ABSTRACT

The classic example of a Type IIb supernova is SN 1993J, which had a cool extended progenitor surrounded by a dense wind. There is evidence for another category of Type IIb supernova that has a more compact progenitor with a lower density, probably fast, wind. Distinguishing features of the compact category are weak optical emission from the shock heated envelope at early times, nonexistent or very weak H emission in the late nebular phase, rapidly evolving radio emission, rapid expansion of the radio shell, and expected nonthermal as opposed to thermal X-ray emission. Type IIb supernovae that have one or more of these features include SNe 1996cb, 2001ig, 2003bg, 2008ax, and 2008bo. All of these with sufficient radio data (the last four) show evidence for presupernova wind variability. We estimate a progenitor envelope radius \( \sim 1 \times 10^{13} \text{ cm} \) for SN 2008ax, a value consistent with a compact Wolf-Rayet progenitor. Supernovae in the SN 1993J extended category include SN 2001gd and probably the Cas A supernova. We suggest that the compact Type IIb events be designated Type cIIb and the extended ones Type eIIb. The H envelope mass dividing these categories is \( \sim 0.1 M_\odot \).

Key words: circumstellar matter – shock waves – supernovae: general – supernovae: individual (SN 1993J, SN 2008ax)

1. INTRODUCTION

A Type IIb supernova has a spectrum with high-velocity H lines near maximum, but in the late nebular phases more closely resembles a Type Ib supernova, with weak or absent H lines. The first supernova placed in this category was SN 1987K (Filippenko 1988). However, it was the nearby SN 1993J in M81 that has come to best define the properties of a SN IIb. In this case, the progenitor star was identified as a K supergiant (Aldering et al. 1994), consistent with the interpretation of the early light curve which required a stellar radius of \( \sim 4 \times 10^{13} \text{ cm} \) (Woosley et al. 1994). Such a star is expected to have a slow, dense wind, and there is radio and X-ray evidence for a wind with mass-loss rate \( M \approx 4 \times 10^{-5} M_\odot \text{ yr}^{-1} \) for an assumed wind velocity of \( v_w = 10 \text{ km s}^{-1} \) (Fransson et al. 1996; Fransson & Björnsson 1998). Radio VLBI observations provide strong interaction picture (Marcaide et al. 1997; Bartel et al. 2002). The interaction with the dense wind also produces some Hα emission in the late nebular phase (Matheson et al. 2000).

A consistent scenario for SN 1993J is thus the explosion of an extended star that interacts with the dense wind from the progenitor star. However, there is also evidence for Type IIb supernovae arising from compact stars, and that is the topic addressed here. Some of that evidence has already been presented for SN 2001ig (Ryder et al. 2004), SN 2003bg (Soderberg et al. 2006), and SN 2008ax (Pastorello et al. 2008). In Section 2, we present the differences between SNe IIb that have extended or compact progenitors. The results are discussed in Section 3.

2. TYPE IIb SUPERNOVA CATEGORIES

2.1. The Progenitor Star and Early Light Curve Evolution

The most direct way to observe the progenitor star is in presupernova observations. This has been possible for SN 1993J, as discussed above, and recently has been possible for SN 2008ax. Crockett et al. (2008) find that the progenitor of the Type IIb SN 2008ax is either a single, He-rich, Wolf-Rayet (WR) star or a stripped star in an interacting binary in a low mass cluster.

The light curve evolution in the first days after the explosion, which is the time of cooling envelope emission after shock breakout, provides a good indicator of the initial stellar extent. The cooling envelope emission is more luminous for a more extended star because of the larger emitting area and adiabatic expansion losses are less important for an extended star. The early peak luminosity and first 10 days of evolution provided evidence for a large radius, \( \sim 4 \times 10^{13} \text{ cm} \) for the progenitor of SN 1993J (Woosley et al. 1994).

In the case of SN 2008ax, a comparable early luminous phase was absent in the light curve (Pastorello et al. 2008, Figure 11). Very early observations with Swift did show evidence for an initial peak in the \( uvw1, u, \) and \( b \) bands (Roming et al. 2009). The luminosity level of the emission is comparable to, although slightly fainter than, similar emission observed in the Type IIb SN 1999ex (Stritzinger et al. 2002). We used the cooling envelope theory of Chevalier & Fransson (2008) to model the \( uvw2, uvw1, u, b \) emission on day 1.7 (Roming et al. 2009) and the \( g, r, i, z \) emission on day 1.9 (Pastorello et al. 2008). The magnitude results of Roming et al. (2009) were converted to fluxes using the flux conversion factors, pivot wavelengths, and bandpass widths for the UVOT as reported in Poole et al. (2008). For a distance of \( 9.6 \) Mpc, a blackbody fit to the fluxes gives an effective temperature \( T \approx 6000 \text{ K} \) and a photospheric radius \( r_{ph} = 4.3 \times 10^{14} \text{ cm} \) on day 1.8. Taking an ejecta mass of \( M_{ej} = 3.8 M_\odot \) and an energy of \( E = 1.5 \times 10^{51} \text{ erg} \) from the model of Tsvetkov et al. (2009), Equation (2) of Chevalier & Fransson (2008) yields \( r_{ph} = 3.8 \times 10^{14} \text{ cm} \), in good agreement with the observed value. Equation (5) of Chevalier & Fransson (2008) and the observed \( T \) yield a progenitor radius of \( R = 1 \times 10^{14} \text{ cm} \). However, the temperature is sufficiently low that recombination is becoming important, so that the model of Chevalier & Fransson (2008)
is inaccurate. The progenitor radius estimate should still be valid to within a factor of 2–3, showing that the progenitor was compact, with a radius consistent with a WR star. The radius determined here is that of the stellar envelope; the photospheric radius may be a factor of 2–3 larger due to the stellar wind (see Figure 1 of Li 2007). Although the explosion parameters for SN 2008ax are similar to SN 1993J (Pastorello et al. 2008; Tsvetkov et al. 2009), the progenitor is very different, as indicated by the progenitor observations and the early light curve.

For a compact star, the cooling envelope emission lasts for only a few days, so that observations must be carried out very soon after the explosion for this phase to be detected. Observations that rule out an extended progenitor may be the most that can be obtained. For the Type IIb SN 1996cb, there are light curve observations showing that an early luminous phase like that of SN 1993J was not present (Qiu et al. 1999).

2.2. Circumstellar Interaction

Circumstellar interaction depends on the progenitor radius in that more compact stars have faster, and thus more rarefied, winds and shock acceleration at the time of breakout extends to higher velocities in compact stars. Radio emission is an excellent indicator of circumstellar interaction, and Figure 1 shows peak radio luminosity versus time of peak for SN Ib/c and SN Ib. Synchrotron self-absorption (SSA) is expected to be the dominant absorption mechanism for the high velocities present in SN Ib/c and can be used to estimate the radio shell velocity at the time of the peak radio luminosity (Chevalier 1998). The SN Ib designation has been given to SN 1993J, SN 2001gd (Matheson et al. 2001), SN 2001ig (Phillips et al. 2001), SN 2003bg (Hamuy et al. 2009), and SN 2008ax (Pastorello et al. 2008). Figure 1 shows that there is a class of SN Ib that have radio properties similar to those of SN Ib/c, i.e., they have rapid radio evolution for a given luminosity, indicating velocities of 30,000–50,000 km s$^{-1}$. These velocities are expected for the explosion of a WR star because of strong shock acceleration in the outer parts of the star and the low wind density resulting from a high wind velocity (Chevalier & Fransson 2006). They are designated here as SN cIIb because of the expectation that they have relatively compact progenitors. There is direct light curve and progenitor evidence for this in the case of SN 2008ax, as discussed above. SN 1993J is placed in the SN cIIb category because of its extended progenitor, as is SN 2001gd, because of its radio properties. In addition to the radio light curve information on SN 2001gd (Stockdale et al. 2007), there are also VLBI observations on days 286 and 582 from explosion, which combine to give a mean velocity $\sim 9100$ km s$^{-1}$ on day 434 with 20% uncertainty (Pérez-Torres et al. 2005). This velocity is consistent with that found from the radio light curves (Figure 1) and is somewhat less than that observed for the interaction shell in SN 1993J at a comparable time, $\sim 14,000$ km s$^{-1}$ (Bartel et al. 2002; Marcaide et al. 1997). VLBI observations of SN 2008ax (Martí-Vidal et al. 2009) indicate a velocity $\sim 52,000$ km s$^{-1}$ (in a plausible model) at an age of 33 days, supporting the SSA model. The highest H velocity in optical lines was only about half this, as noted by Martí-Vidal et al. (2009). This is not a problem for the Type cIIb case because the high-velocity shocked H is nonradiative, as discussed below. The unshocked gas is of such low density that it is not seen. There do not seem to be sufficient early radio observations of SN 2008ax (Roming et al. 2009) to test for SSA from the light curves, but in the case of SN 2003bg, there is support for the SSA model (Soderberg et al. 2006).

The SSA model of Chevalier & Fransson (2006) can be used to obtain estimates of the mass-loss properties of the compact supernovae. We characterize the mass-loss density by $A_*$, where $M/v_w = A_* \times 10^{-3} M_\odot$ yr$^{-1}$/1000 km s$^{-1}$ and find $A_* \epsilon B_{-1}^1 \epsilon_\gamma ^{1/2} = 3$ for SN 2001ig, 13 for SN 2003bg, and 0.65 for SN 2008ax; here, $\epsilon_\gamma$ is the fraction of the postshock energy density in magnetic field in units of 0.1 and $\alpha$ is the ratio of relativistic electron energy density to magnetic energy density. The results for SN 2001ig and SN 2003bg are the same as in Chevalier & Fransson (2006) and that for SN 2008ax uses the observations of Roming et al. (2009). Assuming that the efficiency of production of the radio emission is comparable for the different objects, the variation in the radio luminosities of the supernovae translates into a variation in the progenitor mass-loss densities, by a factor of 20.

Other Type IIb supernovae have been detected in the radio, but are not included in Figure 1 because the available data do not allow the maximum luminosity to be accurately determined. However, there is some information. SN 2008bo showed optical properties similar to SN 2008ax, including deep Hz absorption (Navasardyan et al. 2008). There were early radio detections of the supernova and a later (age $\sim 20$ days) rebrightening (Stockdale et al. 2008). At a distance of 21 Mpc, the radio luminosity was $\sim 1.5$ times lower than that of SN 2008ax and the emission became optically thin somewhat earlier, so this object extends the apparent wind density to slightly lower values. There are also two radio observations of the Type IIb SN 1996cb that indicate a $\tau = 1$ frequency of $\sim 11$ GHz on 1996 December 21 (van Dyk et al. 1996). The observations indicate that it also lies on the $L_p - t_p$ plot close to SN 2008ax.

X-ray emission is another signature of circumstellar interaction. Chevalier & Fransson (2006) find that the X-ray emission from SNe Ib/c is probably due to a nonthermal mechanism: inverse Compton emission near optical maximum light and synchrotron emission at later times. The general expectation

Figure 1. Peak spectral radio luminosity vs. the product of the time of the peak and the frequency of the measurement for supernovae of Types Ib/c and Ib. The observed supernovae are designated by the last two digits of the year and letter(s). References to the recent radio observations are Soderberg et al. (2008) for SN 2008ax, Roming et al. (2009) for SN 2008ax, and Soderberg et al. (2010) for SN 2009bb; other references can be found in Chevalier & Fransson (2006). The dashed lines show the mean velocity of the radio shell if SSA is responsible for the flux peak; a particle spectral index $p = 3$ is assumed (see Chevalier 1998).
is that Type cIIb events should have nonthermal X-ray emission, while Type cIIb events similar to SN 1993J should have dominant thermal X-ray emission, as in SN 1993J (Fransson et al. 1996). There are not yet sufficiently well-observed Type cIIb events to test this from the spectra themselves. However, Roming et al. (2009) found a decrease in the X-ray luminosity of SN 2008ax from 6.0 \pm 1.9 \times 10^{38} \text{ erg s}^{-1} in the first month to 1.4 \pm 0.9 \times 10^{38} \text{ erg s}^{-1} in the second month. This is the magnitude of decline that would be expected in going from an inverse Compton component near optical maximum to a synchrotron component a month later (Figure 1 of Chevalier & Fransson 2006).

Finally, another signature of a dense circumstellar medium is optical emission from gas heated and ionized by radiation from reverse shock heated gas (Chevalier & Fransson 1994). The optical emission can be either from freely expanding ejecta or from a dense shell formed as a result of radiative cooling. SN 1993J did show evidence for persistent Hα emission to an age of 2500 days (Matheson et al. 2000); the box-like line profile and other characteristics were consistent with circumstellar interaction. The early Hα emission from SN 1993J showed a decline consistent with a radioactive power source; the late steady phase started at an age of 300–350 days (Houck & Fransson 1996). The estimated wind density in SN 1993J corresponds to $A_\alpha \approx 400$ (Fransson et al. 1996), which is a factor of $>30$ larger than the wind densities deduced here for the SNe cIIb. Cooling is primarily by bremsstrahlung and the reverse shock is nonradiative over the times of observations for SN cIIb. The low density and large shock radius imply that Hα from circumstellar interaction should be undetectable in the late nebular phase. However, Stritzinger et al. (2009) suggest that circumstellar interaction powers Hα emission in the nebular phase from the Type Ib SN 2007Y, even though upper limits on the radio emission yield $A_\alpha \lesssim 0.1$. The explanation is probably that the observations are on days 230 and 270, when radioactivity is still a plausible power source. Observations of Hα at times $\gtrsim 1$ yr are needed to distinguish between the steady emission that can occur in SNe cIIb and the continued drop expected in SNe cIIb.

2.3. Structure in Wind

Both SN 2001ig (Ryder et al. 2004) and SN 2003bg (Soderberg et al. 2006) showed structure in their radio light curves that was interpreted as density structure in the wind region. Ryder et al. (2004) suggested that the structure was due to a binary companion, as has been observed in the pinwheel dust structure around some WR stars. Ryder et al. (2006) in fact found evidence for a possible companion star at the site of the supernova. However, the star is of type late-B to late-F; such a star would have too weak a wind to have much effect on the strong wind deduced for the progenitor of SN 2001ig. Soderberg et al. (2006) argued for stellar variability rather than a binary companion, based on the similarity between the radio evolution of SN 2001ig and SN 2003bg.

The additional cases of Type cIIb supernovae also show evidence for wind density variations. The radio light curves of SN 2008ax show a peak in the optically thin phase at $t \approx 60$ days (Roming et al. 2009). In the case of SN 2008bo, there is a possible rebrightening at $t \approx 20$ days (Stockdale et al. 2008). There is thus evidence for density variations in every proposed Type cIIb supernova for which there are sufficient radio observations to show the effect. On the other hand, the Type Ib event SN 2008D (Soderberg et al. 2008) and the Type Ic events SN 2003L (Soderberg et al. 2005) and SN 2009bb (Soderberg et al. 2010) show smooth light curves. For SN 2003bg, Soderberg et al. (2006) estimated that the time between the higher density outflows was $\sim 12(1000 \text{ km s}^{-1}/v_w) \text{ yr}$, taking a timescale of 120 days to the first feature. Kotak & Vink (2006) took a timescale of 150 days and derived a period for the mass-loss events of $\sim 25(200 \text{ km s}^{-1}/v_w) \text{ yr}$ for SN 2003bg and SN 2001ig. The main difference between these estimates is that Kotak & Vink (2006) used an optically determined maximum ejecta velocity of 15,000 km s$^{-1}$ at 14 days to determine the expansion of the radio emitting region, whereas Soderberg et al. (2006) used the SSA model for the radio emission to determine a mean velocity of about 40,000 km s$^{-1}$. As discussed above and shown by the VLBI observations of SN 2008ax, the highest velocity ejecta may not be detectable at optical wavelengths. The variability timescales for SN 2008ax and SN 2008bo are not well defined, but appear to be shorter than in the first two cases.

As noted by Kotak & Vink (2006), the timescale of decades is consistent with the variability timescale of luminous blue variables (LBVs) undergoing S Doradus-type variations and they propose such stars as progenitors. An example of such a star is AG Car, which has been followed from its minimum (hotter) state through a cooler phase (Stahl et al. 2001). In its minimum state, the mass-loss rate is $\sim 3 \times 10^{-5} M_\odot \text{ yr}^{-1}$ and $v_w \approx 300 \text{ km s}^{-1}$, so that $A_\alpha \approx 10$. This is at the high end, but within the range, of wind densities discussed here for the Type cIIb events. However, the radius of AG Car in its compact state is $50 R_\odot = 3.5 \times 10^{12}$ cm (Stahl et al. 2001). This radius is a factor $\gtrsim 10$ times the radius deduced here for the progenitor of SN 2008ax and the radii of WR stars. Also, Stahl et al. (2001) estimate a mass-loss rate of $\sim 1.5 \times 10^{-4} M_\odot \text{ yr}^{-1}$ and $v_w \approx 150 \text{ km s}^{-1}$ in the cool state, so that the wind density is $\sim 10$ times higher than in the hot state. The density contrast is higher if the faster wind sweeps the slower wind into a shell. The shell densities are higher than appear present in the Type cIIb events and are closer to the shell interaction observed in SN 2006jc (Foley et al. 2007). S Doradus stars with lower luminosities than AG Car, which are more likely progenitors of the objects discussed here, have even larger radii.

Kotak & Vink (2006) note that a WR progenitor is possible if the star becomes a WR star just before the supernova so it still interacted with mass loss from the LBV phase. However this would require the transition $< 25 \text{ yr}$ before the explosion. In addition, the fast WR wind would modify the close in circumstellar medium. Finally, the ejecta masses for SNe cIIb are not particularly large: estimates are 2.5–5 $M_\odot$ for SN 1996cb (Deng et al. 2001), $\sim 4 M_\odot$ for SN 2003bg (Mazzali et al. 2009), and $\sim 3.8 M_\odot$ for SN 2008ax (Tsvetkov et al. 2009). Unless a considerable amount of matter goes into a black hole central remnant, these masses are less than expected for the cores of LBV stars. Overall, the evidence points to progenitors for Type cIIb supernovae that are less massive and more compact than LBVs, and are more consistent with WR stars. Only a weak variation in wind properties is necessary to produce the observed radio variations. However, the possibility that the mechanism is similar to that producing S Doradus variations in LBVs cannot be ruled out.

3. DISCUSSION

One expectation of the two types of IIb is that the Type cIIb events should have a lower H mass envelope so that a large radial extent cannot be sustained. For SN 1993J, Woosley et al.
(1994) estimate a H mass of $0.2 \pm 0.05 \, M_\odot$. For SN 2003bg, Mazzali et al. (2009) estimate 0.05 $M_\odot$ of H, in keeping with expectations. However, Qiu et al. (1999) suggest that SN 1996cb has more H than SN 1993J, although Deng et al. (2001) estimate 0.1–0.2 $M_\odot$ of H if the explosion energy is $10^{51}$ erg. The implied dividing line between the types is $\sim 0.1 \, M_\odot$.

For lower amounts of H, we expect that the Type cIIb objects merge into the Type Ib’s. A recent example of a Type Ib with H is SN 2007Y which showed high velocity ($\sim 10,000 \, \text{km s}^{-1}$) H absorption near maximum light (Stritzinger et al. 2009). The finding of H in the spectra of Type Ib events is common, which raises expectations. However, Qiu et al. (1999) suggest that SN 1996cb has more H than SN 1993J, although Deng et al. (2001) estimate $\sim 1–0 \, M_\odot$. Branch et al. (2002) estimate that a H mass $\sim 0.1 \, M_\odot$ is typically needed to produce the required optical depth in Hα. There may not be a clear separation of the Type cIIb and Type Ib events, but a gradual transition depending on remaining H mass.

The Cas A supernova was recently shown to be of Type IIb by the spectrum of its light echo (Krause et al. 2008), which raises the question of whether the progenitor was compact or extended. Studies of the supernova remnant have not been conclusive; Chevalier & Oishi (2003) argued that the progenitor was extended with the dense wind extending to the stellar surface, but there have been arguments for a blue phase before the supernova (Hwang & Laming 2009). The Type IIb identification was made on the basis of the close correspondence of the echo spectrum with the time integrated spectrum of SN 1993J. The Hα line in the echo spectrum appears to be closer to the maximum light Hα in SN 1993J than in SN 2003bg (Hamuy et al. 2009), but a more detailed comparison with the time integrated spectrum of a Type cIIb event would be useful.

The existing observations that allow a distinction between Type cIIb and eIIb supernovae, primarily at radio wavelengths, indicate a clear separation between the two types of events, but the numbers are small. Future time domain surveys should increase the discovery rate of Type Ib events so that this issue can be resolved. In addition, the early discovery of supernovae ($\lesssim 2$ days from explosion) will allow the classification of the events from their shock breakout and cooling envelope emission.

We are grateful to the referee for a helpful report and acknowledge support from NSF grant AST-0807727 (RAC), a Hubble Fellowship (AMS), and Swift GI program 0NNX09AR05G.

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