THE ENVIRONMENTS OF TYPE IB/C SUPERNOVAE

S. D. VAN DYK, A. J. BARTH AND A. V. FILIPPENKO
Astronomy Department, University of California,
Berkeley CA 94720-3411 USA

1. Introduction

Up to about 1985, supernovae (SNe) generally were placed into the two Minkowski classes, type I and type II, defined by the absence or presence, respectively, of hydrogen in their optical spectra. Around that time it was acknowledged that several type I SNe were systematically peculiar, both spectroscopically and photometrically (Elias *et al.* 1985; Wheeler & Levreault 1985; Uomoto & Kirshner 1985; Branch 1986; Filippenko 1986), by missing the characteristic Si II spectral feature near 6150 Å, having distinct infrared light curves, being optically redder and subluminous, and showing radio emission (Sramek *et al.* 1984). These SNe were designated as type Ib (Elias *et al.* 1985; Branch 1986) to distinguish them from the classical type Ia. Harkness *et al.* (1987) identified He I lines in spectra of the SN Ib 1984L, but some subsequent examples showed no He in their spectra and were further subclassified as Type Ic (Wheeler & Harkness 1990). The two subtypes, however, are nearly indistinguishable at late times. In this Symposium the entire class has been referred to as type Ib/c SNe. A recent bright example is SN 1994I in M51 (Filippenko *et al.* 1994).

It has been realized that what makes SNe Ib/c different must also extend to the nature of their progenitor stars (e.g., Wheeler & Levreault 1985). Constraints on the progenitor can be obtained not only through observations of each event (see Leibundgut, these proceedings) and through theoretical modelling (see Nomoto, these proceedings), but also by examining the relationship of these SNe with their environment. Here we look at this environment on progressively smaller scales. Since only 32 *bona fide* members of this subclass exist, it must be kept in mind that small-number statistics are clearly a problem. Yet, even with this small sample, we are developing a clearer picture of the progenitor population for SNe Ib/c.

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 135–140.

2. Global Environment

SNe Ib/c are found only in late-type galaxies (Porter & Filippenko 1987; van den Bergh & Tammann 1991). This implies that these SNe likely arise only from young massive stars, as do type II SNe. However, unlike SNe II, somehow during the lifetime of the progenitor star, the hydrogen envelope must have been entirely stripped away. Two hypotheses have been offered to accomplish this: (1) a Wolf-Rayet (W-R) star progenitor, or, (2) a progenitor in a massive interacting binary system. A previous discussion of W-R stars as SNe Ib/c progenitors can be found in Filippenko (1991). From the global standpoint, the rate of SNe Ib/c in these galaxies (van den Bergh & Tammann 1991) is in conflict with hypothesis (1), since W-R stars, which evolve from stars with $M_{\rm ZAMS} \gtrsim 25$–$40\,{\rm M}_\odot$ (Maeder & Conti 1994), cannot provide enough progenitors.

3. Local Interstellar Environment

Anecdotally, it is known that SNe Ib/c tend to occur in or near H II regions (e.g., Porter & Filippenko 1987). Kennicutt *et al.* (1989) showed that giant H II regions in late-type galaxies are the sites of the majority of massive star formation. Thus, if one finds SNe in or near H II regions, it is likely that their progenitors were massive stars. Van Dyk (1992) examined the association of SNe of all types, including 9 SNe Ib/c, with H II regions in late-type galaxies. Recently, Van Dyk & Hamuy (1993) extended this survey, considering 31 SNe II and 15 SNe Ib/c. Both studies found little difference between the association of SNe Ib/c and of SNe II with H II regions. Here, we continue to explore this with a sample of 16 SNe Ib/c.

H II regions are mapped through narrow-band Hα imaging. Association of SNe with H II regions is established by comparing the projected angular separation (Δ) of each SN from the center of its nearest H II region with the maximum angular radial extent ($r_{\rm max}$) of the H II region measured toward the SN position. Continuum-subtracted, flux-calibrated CCD data on nearly face-on galaxies have been acquired at KPNO, CTIO, Lowell Observatory, and Lick Observatory, as well as from other investigators. The H II region detection limit is $\gtrsim$(2–3) 10^{37} erg s^{-1}. We have measured $r_{\rm max}$ at a surface brightness level $\gtrsim$3 10^{-18} erg cm^{-2} s^{-1} arcsec^{-2}. As in Van Dyk & Hamuy (1993), we use absolute positions or precise nuclear offsets when available. Astrometry for the CCD images with $\lesssim 1''$ accuracy is achieved using star positions on the images measured with the STScI GASP[1] system.

[1] GASP is the Guide Star Astrometric Support Program available at the Space Telescope Science Institute (STScI).

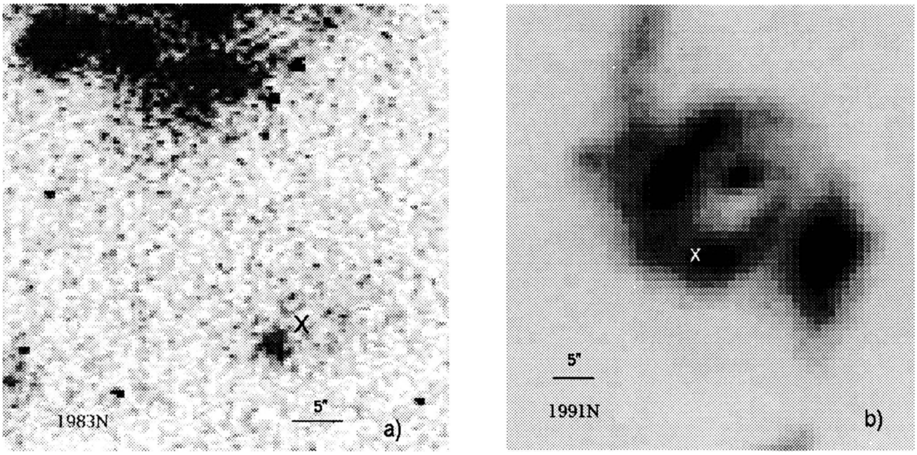

Figure 1. Hα images of the environments of (a) the type Ib SN 1983N in M83 and (b) the Type Ic SN 1991N in NGC 3310, showing the differing relationships of these two SNe with nearby H II regions. North is up, and East is to the left.

In Fig. 1 we show the local interstellar environments of the two SNe Ib/c 1983N and 1991N.

For each SN Ib/c we determine the ratio $R \equiv \Delta/r_{\rm max}$. We then consider the proportion of SNe Ib/c with $R \leq 1$. Unfortunately, not all SNe in our sample can be treated equally. For lack of a better weighting scheme when calculating this proportion, those SNe having absolute positions or precise nuclear offsets are arbitrarily given 3 times the weight of those SNe before about 1980 with poorer nuclear offsets and 1.5 times the weight of those SNe after about 1980 with poorer offsets. (What are needed, of course, are accurate positions for all SNe.) We find this proportion to be 0.57 ± 0.12 (statistical error) for SNe Ib/c. Comparing this to 0.59 ± 0.09 of 32 SNe II with $R \leq 1$, measured and weighted in the same manner, we find no significant difference. This suggests that the progenitors for both types may be very similar in ZAMS mass range, probably $8 \lesssim M(\mathrm{M}_{\odot}) \lesssim 25$–40. W-R star progenitors are less likely, since a closer association of SNe Ib/c with H II regions might be expected for consistency with this hypothesis, although not all W-R stars in galaxies will necessarily be associated with bright starburst H II regions.

In addition to the lower-resolution ground-based data, we have also examined two SNe Ib/c environments using pre-repair *Hubble Space Telescope* (HST) archive data. These are broad-band, rather than narrow-band, images. In Fig. 2a we show a 200-s FOC UV image through the F220W filter for the site of SN 1991N. The site is midway between two probable large clusters of O-type stars. Photometry and improvement of the astrometry

https://doi.org/10.1017/S0074180900055625 Published online by Cambridge University Press

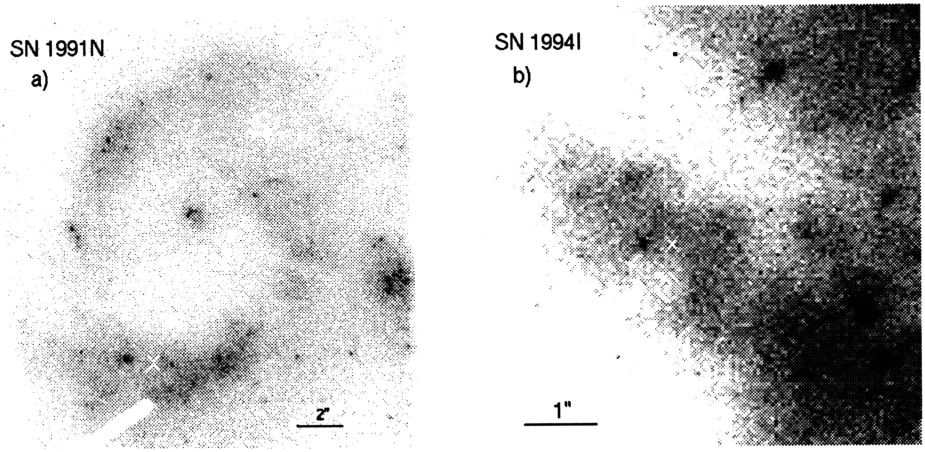

Figure 2. **HST images of the environments of the type Ic supernovae (a) 1991N in NGC 3310 and (b) 1994I in M51. North is up, and East is to the left.**

is being done for this image.

In Fig. 2b we show a 1100-s PC image made through the F555W filter for the site of SN 1994I. We find a diffuse background of unresolved stars at the site. We estimate an upper limit ($3\,\sigma$) for the progenitor of $V \gtrsim 23.5$ mag. Assuming a distance of 6.8–9.7 Mpc and $A_V \simeq 1.5$–2.0 mag (Ho & Filippenko 1995), the progenitor had $M_V \gtrsim -7.7$ to -8.4 mag. Unfortunately, this upper limit to the luminosity is not very restrictive; it is brighter than supergiants and many W-R stars (e.g., Torres-Dodgen & Massey 1988).

Based on just these two HST images we can neither eliminate the W-R hypothesis nor support the competing massive binary hypothesis. Additional archive images, especially the more valuable post-repair ones, will soon become available. Inevitably, HST imaging will be the best way to detail the interstellar and stellar environments for SNe and begin to place rigorous mass constraints on the progenitors. In the cases of SNe 1983N and 1994I it should also eventually be possible to locate, through HST imaging, any possible surviving binary companion to the progenitor.

4. Circumstellar Environment

SNe Ib/c, like SNe II, are radio emitters (Weiler *et al.* 1986). This was first discovered for SN 1983N by Sramek *et al.* (1984). The other cases include SNe 1984L, 1990B, and 1994I. Most radio supernovae (RSNe) share the common properties of non-thermal emission with high brightness temperature, light curve "turn-on" at shorter wavelengths first and longer wavelengths later, a rapid increase in flux density with time at each wavelength, with a power-law decline after maximum, and a decreasing spectral index

https://doi.org/10.1017/S0074180900055625 Published online by Cambridge University Press

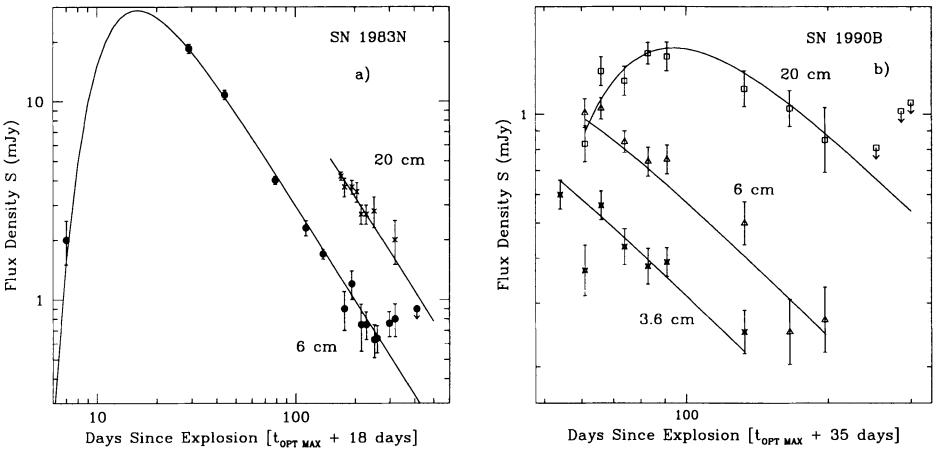

Figure 3. **Radio light curves for (a) the type Ib SN 1983N (Weiler *et al.* 1986) and (b) the type Ic SN 1990B in NGC 4568 (Van Dyk *et al.* 1993).**

between two wavelengths, with the spectral index α inevitably approaching an optically thin, non-thermal, constant negative value (Weiler *et al.* 1986). RSNe Ib/c show a steep spectral index, rapid "turn-on" at 6 cm before optical maximum, rapid decline after maximum, and homogeneity in spectral luminosity at 6 cm ($\sim 10^{27}$ erg s^{-1} Hz^{-1}). This behavior is in contrast to the slower, more gradual, more heterogeneous behavior for RSNe II.

In Fig. 3 we show radio light curves for the two well-studied RSNe Ib/c 1983N and 1990B.

The radio emission from SNe has been successfully interpreted using the Chevalier (1984) "mini-shell" model, where non-thermal synchrotron emission is produced via interaction of the SN shock with the high-density circumstellar matter produced by a red supergiant progenitor star through mass-loss in the form of a stellar wind prior to explosion. The synchrotron emission is assumed to be free-free absorbed by the fully ionized wind matter. Both the synchrotron luminosity and the absorption depend on the circumstellar density, which is proportional to the ratio of the mass-loss rate $\dot{M}$ to the wind speed w (Weiler *et al.* 1986) for a spherically symmetric wind. For RSNe Ib/c, $\dot{M}/w \approx 10^{-6}\,M_\odot\,yr^{-1}/(km\,s^{-1})$. For a W-R star with a fast ($w \sim 10^3\,km\,s^{-1}$), low-density wind, the required $\dot{M}$ ($\sim 10^{-3}\,M_\odot\,yr^{-1}$) is much larger than typically observed for these stars (e.g., Conti 1988), and would result in a low-density bubble around the star prior to explosion, rather than a high-density shell necessary to produce the rapidly evolving, luminous radio emission. We can then reasonably exclude the W-R model. The homogeneity in radio properties for SNe Ib/c implies a homogeneity

https://doi.org/10.1017/S0074180900055625 Published online by Cambridge University Press

in circumstellar environments, which must be different from SNe II circumstellar environments. Interaction in a massive binary system could provide this difference.

Acknowledgements. This work was partially based on observations made with the NASA/ESA HST, obtained from the data archive at STScI, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Financial support was provided by NASA through grant number AR-4302.01-92A from STScI.

References

Branch, D. 1986, ApJ 300, L51
Chevalier, R.A. 1984, ApJ 285, L63
Conti, P.S. 1988, in *O Stars & Wolf-Rayet Stars*, P.S. Conti & A.B. Underhill (Eds.), p. 81
Elias, J.H., Matthews, K., Neugebauer, G. & Persson, S.E. 1985, ApJ 296, 379
Filippenko, A.V. 1986, in *Highlights of Astronomy*, J.-P. Swings (Ed.), Reidel (Dordrecht), p. 589
Filippenko, A.V. 1991, in *Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies*, K.A. van der Hucht & B. Hidayat (Eds.), Kluwer (Dordrecht), p. 529
Filippenko, A.V., Matheson, T. & Barth, A.J. 1994, IAU Circ. 5964
Harkness, R.P. *et al.* 1987, ApJ 317, 355
Ho, L.C. & Filippenko, A.V. 1995, ApJ (in press)
Kennicutt, R.C., Jr., Edgar, B.K. & Hodge, P.W. 1989, ApJ 337, 761
Maeder, A. & Conti, P.S. 1994, ARA&A 32, 227
Porter, A.C. & Filippenko, A.V. 1986, AJ 93, 1372
Sramek, R.A., Panagia, N. & Weiler, K.W. 1984, ApJ 285, L59
Torres-Dodgen, A.V. & Massey, P. 1988, AJ 96, 1076
Uomoto, A. & Kirshner, R.P. 1985, A&A 149, L7
van den Bergh, S. & Tammann, G.A. 1991, ARA&A 29, 363
Van Dyk, S.D. 1992, AJ 103, 1788
Van Dyk, S.D., & Hamuy, M. 1993, in *Massive Stars: Their Lives in the Interstellar Medium*, J.P. Cassinelli & E.B. Churchwell (Eds.), ASP Conf. Ser. Vol. 35, p. 440
Van Dyk, S.D., Sramek, R.A., Weiler, K.W. & Panagia, N. 1993, ApJ 409, 162
Weiler, K.W., Sramek, R. A., Panagia, N., van der Hulst, J.M. & Salvati, M. 1986, ApJ 301, 790
Wheeler, J.C. & Harkness, R. P. 1990, Rept. Progr. Phys. 53, 1467
Wheeler, J.C. & Levreault, R. 1985, ApJ 294, L17