Title
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Journal
Journal of Astrophysics and Astronomy, 5(4)

ISSN
0250-6335

Author
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Publication Date
1984-12-01

DOI
10.1007/bf02714467

J. Astrophys. Astr. (1984) 5, 389–402

Binary Progenitors of Supernovae

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(*Invited article*)

Abstract. Supernovae of both Type I (hydrogen-poor) and Type II (hydrogen-rich) can be expected to occur among binary stars. Among massive stars ($\gtrsim 10\ M_\odot$), the companion makes it more difficult for the primary to develop an unstable core of $\gtrsim 1.4\ M_\odot$ while still retaining the extended, hydrogen-rich envelope needed to make a typical Type II light curve. Among 1–10 $M_\odot$ stars, on the other hand, a companion plays a vital role in currently popular models for Type I events, by transferring material to the primary after it has become a stable white dwarf, and so driving it to conditions where either core collapse or explosive nuclear burning will occur. Several difficulties (involving nucleosynthesis, numbers and lifetimes of progenitors, the mass-transfer mechanism, *etc.*) still exist in these models. Some of them are overcome by a recent, promising scenario in which the secondary also evolves to a degenerate configuration, and the two white dwarfs spiral together to produce a hydrogen-free explosion, long after single stars of the same initial masses have ceased to be capable of fireworks.

Key words: supernovae, progenitors—binary stars, evolution

At least half the stars in the sky are double or multiple (Abt & Levy 1976, 1978); and one star in every few hundred must become a supernova in order to produce the event rate observed in massive spiral galaxies like the Milky Way (Tammann 1982); thus, one star out of 300 to 1000 ought to be a binary supernova progenitor. In some cases, the companion will be an innocent bystander to the fireworks, or even inhibit them somewhat. In other cases, it will be a vital participant.

1. Supernovae among single stars

Supernova (SN) events are characterized by the rapid release of large amounts of energy (Baade & Zwicky 1934). Thus the essential requirement for their production is that a star gets itself into a condition where its structure changes suddenly and exoergically. Fig. 1 (which was assembled from the references on single star evolution cited by Trimble, 1982a) presents the possible states of stellar interiors in the central temperature *vs.* central density plane. It reveals two regimes of rapid, exoergic change.

First, a star that wanders into an area where the ratio of specific heats, γ, is less than 4/3 will experience core collapse and release of gravitational potential energy on a timescale R/V_{sound} (milliseconds). A low ratio of specific heats can result from (a) electron-positron pair production at high temperature and low density, (b) photodissociation of iron nuclei at high temperature and intermediate density, (c) electron

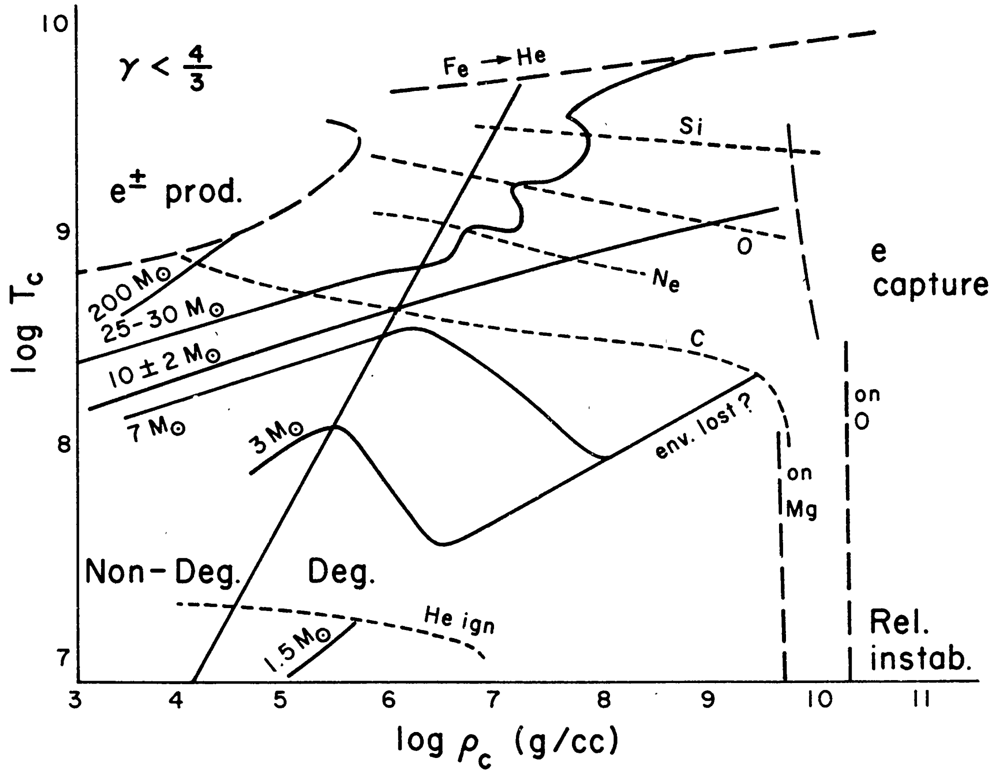

Figure 1. Stellar evolution in the central temperature *vs.* central density plane. The straight, diagonal solid line divides the plane into degenerate and non-degenerate regions. The nearly-horizontal, short-dashed lines indicate loci on which helium, carbon, neon, oxygen, and silicon ignite (*i.e.* energy production by their burning exceeds losses by neutrinos above these lines). The long-dashed lines mark off regions where the ratio of specific heats, γ, is less than $\frac{4}{3}$, so that core collapse will occur. The cause of the soft equation of state is electron-positron pair production in the upper left corner; photodisintegration of iron at the top; electron capture (at slightly different densities for different nuclides) to the right, and general relativistic instabilities at the extreme right. The curving solid lines are evolutionary tracks for stars of the masses indicated. Stars progress in the direction of higher central temperature and density. Those which cross the long-dashed lines should experience core collapse. Those which cross short-dashed lines in the degenerate regime will experience explosive nuclear burning, which can (especially for carbon) disrupt the star. Stars of less than 6–8 $M_\odot$ probably lose their envelopes and stop burning before reaching the carbon-ignition line. The figure was assembled from the references on single-star evolution cited by Trimble (1982a).

capture on intermediate weight nuclei at high density and a range of temperatures, or (d) general relativistic effects at very high densities. The results will depend both on the amount of energy released and on the mechanism of its propagation outward through the rest of the star.

Second, a star with a degenerate core that crosses the line on which a nuclear fuel ignites (*i.e.* energy production exceeds neutrino losses) will experience nuclear energy release at a rate that grows exponentially with time until the central temperature rises high enough to relieve the degeneracy. Fuels that may ignite this way include helium, carbon, neon, oxygen, and silicon. The results will depend primarily on the ratio of energy released to gravitational binding energy of the core.

The sample evolutionary tracks in the figure show that several different classes of stars can enter the assorted instability zones. First, supermassive stars ($M \gtrsim 100\ M_\odot$)

invariably cross into the pair production regime before oxygen burning is complete (Bond, Arnett & Carr 1984). The most massive ones leave black holes, the others explode. Such stars, if they exist at all in our galaxy, are too rare to be responsible for more than 1 per cent or so of the observed SN rate, though one extragalactic event, SN 1961v, the proto-Type V, has been blamed on a supermassive star (Chevalier 1981).

Next, standard models of 12–100 $M_{\odot}$ stars (Arnett 1977; Lamb, Iben & Howard 1976; Woosley & Weaver 1982) cross into the iron-disintegration regime, and those of 8–12 $M_{\odot}$ into the electron-capture regime (Nomoto 1984). These groups of stars are generally thought to be responsible for the bulk of nucleosynthesis and the majority of pulsar births respectively. Current birthrates of 8–100 $M_{\odot}$ stars in galaxies match, at least roughly, the rates of Type II supernovae they are believed to produce (Trimble 1982a; Kennicutt 1984).

Finally, some fuel may ignite degenerately. For the massive stars that burn Ne, O, and Si, the energy release is sufficiently less than the gravitational binding energy that nothing much happens (Arnett 1977). In low-mass stars that ignite helium degenerately, on the other hand, the degeneracy is raised when only a small fraction of the helium has burned (Cole & Deupree 1981), and the star, shaken but structurally still sound, continues its life as a horizontal branch or clump object. But carbon ignition, like the Baby Bear's porridge, is just right, occurring at an intermediate density such that nearly complete burning is needed to raise the degeneracy and the energy release exceeds the gravitational binding.

Arnett (1969) showed that a model 5 $M_{\odot}$ star without mass loss would evolve to degenerate carbon ignition and disrupt itself completely, producing something rather like a Type I supernova; and Paczyński (1970) demonstrated that all mass-conserving models in the range 3–8 $M_{\odot}$ should converge to the same sort of event. But real stars must not do this, or we would see an SN I every five years or so, far in excess of the observed rate, and would be drowning in iron-peak elements, made at a rate of $\sim 1\ M_{\odot}$ from every such event. A wide range of observational data and theoretical arguments now indicate (Morris, Jura & Zuckerman 1984) that the vast majority of stars below 6–8 $M_{\odot}$ lose so much mass during the asymptotic giant (double shell burning) phase that nuclear reactions cease before the CO core reaches ignition conditions. The material shed appears as circumstellar shells and planetary nebulae; the core cools to a normal white dwarf.

It is not implausible that a very few intermediate mass stars with anomalously large mixed cores (due perhaps to rapid rotation) shed only their hydrogen envelopes and produce carbon-detonation SN I's among relatively young stellar populations in spiral and irregular galaxies (Shklovskiĭ 1983; Saio & Wheeler 1980; Tinsley 1980). But this mechanism cannot account for SN I seen among the old stars in elliptical galaxies (van den Bergh 1980, 1982). For these, processes in close binaries provide the only currently popular models.

2. Massive binaries, neutron stars, and Type II supernovae

2.1 *Wide Systems*

Truly single stars are, in general, quite rare (Abt 1983); and this seems also to be true (Stone 1981, 1982; Garmany, Conti & Massey 1980) for unevolved O and early B stars that are expected to produce SN II's via iron photodisintegration and electron capture respectively. Any system with large enough velocity amplitude to be picked up as a spectroscopic binary (Garmany, Conti & Massey 1980; Batten, Fletcher & Mann 1978) also has a small enough semi-major axis that the stars will interact before the primary completes its evolution. This is true even for rather extreme cases like VV Cep, consisting of two $\sim 18\,M_\odot$ stars in a 20-year orbit, which nevertheless shows spectroscopic evidence for gas streaming from the supergiant to and around the B star. These interacting binaries belong to the next section.

About one-third of the rather small sample of normal Population I O stars studied by Stone (1981) seem to have only visual companions. Another third have spectroscopic companions, and almost a third have both. Although no O or B visual binaries have first-class orbit determinations (Popper 1980), their periods should be $\gtrsim 30$ yr and their separations larger than the stellar radii will ever be. Both primaries and secondaries in these systems should evolve like model single stars.

We are still not, however, quite out of the woods. The current majority viewpoint is that all or most single and wide binary OB stars shed their entire hydrogen-rich envelopes during post-main-sequence evolution, becoming first Of, then Wolf-Rayet (WR) stars (Conti *et al.* 1983; Falk & Mitalas 1983; Bertelli, Bressan & Chiosi 1984). This is very worrisome. Although 0.1–0.3 $M_\odot$ of hydrogen probably suffices to produce the spectral lines observed in SN II's (D. Branch 1984, personal communication), we need something like 3–5 $M_\odot$ of extended hydrogen envelope to get the light curve right (T. A. Weaver 1984, personal communication; Woosley & Weaver 1984).

If the pre-SN envelope is compact, most of the shock energy driving the event goes into expanding the envelope rather than into radiation, yielding a very dim SN. And if there is too little hydrogen in the envelope, its recombination cannot produce the prolonged plateau phase seen in most Type II light curves. Core collapses in stars with very small remaining hydrogen envelopes are perhaps responsible for the $\sim \frac{1}{3}$ of SN II's with no plateau phase (Litvinova & Nadyozhin 1983). If Flamsteed's star of 1685 gave birth to Cas A, it may have been an anemic event of this type (Chevalier 1976). When the envelope has been completely stripped after a WR phase, we could still expect a normal supernova remnant eventually to be energized by the ejecta (Arnett 1982), and there might in principle be enough Ni^{56} made to produce a faint Type I event, but we surely cannot get a standard SN II (Woosley & Weaver 1984).

I regard this problem as a fairly serious one (Trimble 1984). It can possibly be resolved within the standard picture if (*pace* Conti *et al.* 1983) only O main-sequence stars $\gtrsim 15\,M_\odot$ are stripped to make Wolf-Rayets (followed by at most very dim supervonae and ejection of several solar masses of heavy elements per event). Then B main-sequence stars of 6 or 8–15 $M_\odot$ might retain enough hydrogen envelope to look like SN II's (for either mechanism of core collapse). A hint that this may be so comes from the Cepheid variables, most of which, whether single or in wide binaries like α UMi, manage to get at least as far as core helium burning with most of their main-sequence mass ($\sim 10\,M_\odot$) intact (Iben 1983; Carson & Stothers 1984).

Less conventionally, Underhill (1983, 1984; Underhill & Bhatia 1984) has proposed that the rest of us have badly misinterpreted OB star winds (which she believes carry away very little mass) and Wolf-Rayet spectra (which she models with essentially normal He/H ratios ~ 0.1). Even Underhill's WRs have radii much less than the few $\times 10^{13}$ cm needed to make a standard Type II light curve. Lest we despair completely, it is worth remembering that there do exist massive, bright, highly evolved, extended, cool supergiants, whose spectra are still dominated by hydrogen (H^- continuous opacity), among single stars (Betelgeuse), visual binaries (Antares), and spectroscopic binaries (KQ Per).

We have no direct information on which stars in wide binaries will leave neutron stars (NS) and which black holes (BH) (Woosley & Weaver 1984), though the difficulties in getting core bounce ejection to work for any but the smallest iron cores (Takahara & Sato 1983) would suggest O → BH; B → NS. There remains the long-standing problem of the poor correlation between real neutron stars (pulsars or otherwise) and real supernova remnants. Neither wide nor close companions seem to help with this in any way, and I shall not address it further here.

In any case, demise of the primary in massive wide binaries normally disrupts the system. We expect this on theoretical grounds, because without mass transfer between the components, the primary is still the more massive star when it dies (thus can eject more than half the total mass, the criterion for unbinding a system by spherically symmetric, impulsive mass loss), and because the system is only loosely bound. Post-disruption velocities will be $\lesssim 20\,\mathrm{km\,s^{-1}}$, like the predisruption orbital velocities. Observational confirmation comes from the pulsars and OB runaway stars. The four known binary pulsars all have periods $\leqslant 3$ yr and can be modelled as the products of initially close, interacting binaries (van den Heuval & Taam 1984). No wider systems are known, although the same techniques that reveal secular period changes as small as $\dot{P}/P = 10^{-7}\,\mathrm{yr^{-1}}$ should be sensitive to changes in orbital velocity associated with periods up to at least 500 yr. Among the OB runaways, about half show low-mass spectroscopic companions (Stone 1982), at least half of which, in turn, are probably neutron stars whose formation accelerated the systems without disrupting them (de Cuyper 1982). None shows a visual companion (Stone 1981, 1982). But many of the predecessors should have been triples, implying that the visual systems were disrupted when the neutron stars formed. The same remarks apply to the absence of known visual companions to X-ray binaries.

In summary, then, companions in massive wide binaries are normally mere innocent bystanders to the supernova explosions of their primaries and are usually liberated in the process.

2.2 *Close Systems*

At least 30 per cent of unevolved O stars are spectroscopic binaries (Garmany, Conti & Massey 1980), most of those detected having mass ratios fairly close to one (distinct from later types, and apparently not entirely an observational selection effect; Abt 1983). Such stars necessarily interact during their evolution, the best-known process being mass transfer when the primary (and later the secondary) expands to fill its inner Lagrangian surface (Roche lobe). Evolutionary models of such interacting massive binaries go back almost 20 years (Paczyński 1966, 1967; Plavec 1967; Kippenhahn & Weigert 1967; Snezhko 1967). More recent ones are exceedingly numerous, often include the effects of mass and angular momentum lost to the system, and typically follow the stars to the bitter end of the two compact (or disrupted) remnants (Doom & De Grève 1983; Yungel'son & Masevich 1983; Vanbeveren 1983; Kornilov & Lipunov 1984; van den Heuvel 1981a, b; van den Heuvel & Taam 1984; de Loore & Sutantyo 1984; and many others).

From the point of view of supernova production, the differences from single star evolution are largely bad! Mass transfer strips the primary (and probably also the secondary) even more thoroughly than single-star winds. And when the stripping begins during hydrogen burning, it makes building a core in excess of the Chandrasekhar limiting mass (needed for most SN mechanisms) considerably more difficult. This raises the cut between white dwarf producers and neutron star producers to 12–15 $M_{\odot}$ (Webbink 1979). The result is a 30–50 per cent reduction in the Type II supernova rate expected from a stellar population like that currently being formed in our Galaxy (Scalo 1984).

The stripped, though still intact, primary (and later secondary) should look for a time like a Wolf-Rayet star, for initial masses from at least 17 (Doom & De Grève) to 100 $M_{\odot}$ (Stickland *et al.* 1984 on CQ Cep). This was, in fact, the first plausible mechanism suggested for making WRs (Paczyński 1967). Unfortunately, known binary WRs look much the same as those for which no companion can be detected; and the fraction of WRs that are close binaries is close enough to that among their main-sequence ancestors ($\sim$ 50 per cent, Hidayat, Admiranto & van der Hucht 1984; Lamontagne, Moffat & Seggewiss 1983) to suggest that wind stripping dominates, at least in the later phases, and that the companion is, once again, an innocent bystander.

In contrast to the single star and wide binary cases, we know a bit about the neutron-star/black-hole mass cut for close systems. An analysis of the black-hole candidate system LMC X-3 (van den Heuvel & Habets 1984) suggests that a main-sequence primary of at least 50 ± 10 $M_{\odot}$ is needed for black hole production. It would be quite self-consistent to say that this does not differ between wide and close binaries, but it could also be larger for the close systems, like the WD/NS cut.

Also in contrast to the wide binary case, the first supernova event frequently does not disrupt a close, massive system. We expect this on theoretical grounds (de Cuyper 1982), because mass transfer and loss in the system guarantee that the star that explodes first is, by then, the less massive component, so that no spherically symmetric explosion can unbind the system (Trimble & Rees 1971), and because the potential well is much deeper than for wide systems. The explosion of the secondary, in contrast, can be expected to disrupt frequently. Observational confirmation again comes from OB runaway stars, pulsars, and X-ray binaries.

About half the OB runaways (Stone 1982) and some WR runaways (Isserstedt, Moffat & Niemala 1983) have low-mass spectroscopic companions, of which, in turn, at least half are probably neutron stars or other compact configurations (de Cuyper 1982). The few known binary pulsars have orbital periods of 0.32, 1.03, $\sim$ 120, and 1232 days, and all are most convincingly evolved from close systems, two of initially high mass and two low (van den Heuvel & Taam 1984). Next, the observed numbers and expected lifetimes of massive X-ray binaries require that most existing massive OB + WR systems must evolve into them without disruption (van den Heuvel 1981a, b; Doom & De Grève 1983; *etc.*). Finally, the great preponderance of single pulsars suggests that the first NS produced typically has its low-frequency emission quenched by gas from its close companion, while the transformation of the secondary to a second pulsar unbinds the system.

In summary, then, the companions in close, massive binary systems generally affect the evolution of their primaries in ways inimical to the production of Type II supernovae that resemble observed events. The systems generally remain bound through the first neutron-star or black-hole formation process, and not the second.

3. Low-mass binaries, cataclysmic variables, and Type I supernovae

3.1 *Wide Systems*

There seems to be nothing to say about these systems except that (1) if the primary manages to produce a supernova, it will be of the single-star, carbon-deflagration sort mentioned in Section I, with the companion only an on-looker, and (2) since such events completely disrupt the star concerned, they will, *a fortiori*, disrupt the system.

3.2 *Close Systems—the Recent Concensus*

We ended Section I with the point that single-star Type I supernovae require a combination of events that might not occur anywhere and cannot occur among the old, low-mass stars that dominate elliptical galaxies. The idea that one could overcome the difficulties with close-binary, mass-transfer models caught on rather suddenly in the early 70's (Wheeler & Hansen 1971; Truran & Cameron 1971; Hartwick 1972; Whelan & Iben 1973; Mazurek 1973).

The general picture is that a primary of any mass 1–7 or more $M_\odot$ produces a white dwarf, which then waits patiently for the secondary to evolve away from the main sequence and transfer mass back onto it. The white dwarf's mass grows until it (1) collapses by electron capture on O, Ne, and Mg to a neutron star, (2) ignites helium off centre, detonating the helium layer and leaving a CO core behind still at white-dwarf densities, (3) ignites carbon off centre, so that dual-detonation waves propagate inward and outward, incinerating and disrupting the whole star, or (4) ignites carbon at the centre, so that a deflagration runaway burns only the central part of the star, but the whole thing is disrupted (Woosley, Axelrod & Weaver 1984 and earlier references therein). Which of these happens depends on (1) the mass and composition of the primary white dwarf ($\lesssim 0.45\ M_\odot$ of He, 0.45–1.1 $M_\odot$ of CO, or 1.1–1.4 $M_\odot$ of Ne-O-Mg), (2) how long the WD cools before back transfer begins (Isern, Labay & Canal 1984), (3) the rate at which fresh material arrives, and (4) the composition of the accreted material, via the amount of heating produced when it burns.

One charm of this scenario is that the supernova event follows star formation after a time set by the lifespan of the lower-mass secondary, which can be long, yet the system has the mass of the primary to draw on, greatly improving the chances of getting close enough to 1.4 $M_\odot$ for one of the four instabilities mentioned above to set in. Additional advantages are: First, there exists a fairly numerous class of objects, the cataclysmic variables (CVs, including novae, dwarf novae, recurrent novae, nova-like variables, symbiotic stars, and polars), which can be claimed as *en route* to producing such SN I's. Second, models based on this picture (summarized in Wheeler 1980, Trimble 1982a, Rees & Stoneham 1982, and Iben & Tutukov 1984) provide fairly good matches to the spectra and light curves observed for Type I supernovae.

The spectra near maximum light consist of an underlying blackbody from a ~ 8000 K photosphere expanding at $\sim 10000\ \mathrm{km\,s^{-1}}$, plus broad P Cygni lines of common elements in roughly solar proportions, apart from a complete absence of hydrogen (Branch 1982). For instance, the products of the deflagrations studied by Nomoto, Thielemann & Wheeler (1984) provide the right line intensities for SN 1981b if layers of the star are well mixed (Branch 1984 and personal communication). Spectra well past maximum light are dominated by iron lines. There is not yet complete agreement upon their interpretation, but one possibility is a large excess of iron and cobalt (Axelrod 1980). This is important because the model light curves (Weaver, Axelrod & Woosley 1980; Woosley, Weaver & Taam 1980) have two main energy inputs, instantaneous release as carbon and oxygen burn to iron-peak elements, especially Ni^{56}, and gradual release as the Ni^{56} beta decays via Co^{56} to Fe^{56} (half lives 6 and 77 days). Next, such events, when the white dwarf disrupts, contribute significant amounts of oxygen-burning products (both abundant and rare species) to the galactic supply. This will be especially important if very massive stars typically trap their entire iron cores in black holes.

Finally, the case where the white dwarf collapses gently rather than exploding is (apart from assorted capture mechanisms) seemingly the only way to make the low mass X-ray binaries like Her X-1 (Webbink, Rappaport & Savonije 1983; de Loore & Sutantyo 1984; van den Heuvel 1981a, b). In fact, one must be a bit careful not to let this happen too often and overproduce such systems (Taam & Fryxell 1984; Iben & Tutukov 1984). The implication is that an accreting white dwarf deflagrates or detonates and disrupts (either itself or at least the system) in all but perhaps those very few cases where its initial mass was very close to the Chandrasekhar limit (as in the systems discussed by Law & Ritter 1983). Van den Heuval & Taam (1984) use this process also to account for the two binary pulsars with low-mass companions. Such triggered collapses occur much slower than the free-fall timescale, and so are unlikely to give shock-wave ejection or make SNRs (Lipunov 1983).

A very large fraction of the people currently working on supernovae are convinced that some version of this close-binary scenario is responsible for many, most, or all Type I events (but see Imshennik & Nadëzhin 1983 for contrasting views). There are, however, several problems with the scheme, some affecting only details and some possibly fundamental. Section 3.3 addresses these.

3.3 *Problems with the Concensus Model*

The objections initially voiced to all carbon detonation supernovae were (Ostriker, Richstone & Thuan 1974) that, if they were at all common (a) the pulsar production rate would not be sufficient to keep up the observed supply, and (b) we would be drowning in iron. The first of these problems has somewhat changed its form in the intervening decade. Many supernova remnants, including those associated with the 1572 and 1604 (Tycho and Kepler) events, simply do not contain neutron stars of the same age as the remnants (Helfand & Becker 1984). Thus we cannot object, *a priori*, to a supernova mechanism that leaves no compact core! The lack of correlation between SNe, SNRs, and NSs remains a puzzle (Srinivasan, Bhattacharya & Dwarakanath 1984, and many others), and we are not going to explain it here.

The iron problem is still with us. Sutherland & Wheeler (1984) note that the maximum amount of iron we can tolerate from Type I supernovae occurring every 50–100 yr in our galaxy is about 0.7 $M_{\odot}$, and that this is just about the minimum needed to give the disrupted star the observed expansion velocity. This much burning makes the event intrinsically rather bright, corresponding to a large extragalactic distance scale. The authors go so far as to say that, if the scale should be established at $H_0 \geqslant 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ by other means, then the carbon detonation/deflagration model of SN I would have to be abandoned.

Woosley, Axelrod & Weaver (1984) conclude, somewhat more gently, that no single model simultaneously yields believable element and isotope ratios in its burning products while matching typical light curves and spectra. They, however, suggest possible ways out through variations from one event to another and/or departures from the bare, spherically symmetric white dwarfs of their models.

Another difficulty with the concensus scenario is a statistical one: are there enough progenitors? Recent discussions, both simple (Greggio & Renzini 1983; Trimble 1982b) and elaborate (Iben & Tutukov 1984; Patterson 1984) conclude that our own galaxy is rather close to the ragged edge. Making enough cataclysmic variables is easy—either a few per cent of the low-to-intermediate mass binaries might function that way for $\sim 10^9$ yr each, or they might all do it for a few per cent of their lifetimes. But the SN I's are more difficult—nearly all binaries capable of growing an explosive ($\sim$ Chandrasekhar mass) white dwarf must do so without more mass being lost from the system than would be shed by similar single stars. I find this somewhat unlikely-sounding, given that the process of bringing the stars close enough together to get a cataclysmic system requires considerable angular momentum (hence mass) to be lost in a common envelope phase (Paczyński 1976).

There are, however, a good many factors of two to play with. And, if we look at measured masses of CVs (24 systems tabulated by Patterson 1984, 39 tabulated by Ritter 1984, with considerable overlap), we see that about a quarter of them already have white dwarf masses $\gtrsim 1\ M_\odot$ and about 40 per cent have total masses in excess of $1.4\ M_\odot$. These could all become SN I's if no further mass were lost, and they may be just about enough (Patterson 1984, *etc.*), except that the novae, at least, expel material from the system at least as fast as the secondary tries to give it to the primary.

Patterson (1984) also worries about the eventual fate of CVs that do not give rise to supernovae. It now seems likely (Nather 1984) that continued mass transfer and ejection erodes them down to very small, short-period binary white dwarfs, of which we currently know three examples (AM CVn, GP Com, PG 1346 + 082).

The preceding three paragraphs apply to population I stars in our own galaxy. We do not directly know the formation rate of binaries as a function of stellar mass and separation for any other galaxy, except for the very brightest stars in Andromeda and the Magellanic Clouds, which eclipse about as often as similar Milky Way stars (Herczeg 1982a, b). In particular, there is no information on the giant elliptical galaxies, for which these binary models seem most vital.

We might, therefore, be tempted to assume without further worry that the binary formation rate, like the initial mass function (Scalo 1984) varies rather little from place to place, were it not for an apparent severe deficit of binaries among galactic Population II stars, which are as old as giant elliptical populations, though much poorer in heavy elements.

The precise extent of the deficit is debated from time to time, but there are no confirmed eclipsing (main sequence or giant) binaries among the globular clusters (Hogg 1973; Webbink 1980) or in the dwarf spheroidal Draco (Herczeg 1982a, b). In addition, several searches for radial velocity variability among globular cluster stars (Mayor *et al.* 1984 on 47 Tuc, with references to earlier work) have found only atmospheric effects and no spectroscopic binaries, though corresponding investigations of open clusters found many. The tightness of the main sequence in many globular cluster colour-magnitude diagrams (Richer & Fahlman 1984, on M 4; Sandage & Katem 1983, on M 92) says that at most a few per cent of the stars are binaries with mass ratios $\gtrsim 0.7$ (among the commonest sorts in the solar neighbourhood). Even among field subdwarfs, colours suggest a lower-than-average binary incidence (Eggen 1983; Carney 1983). Finally, although the globular clusters have their fair share and more of cataclysmic variables and low-mass X-ray binaries, these were probably formed by capture processes among previously single neutron stars, white dwarfs, and main-sequence stars (Hertz & Grindlay 1983, 1984). Thus, we really cannot guess, even to order of magnitude, how many binary progenitors are available to make Type I supernovae in elliptical galaxies. Shklovskiĭ (1978) has associated the declining SN I rate along the galaxy type sequence Sc–Sb–Sa–S0–E with declining binary frequency.

The problems noted thus far—non-production of pulsars, over-production of iron, and possible shortage of progenitors—apply to essentially all versions of the concensus model. Still, none of them sounds absolutely fatal. There are, however, two additional problems, potentially more serious, which a recent modification of the standard model enables us to avoid. If cataclysmic variables are the immediate predecessors of Type I supernovae, then (1) the material being transferred to the white dwarf is necessarily mostly hydrogen, and (2) the maximum available time from star formation to explosion is the nuclear-burning lifetime of the secondary.

Having hydrogen around is, on the whole, a bad thing (Sutherland & Wheeler 1984), since type I spectra do not show any, and, unless the hydrogen is accreted at a carefully selected rate (which the secondary may not know about), it burns in violent flashes every 10^{4-5} yr, making nova explosions, (Sion, Acierno & Tomsczyk 1979). These blow off everything that was accreted, and perhaps some material from the white dwarf as well, so the white dwarf mass does not increase with time. The timescale problem arises because the secondary must be massive enough to be a useful donor, but small enough to live $\sim 10^{10}$ yr. In this connection, it is of interest that the Type I event 1983n, whose radio emission (because of the kind of circumstellar shell needed to make it) appears to imply initial masses near $8 + 6.5\ M_{\odot}$ (Sramek, Panagia & Weiler 1984; Chevalier 1984), occurred in a spiral galaxy with considerable current star formation (M 83). On the other hand, some of the SN I's whose infrared emission seems to be a 'light echo' from dust in similar shells (Evans *et al.* 1983) were in ellipticals.

The hydrogen and timescale problems both go away if the progenitor's biography has a chapter in which the secondary completes its evolution becoming a second white dwarf (with or without CV phase), and the two degenerate stars then spiral together as angular momentum is drained from the system by gravitational radiation (Dyson 1963; Kraft, Mathews & Greenstein 1962) or magnetic braking (Taam 1983; Patterson 1984). The transferred material will be largely helium or carbon and oxygen, with a normal admixture of heavier elements. This will neither flash nor contaminate the eventual spectrum. And the time available is expanded by however long it takes the pair to spiral together—anything from 10^8 to $> 10^{10}$ yr, for plausible initial separations, with the longer times perhaps more likely.

In addition, the merger process can provide a good deal of extra heating, so that considerably less than a Chandrasekhar mass may be able to detonate. The white-dwarf-red-giant death spiral scenario of Sparks & Stecher (1974) shares this last advantage. And models where the donor star has already been stripped to a helium star avoid the hydrogen shell flash problem (Fujimoto & Sugimoto 1982). But only the double degenerate dwarf version has all three virtues. Webbink (1979) mentioned the possibility in a single sentence, while Tutukov & Yungel'son (1979) approached it peripherally. I first heard of the scenario from B. Paczyński (1982, personal communication and 1983) in connection with the question of identifying pre-explosion systems. Recent detailed discussions have been published by Iben & Tutukov (1984) and Webbink (1984).

Among the unanswered questions are how can we identify the precursor pairs and how many of them exist. The current white dwarf formation rate in the galaxy is about 0.5–1.0 yr (Guseinov, Novruzova & Rustamov 1983; Weidemann & Koester 1983), so we need 2–5 per cent of existing white dwarfs (in steady state) to be reasonably massive binaries with timescales for angular momentum loss $\lesssim 10^{10}$ yr to keep up the SN I rate. The number presently known is zero. The three very close double white dwarfs (prototype AM CVn) all have total masses $\lesssim 0.5\ M_{\odot}$, which will not do (Nather 1984). And known more massive systems (like the Sanduleak–Pesch object, Greenstein, Dolez & Vauclair 1983; and G 107 − 70, Harrington, Christy & Strand 1981) are visual binaries, with spiraling-in timescales rather in excess of the lifetime of the proton. Double degenerate dwarfs, even with orbital periods $\lesssim 3$ h, are exceedingly unlikely to eclipse. Thus the proper phenomena to look for are variable radial velocity or spectral peculiarities (B. Paczyński 1982, personal communication). Eggen (1984) has reported one white dwarf (CoD −48°3636) with possibly double lines (though I suspect these could be single broad lines with emission cores). And Greenstein & Trimble (1967) tabulated a handful of white dwarfs whose velocities were discordant on two or more apparently good 200-inch prime focus spectrograph plates. Observers with access to suitable instruments are invited to look for radial velocity variations $\gtrsim 100\ \mathrm{km\,s^{-1}}$ on timescales $\lesssim 3$ h for these stars and any others that appeal to them.

4. Conclusions

Among the massive stars expected to produce Type II (hydrogen-rich) supernovae, the presence of a close companion seems to be largely negative. It can increase the main-sequence mass needed to yield a collapsing core, and, owing to mass transfer from the primary to the secondary (and later, back again), the companion enhances the stripping of the stellar hydrogen envelope produced by single star winds, thus making it harder for the star to give rise to a typical SN II light curve.

Among the less massive stars that we think make Type I (hydrogen-free) supernovae, a close companion could be an innocent bystander to carbon detonation/deflagration in the primary, or it can be a vital participant, transferring material to a white dwarf primary and so driving it to explosive conditions. A widely discussed recent scenario allows both stars first to become degenerate dwarfs, which then spiral together, giving rise to a hydrogen-poor explosion arbitrarily long after the star formation event, even for quite massive binaries.

Acknowledgements

My views on the late phases of single and double star evolution have been particularly influenced by the work of W. David Arnett, E. P. J. van den Heuvel, Bohdan Paczyński, and Stanford E. Woosley. Drs David Branch and Thomas Weaver generously and carefully answered questions-by-telephone on the subject of hydrogen in Type II's.

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