ARE WOLF-RAYET STARS THE PROGENITORS OF TYPE Ib/Ic SUPERNOVAE?

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ABSTRACT. I discuss evidence for and against the hypothesis that Type Ib and Type Ic supernovae (SNe) are produced by core collapse in massive, evolved progenitors. A key object is SN 1987K, whose spectroscopic classification changed from Type II to Type Ib/Ic as it aged. The progenitor of SN 1987K may well have been a massive star which experienced incomplete mass loss, leaving a thin outer envelope of hydrogen. However, several arguments are used to conclude that in most SNe Ib/Ic, the pre-supernova mass loss cannot be caused entirely by strong winds as in Wolf-Rayet stars. Mass transfer in close binary systems is probably important, but in such cases the supernova progenitor is not necessarily a Wolf-Rayet star; instead, it may be a relatively quiescent, hot, low-mass helium star that explodes via core collapse. For example, the rapid decline of the light curve of the Type Ic SN 1987M, and its seemingly low ejected mass, are consistent with this idea. It is also possible that some, but not all, SNe Ib/Ic arise from deflagrations or detonations of white dwarfs.

1. INTRODUCTION

The defining property of Type I supernovae (SNe I) is that their optical spectra do not exhibit lines of hydrogen, unlike spectra of SNe II. Three observationally distinct subtypes of SNe I have been identified. During the first month past maximum, "classical SNe I" (now called SNe Ia) show a deep trough near 6150 Å which is believed to be produced by blueshifted Si II λ6355. The early-time spectra of SNe Ib do not show this feature; instead, strong absorption lines of He I are present (Harkness *et al.* 1987). SNe Ic lack both the 6150 Å trough and the He I lines (Wheeler and Harkness 1986). Although physical continuity between SNe Ib and Ic has not yet been proved, some investigators refer to SNe Ic as "helium-poor SNe Ib" (Wheeler *et al.* 1987).

Several months past maximum, the optical spectra of SNe Ia are dominated by blends of hundreds of emission lines, primarily those of [Fe II], [Fe III], and [Co III]. By contrast, late-time spectra of SNe Ib and Ic exhibit strong, relatively unblended emission lines of [O I], [Ca II], and Ca II, with weaker lines of Mg I], Na I, O I, and [C I]; see Figure 2 of Filippenko (1988a), or Figure 3 of Filippenko, Porter, and Sargent (1990; hereafter FPS). No observational differences have yet been found between spectra of SNe Ib and Ic during their "supernebular" phase.

Aside from these defining spectroscopic characteristics, SNe Ib and Ic are known to differ in many ways from SNe Ia. Whereas SNe Ia are generally found in elliptical galaxies and the interarm regions of spiral galaxies, all known SNe Ib and Ic have occurred in late-type spiral galaxies (Sb through Sd), usually in the spiral arms and quite often in luminous

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H II regions. Their blue luminosities are generally lower than those of SNe Ia by 1–2 mag, probably indicating a smaller yield of radioactive Ni^{56}, and their colors near maximum brightness are redder. Their infrared light curves differ significantly from those of SNe Ia, although the optical light curves of most SNe I are similar. Unlike SNe Ia, at least some SNe Ib and Ic exhibit strong radio emission within one year after the explosion. This radiation is produced by the interaction of the ejecta with a circumstellar envelope.

SNe Ia are thought to arise from carbon deflagrations of white dwarfs in binary systems. Most of the observed characteristics of SNe Ib and Ic, on the other hand, suggest that their progenitors are massive, hydrogen-deficient stars, and that the explosion mechanism is core collapse as in SNe II. Specifically, this hypothesis appears to be consistent with (a) the absence of hydrogen, (b) the absence of Si II at early times, (c) the strength of emission lines of intermediate-mass elements at late times, (d) the proximity to spiral arms and H II regions, (e) the low luminosity compared with SNe Ia, and (f) the presence of radio emission. Indeed, many authors (e.g., Begelman and Sarazin 1986; Filippenko and Sargent 1986; Gaskell *et al.* 1986; Schaeffer, Cassé, and Cahen 1987) have concluded that SNe Ib and Ic represent the explosions of Wolf-Rayet (WR) stars. Particularly impressive are the late-time synthetic spectra computed by Fransson and Chevalier (1989) under the assumption that the SN Ib 1985F resulted from core collapse in a 8 $M_\odot$ helium star [25 $M_\odot$ zero-age main sequence (ZAMS) mass].

Here I critically examine the evidence for and against the hypothesis of massive-star progenitors for SNe Ib and Ic. I am primarily concerned with the distinction between the two main types of explosion *mechanisms* — core collapse versus deflagration/detonation — rather than with the question of whether a particular progenitor has sufficiently prominent mass-losing winds to be formally classified as a WR star. White dwarf models of SNe Ib/Ic include those of Branch and Nomoto (1986), Khokhlov and Ergma (1986), Iben *et al.* (1987), and Woosley (1990).

2. SN 1987K: EVIDENCE FOR MASSIVE PROGENITORS

Observationally, one of the most direct links between SNe Ib/Ic and massive stars is SN 1987K in NGC 4651, an object whose spectroscopic classification changed from Type II to Type Ib/Ic as it aged (Filippenko 1988b). Figure 1 shows a series of spectra of SN 1987K. At early times the P Cygni profile of Hα is unmistakable, although its strength is smaller than usual; see Filippenko (1988a) for a comparison with SN 1987A. At late times, there is no evidence for broad Hα emission. Instead, the spectrum is dominated by [O I], [Ca II], and Ca II emission, as are SNe Ib/Ic. (The continuum is stronger than in most SNe Ib/Ic, but contamination by starlight is probably responsible.) This "metamorphosis" is the only one ever seen in a supernova; however, it is possible that significant numbers of SNe II would be observed to undergo similar transformations if they were monitored over sufficiently long time intervals.

The simplest interpretation (Filippenko 1988b) is that the progenitor of SN 1987K was a massive star that lost most, but not all, of its outer layer of hydrogen. At early times, the photospheric spectrum naturally exhibited hydrogen, but emission lines of intermediate-mass elements from the star's interior began to dominate as the density of the ejecta decreased. A progenitor that suffered greater mass loss would have been even more hydrogen-deficient when it exploded via the core collapse mechanism. Consequently, its maximum-light spectrum would have more closely resembled those of normal SNe Ib/Ic.

If the progenitor of SN 1987K was a very massive star (ZAMS mass $\gtrsim$ 30–40 $M_\odot$, perhaps 20–30 $M_\odot$), either single or a member of a wide binary system, the mass loss would have occurred entirely through winds. Immediately prior to the explosion, the progenitor might have been classified as a late-type WN star (e.g., WN8), provided the outer skin of hydrogen was thin enough. Of course, a very massive star in a close binary system might lose part of its mass through transfer to the companion, yet still have the strong winds typical of WR stars.

Suppose, on the other hand, that the progenitor of SN 1987K had relatively *low* ZAMS mass (e.g., 12–20 $M_\odot$). Most likely, it could not have supported a sufficiently high mass-loss rate through winds to be classified as a WR star. If it was a member of a close binary system, however, it may have lost much of its outer envelope by mass transfer onto its companion. Despite not officially being a WR star, it would have been a relatively massive, hydrogen-deficient star that exploded via core collapse, rather than a white dwarf that exploded via deflagration or detonation.

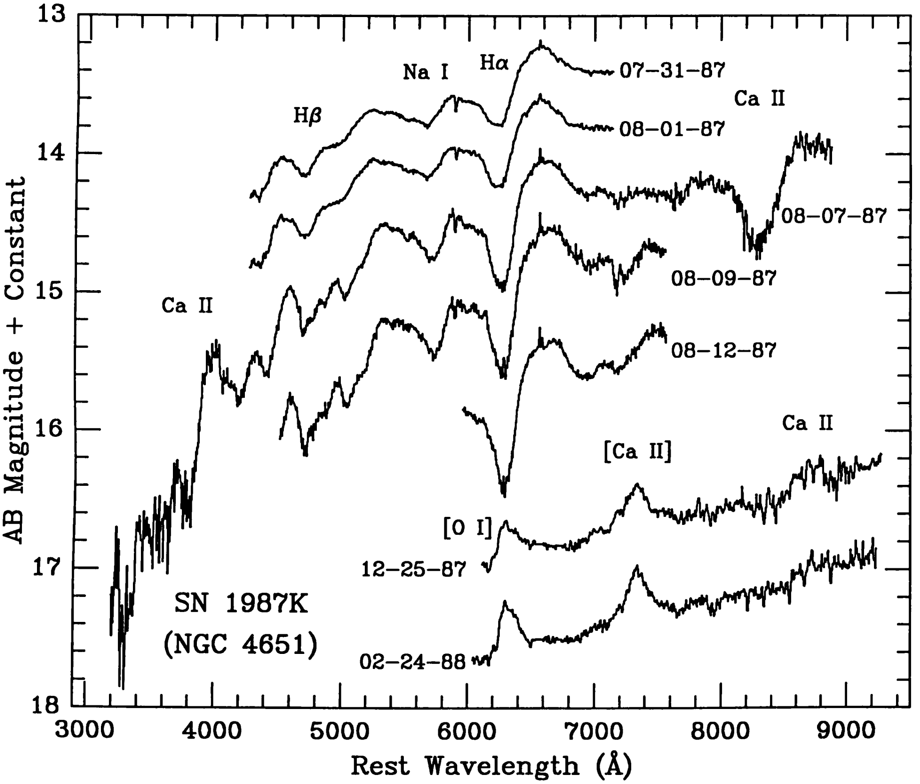

Figure 1: Spectra of SN 1987K, obtained with the 3-m Shane reflector at Lick Observatory. Maximum brightness occurred around 31 July 1987. The redshift of the parent galaxy ($cz = 817$ km s^{-1}) has been removed. AB magnitude $= -2.5 \log f_\nu - 48.6$, where the units of f_ν are ergs s^{-1} cm^{-2} Hz^{-1} (Oke and Gunn 1983). Narrow emission lines, produced by superposed H II regions, have been excised in the late-time spectra for clarity.

3. PROBLEMS WITH THE WOLF-RAYET HYPOTHESIS

There are a number of problems associated with the massive-star hypothesis of SNe Ib/Ic, at least if the progenitors are restricted to *single* stars (or stars in wide binaries) which lose mass through winds alone. These must be examined critically if we are to build confidence in our physical understanding of SNe.

3.1. Progenitor Masses

SNe Ib/Ic are quite *common*; Evans, van den Bergh, and McClure (1989) estimate that collectively, they occur at $\sim$ 1/4 the rate of SNe II. (These authors do not distinguish between SNe Ib and SNe Ic.) If all SNe Ib/Ic have very massive progenitors (ZAMS mass $\gtrsim$ 30–40 $M_\odot$) typical of WR stars, there is probably a severe shortage of progenitors. Furthermore, although many SNe Ib/Ic are associated with luminous H II regions, a significant fraction appear to be far from such areas of very active star formation (e.g., SN 1987M in NGC 2715: FPS). Indeed, the poster presented at this symposium by N. Panagia and V. Laidler claims that SNe Ib/Ic and SNe II appear to have approximately the *same* average distance from H II regions. If *all* the progenitors of SNe Ib/Ic were stars with ZAMS mass > 30 $M_\odot$ (compared with $8 \lesssim M/M_\odot \lesssim 40$ for SNe II), shouldn't SNe Ib/Ic almost *always* be found extremely close to luminous H II regions?

There are three possible solutions to this problem. First, winds in *single* stars of relatively low initial mass ($M \gtrsim 20$ $M_\odot$) might, in certain cases, be sufficiently strong to expel a large fraction, if not all, of the outer hydrogen envelope. A more likely possibility, in my opinion, is that a substantial fraction of SNe Ib/Ic arise from relatively low-mass progenitors (e.g., ZAMS mass 10–40 $M_\odot$) in close *binary* systems, with mass transfer being the dominant mass-loss mechanism. As noted for SN 1987K, such a progenitor would not necessarily be a WR star under the usual definition (i.e., evidence for strong mass loss through winds), but it would nevertheless explode via the core collapse mechanism. Finally, *some* SNe Ib/Ic might have white dwarf progenitors.

3.2. Light Curves

Another problem with models involving massive progenitors is that the predicted light curves are usually too broad, compared with observed light curves for helium stars more massive than 4–6 $M_\odot$ (Ensman and Woosley 1988). In conventional models, these helium cores correspond to ZAMS masses of 15–20 $M_\odot$, and mass loss to the WR stage in a single star is probably not feasible. Progenitors having somewhat higher mass might become WR stars, but the remaining helium cores would be too massive according to most calculations.

The poster by N. Langer and S. Woosley at this symposium (see also Langer 1989) may provide a partial solution to the problem. These authors demonstrate that stars having ZAMS mass between 40 $M_\odot$ and 100 $M_\odot$ all end up with helium core masses of 4–6 $M_\odot$, consistent with the requirements Ensman and Woosley (1988) derived from the analysis of light curves. Such stars do, in fact, go through the WR phase. On the other hand, as discussed previously, there are not enough progenitors in the 40–100 $M_\odot$ range to account for the observed frequency of SNe Ib/Ic, and essentially *all* SNe Ib/Ic should be found very close to luminous H II regions. Another problem is that in some cases, such as SN 1987M, the light curve appears to decline even *more* steeply than those of typical SNe I (Fig. 2). These objects seem inconsistent with even the least massive cores discussed by Ensman and Woosley (1988) and in the poster by Langer and Woosley.

In his talk at this symposium, K. Nomoto presented a different solution that may explain many SNe Ib/Ic (see Shigeyama *et al.* 1990). He showed that stars with a ZAMS mass of 12–16 $M_\odot$ in close *binary* systems yield bare helium cores with $M \approx 3$–4 $M_\odot$. These undergo core collapse, explode, and produce light curves with steep slopes, partly because of extensive mixing of Ni^{56} and clumping of the ejecta. Specifically, both the shape of the light curve and the peak luminosity of SN 1987M are well reproduced by such a model (Nomoto, Filippenko, and Shigeyama 1990). Some SNe Ib/Ic could therefore be hot helium stars in close binary systems, as previously discussed in qualitative terms by Uomoto (1986). Of course, it is also possible that white dwarf progenitors may account for those SNe Ib/Ic whose light curves resemble SN Ia light curves.

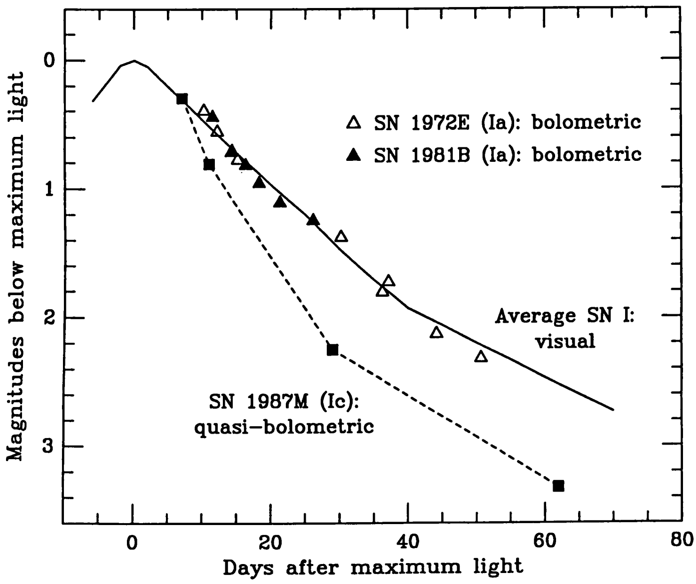

Figure 2: "Quasi-bolometric" ($\lambda\lambda$3280–9100 Å) light curve of SN 1987M (Nomoto, Filippenko, and Shigeyama 1990), compared with the average visual curve of SNe I (Doggett and Branch 1985) and the bolometric measurements of SNe Ia 1972E and 1981B (Graham 1987). The SN 1987M zero points on both axes are uncertain, but the slope of the light curve is unaffected by this. Note that the average early-time *visual* light curve of SNe I (comprised mostly of SNe Ia) provides a good fit to the *bolometric* measurements of SNe Ia. The light curve of SN Ic 1987M, by contrast, is steeper.

3.3. Ejected Mass

The ejected mass of some SNe Ib/Ic appears to be quite small, although there are large uncertainties in the estimates. The mass of ejected oxygen can be calculated from the expression $M_O = 10^8 f([O\ I]) D^2 \exp(2.28/T_4)\ M_\odot$, where D is the distance (Mpc) of the supernova, $10^4 T_4$ is the temperature (K) of the oxygen-emitting gas, and $f([O\ I])$ is the flux (ergs s^{-1} cm^{-2}) of [O I] emission (Uomoto 1986). For some SNe Ib, the mass estimate is quite large, but in the case of SN 1987M it is only $\sim$ 0.4 $M_\odot$ (FPS). Another method used by FPS gives $M \approx$ 0.5–1 $M_\odot$ for the *entire* ejecta. Such small masses seen inconsistent with massive WR progenitors, even if they have pre-supernova masses of only 6 $M_\odot$.

On the other hand, the above method of calculating the oxygen mass depends exponentially on temperature, and the derived number specifically assumed T = 4700 K (based on the continuum colors of SN 1987A at a comparable phase in its development). If the temperature were actually 4000 K, we find $M_O \approx 0.94\ M_\odot$, whereas $M_O \approx 2.1\ M_\odot$ if T = 3500 K. In principle, the most reliable way of obtaining the temperature is to measure the strength of [O I] λ5577 relative to [O I] $\lambda\lambda$6300, 6364. However, this is very difficult in practice because [O I] λ5577 is weak and severely blended with other lines (notably Fe II). The method used by FPS to estimate the total ejected mass is also highly uncertain. Thus, the low ejected masses might not constitute an insurmountable problem, especially in the Shigeyama *et al.* (1990) binary model which invokes the explosion of a 3–4 $M_\odot$ helium core.

If, however, more accurate mass estimates continue to yield very low masses, white dwarf progenitors should be considered seriously.

3.4. Radio Emission

Strong radio emission was detected within one year past maximum in the prototypical SNe Ib 1983N and 1984L, unlike the case in SNe Ia (Panagia, Sramek, and Weiler 1986). If interpreted in the context of the Chevalier (1984) model, the observations of SN 1983N give a value of 5×10^{-7} ($M_\odot$ yr^{-1})/(km s^{-1}) for $\dot{M}/v_w$, the mass-loss rate divided by the wind velocity. If the wind velocity is 2000 km s^{-1}, typical of WR stars, the implied mass-loss rate is $\dot{M} \approx 10^{-3}$ $M_\odot$ yr^{-1}, which greatly exceeds the observed rates in WR stars.

Several possible solutions to this dilemma come to mind. WR stars may, for example, experience a very short-lived phase with high $\dot{M}$ immediately prior to exploding. Such a phase would be very difficult to detect by other means, yet it could produce a substantial circumstellar shell consistent with the radio emission. Alternatively, the SN Ib/Ic could have been a relatively low-mass star in a close binary system, as in the model presented by Shigeyama *et al.* (1990) and by Nomoto, Filippenko, and Shigeyama (1990). If so, the circumstellar shell could be due to a companion with a wind velocity of, say, 10 km s^{-1}. From the observations, the inferred mass-loss rate would then be $\dot{M} \approx 5 \times 10^{-6}$ $M_\odot$ yr^{-1} — quite reasonable for a red supergiant, as discussed by M. Jura at this symposium. The circumstellar gas might also be left over from previous episodes of mass exchange in the close binary system.

It should be noted that, although the radio emission has often been invoked as an argument *against* the white dwarf hypothesis of SNe Ib/Ic, it is actually quite compatible with a white dwarf progenitor in a binary system (Branch 1988). The white dwarf can accrete matter from a red supergiant wind, and the ejecta from the subsequent explosion interact with the wind in the usual manner (Chevalier 1984).

4. CONCLUSIONS

It is clear from the preceding discussion that many SNe Ib/Ic probably do represent the explosions (through core collapse) of hydrogen-deficient, massive stars. However, the question of whether most of these are *Wolf-Rayet stars*, in which mass is lost primarily through winds, is far from settled. Unless single stars of relatively modest mass (ZAMS mass $\approx$ 15–20 $M_\odot$, rather than $M \gtrsim$ 30–40 $M_\odot$) are able to lose their hydrogen envelopes, it seems almost impossible to account for a majority of SNe Ib/Ic with single stars or wide binaries. Many, or even most, SNe Ib/Ic probably come from progenitors in close binary systems, where much of the original mass (M =10–40 $M_\odot$) is actually lost through mass transfer. In this case, the pre-supernova winds are not necessarily strong enough to make the progenitors qualify as WR stars.

Despite this conclusion, it is still quite possible that *some* SNe Ib/Ic may be exploding white dwarfs. Hopefully, with more detailed observations of a larger number of SNe, we will find observational distinctions between these explosion mechanisms. It is even possible that SNe Ib and SNe Ic have physically different progenitors and explosion mechanisms, although the simplest current interpretation is that they represent the same type of object, but with different helium abundances or excitation conditions in the outer atmosphere.

I disagree with the suggestion of Panagia and Laidler, expressed in a poster at this symposium, that all SNe Ib/Ic must have ZAMS masses between 6.5 $M_\odot$ and 8 $M_\odot$. This mass range was obtained under the assumption that all stars initially more massive than 8 $M_\odot$ produce SNe II, but this *precludes* the possibility that SNe Ib/Ic have progenitor masses above 8 $M_{\odot}$. Moreover, according to their analysis, the average distances of SNe Ib/Ic and SNe II from H II regions are comparable; typical SNe Ib/Ic might even be slightly closer to H II regions than are SNe II. This certainly does not imply that SNe Ib/Ic progenitors are significantly *less* massive than the progenitors of SNe II.

Finally, I note that if extreme mass-loss mechanisms such as that of Langer and Woosley *don't* exist, the most massive WR stars may end their lives as black holes not preceded by supernova events. This conclusion is based on the fact that thus far, observers have identified few (if any) SNe which have the expected properties of an exploding, very massive WR star: low optical luminosity, very broad light curve, and absence of hydrogen in the spectrum.

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DISCUSSION

Matteucci: Several years ago, Branch and Nomoto proposed off-center detonation of a white dwarf as a model for Type Ib supernovae, in order to explain the early appearance of helium and iron in the spectra. What is the current status of that idea?
Filippenko: The Branch and Nomoto model leads to a light curve that declines far more rapidly than the observed light curves of Type Ib supernovae, because only the outer layer of helium ($0.3M_{\odot}$) detonates. Thus, it does not explain Type Ib supernovae. The early appearance of strong helium lines is consistent with WR models, since the outer layers of WN stars consist largely of helium. The iron lines are produced by normal iron abundances in the outer atmospheres of these stars, as shown by Wheeler and Harkness.

Langer: Dopita and Lozinskaya told us about an extreme WO star with a wind velocity of about 5000 $km{\cdot}s^{-1}$. Can this help alleviate the problem of large mass loss rates inferred from the radio observations?
Filippenko: Actually, it makes the problem even worse. The radio observations give us a specific value for mass loss rate divided by wind velocity. Thus, the higher the assumed wind velocity, the greater the inferred mass loss rate. What we actually need are *lower* wind velocities in WR stars in order to deduce more reasonable (*i.e.* smaller) mass loss rates.

Yungelson: The numerical model of the binary population of the Galaxy, I was talking about this morning, predicts for the Galaxy one exploding He-star per $\sim$ 300 years. Most of them have $(2.5-10)M_{\odot}$ masses and most probably would not have strong enough stellar winds to produce the WR phenomenon. Rather, prior to explosions they would be observed as hot subdwarfs. These pre-SN are descendants of binary components with initial masses $\sim (10-25)M_{\odot}$.
Filippenko: Yes, it is true that low-mass helium stars may not have sufficiently strong stellar winds to produce the emission lines characteristic of WR stars. In my *talk* I used a loose definition of WR star, (*i.e.*, stripped helium or carbon-oxygen core), since I only wanted to concentrate on *explosion* mechanisms (core collapse *vs.* deflagration or detonation).

Vanbeveren: New evolutionary computations of core He-burning stars with WR-like stellar wind mass loss rates predict that all stars which are able to evolve into a WR phase will end up as a WO star. Do you not expect then to see oxygen right from the beginning of the SN phenomenon rather than a few weeks after the explosion started?
Filippenko: The [OI] emission lines begin to appear between one and two months past maximum. At even earlier times, the density is so high that the [OI] lines are thermalized; they cannot be distinguished from the continuum. However, the OIλ7774 absorption line *is* very strong right from the start in the spectra of Type Ib supernovae.