Symposium).

Wilson, O. C., 1939, Astrophys. J. **90**, 634.

Winkler, P. F., 1981, in NATO81.

Woltjer, L., 1964, Nature **201**, 245.

Woltjer, L., 1967, in *Radio Astronomy and the Galactic System,* IAU Symposium No. 31, edited by H. van Woerden (Academic, New York), p. 479.

Woosley, S. E., W. Hillebrandt, and D. Arnett, 1981, in NATO81.

Woosley, S. E., and T. A. Weaver, 1981, in NATO81.

Woosley, S. E., and T. A. Weaver, 1982a, Ann. N.Y. Acad. Sci. **375**, 357 (10th Texas Symposium).

Woosley, S. E., and T. A. Weaver, 1982b, in *Nuclear Astrophysics,* edited by C. Barnes, D. Clayton, and D. Schramm (Cambridge University, Cambridge, England, in press) and UCRL preprint 84527.

Woosley, S. E., T. A. Weaver, and R. E. Taam, 1980, in *Type I Supernovae,* edited by J. C. Wheeler (University of Texas, Austin, and MacDonald Observatory), p. 96.

Wyckoff, S., and P. A. Wehinger, 1977, Astrophys. Space Sci. **48**, 421.

Yakovlev, D. G., and V. A. Urpin, 1981, Sov. Astron. AJ Lett. **7**, 88.

Ziólkowski, J., 1977, Ann. N.Y. Acad. Sci. **302**, 47 (8th Texas Symposium).

Zwicky, F., 1936a, Proc. Natl. Acad. Sci. USA **22**, 457.

Zwicky, F., 1936b, Proc. Natl. Acad. Sci. USA **22**, 557.

Zwicky, F., 1936c, Publ. Astron. Soc. Pac. **48**, 191.

Zwicky, F., 1938a, Phys. Rev. **54**, 242.

Zwicky, F., 1938b, Publ. Astron. Soc. Pac. **50**, 215.

Zwicky, F., 1938c, Astrophys. J. **88**, 259.

Zwicky, F., 1939, Phys. Rev. **55**, 726.

Zwicky, F., 1940, Rev. Mod. Phys. **12**, 71.

Zwicky, F., 1942, Astrophys. J. **96**, 28.

Zwicky, F., 1958, Handb. Phys. **51**, 766.

Zwicky, F., 1965, in *Stellar Structure,* edited by L. H. Aller and D. B. McLaughlin (University of Chicago, Chicago), p. 367.

Zwicky, F., 1974, in *Supernovae and Their Remnants,* Astrophys. Space Sci. Lib. No. 45, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 1.

Zwicky, F., J. Berger, H. S. Gates, and K. Rudnicki, 1963, Publ. Astron. Soc. Pac. **75**, 236.