RevMexAA (Serie de Conferencias), **30**, 41–48 (2007)

CIRCUMSTELLAR INTERACTION AROUND TYPE IB/C SUPERNOVAE AND THE GRB CONNECTION

R. A. Chevalier[1]

RESUMEN

Las observaciones en radio de supernovas tipo Ib/c sugieren que la interacción circunestelar tiene lugar dentro de un amplio rango de densidades de los vientos, comparables a las vistas en estrellas Wolf-Rayet galácticas. Se requiere una producción eficiente de campo magnético en la región chocada. La emisión de rayos X observada en las supernovas Tipo Ib/c es más alta de lo que se esperaría por el mecanismo térmico o Compton inverso; una interpretación sincrotrón requiere un aplanamiento del espectro de energía de los electrones en altas energías, como pudiera ocurrir en la onda de choque dominada por rayos cósmicos. Las variaciones en la densidad del viento que se indican en dos supernovas pueden ser debidas a una compañera binaria, aunque es posible la pérdida de masa variable por una sola estrella. Aparte de la radiación óptica de la supernova, la emisión proveniente de la cercana SN 2006aj/GRB 060218 parece estar producida por una máquina central, mientras que la SN 1998bw/GRB 980425 pudiera estar producida ya sea por una máquina central, o por el material eyectado de la supernova.

ABSTRACT

Radio observations of Type Ib/c supernovae suggest that circumstellar interaction takes place with a wide range of wind densities, comparable to that seen in Galactic Wolf-Rayet stars. Efficient production of magnetic field in the shocked region is needed. The X-ray emission observed from some Type Ib/c supernovae is higher than would be expected by the thermal or inverse Compton mechanisms; a synchrotron interpretation requires a flattening of the electron energy spectrum at high energies, as might occur in a cosmic ray dominated shock wave. The wind density variations that are indicated in two supernovae may be due to a binary companion, although variable mass loss from a single star remains a possibility. Other than the optical supernova radiation, the emission from the nearby SN 2006aj/GRB 060218 appears to be powered by a central engine, while that from SN 1998bw/GRB 980425 could be powered by either a central engine or the outer supernova ejecta.

Key Words: **GAMMA RAYS: BURSTS — STARS: MASS LOSS — SUPERNOVAE: GENERAL**

1. INTRODUCTION

Type I b/c supernovae (SNe Ib/c) have come to the fore of supernova research because of their association with gamma-ray bursts (GRBs) and the fact that they represent a significant mode of massive star death. They are thought to be the explosion of massive stars that have lost all, or nearly all, of their H envelopes; the SNe Ib have prominent He lines in their spectra and the SNe Ic do not. They explode as relatively compact Wolf-Rayet stars and thus have optical light curves that are dominated by power input from radioactivity.

Circumstellar interaction for these objects is of special interest because of the extensive mass loss that has occurred leading up to the supernova and because of GRB connection. Here, I describe some of the general aspects of the interaction (§ 2), discuss events of special interest (§ 3), consider the relation between SNe Ib/c and apparently low energy GRBs (§ 4), and summarize the issues (§ 5).

2. GENERAL ASPECTS OF CIRCUMSTELLAR EMISSION

The most extensive observations of circumstellar interaction are at radio wavelengths (Sramek et al. 2005). The general picture of the interaction is that in the initial stellar explosion, the shock wave accelerates through the outer part of the star leading to a steep power law density profile in the freely expanding ejecta. The maximum velocity that is achieved is partly determined by the radius of the progenitor star because the shock acceleration stops when the radiation is able to freely stream away at the time of shock breakout. A more compact star has greater shock acceleration because there is a larger ratio between the average stellar density and the density at the photosphere. Once the supernova shock has broken out of the star and a shock wave develops in the

[1]Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA (rac5x@virginia.edu).

surrounding wind, a shocked layer forms bounded by a reverse shock on the inside and a forward shock on the outside. The shock waves give rise to particle acceleration and radio synchrotron emission.

At early times, there is absorption of the radio emission by synchrotron self-absorption (SSA); additional processes, such as free-free absorption by unshocked wind gas ahead of the forward shock wave, may also play a role. In the case of SNe Ib/c, the circumstellar density is relatively low because of the high progenitor wind velocity and the shock velocity is high, which favors SSA as the dominant process (Chevalier 1998). Observations of radio light curves support the hypothesis that it is dominant in those cases where detailed observations are available (Soderberg et al. 2005, 2006). Figure 1 shows the positions of well observed radio supernovae in a plot of peak radio luminosity vs. time of the peak of the radio light curve. If the dominant absorption process is SSA, application of synchrotron theory allows the radius of the radio emitting region, and thus the velocity, to be found. There is the assumption of energy equipartition between the magnetic field and the relativistic electrons, but the results are insensitive to this assumption.

Figure 1 shows that the typical velocity of the SNe Ib/c near maximum radio luminosity is $\sim$ 30,000 km s^{-1}, which is systematically higher that the velocities present in SNe II. There are several reasons for this difference. First, there are higher initial velocities in the SNe Ib/c because of their more compact progenitors. The maximum velocity can be $\sim 100,000$ km s^{-1} for typical supernova parameters. In the case of SNe IIP (plateau light curve), with red supergiant progenitors, the maximum velocity may be $\sim 15,000$ km s^{-1}. Second, the Wolf-Rayet star progenitors of SNe Ib/c have winds with a high typical velocity, $\sim$ 1000 km s^{-1}, leading to a low circumstellar density. There is thus relatively less deceleration during the circumstellar interaction. Finally, the strong mass loss during the stellar evolution can lead to a relatively low mass at the time of the SN Ib/c explosion. The high energy-to-mass ratio leads to a higher mean velocity for the ejecta and thus to a high interaction velocity.

Figure 1 also shows that there is a large range in radio luminosities of the the SNe Ib/c. In the case of a radio light curve with SSA, there is not sufficient information to deduce the physical parameters for the interaction, but Chevalier & Fransson (2006) noted that the range in luminosity roughly corresponds to the range of circumstellar density inferred for Galactic Wolf-Rayet stars if the efficiency of pro-

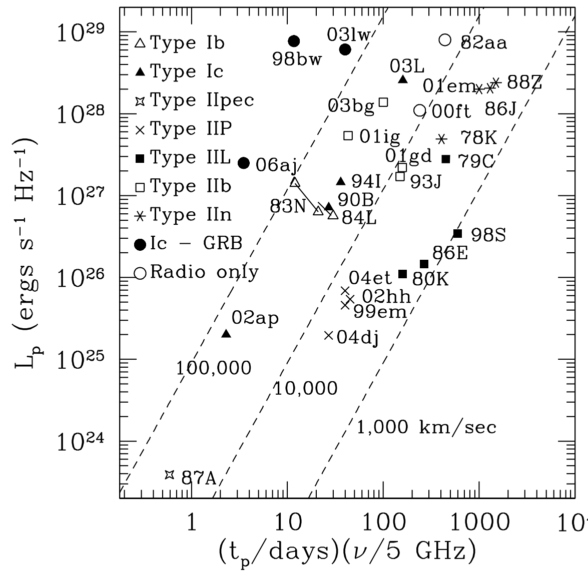

Fig. 1. Peak luminosity and corresponding epoch for the well-observed radio supernovae. The dashed lines give curves of constant expansion velocity, *assuming* synchrotron self-absorption at early times (updated version of Figure 4 in Chevalier 1998).

duction of magnetic fields and relativistic electrons is fairly high ($\epsilon_e \approx \epsilon_B \approx 0.1$). Here, the ϵ's are the ratios of energy densities in particles and fields to $\rho_0 v_s^2$, where ρ_0 and v_s are the preshock density and velocity of the forward shock wave. The magnetic field must be amplified in the interaction region and cannot just be the compressed wind field (Chevalier 1998). One possibility for amplification is the hydrodynamic instabilities that occur near the contact discontinuity (Jun & Norman 1996); however, it is not clear that this can achieve the required efficiency. Another possibility is that there are instabilities associated with efficient cosmic ray acceleration that can increase the magnetic field (Bell 2004). This mechanism has the property that it is more efficient at higher shock velocities, which would explain why the SNe Ib/c have more efficient production of synchrotron radiation than do Galactic supernova remnants.

X-ray emission has been detected from a number of SNe Ib/c, but there are not extensive light curves as there are for some at radio wavelengths. In general, the required emission cannot be thermal unless the circumstellar density is considerably higher than expected around a Wolf-Rayet star. Although this scenario cannot be completely ruled out, it is more plausible that the radiation mechanism is nonthermal. The possibilities are inverse Compton emission and synchrotron radiation. Inverse Compton emission involves the scattering of photospheric photons with the relativistic electrons in the interaction region and is thus most likely to be important near optical maximum light. The Type Ic SN 2002ap has an early observation from *XMM* that can be interpreted in terms of inverse Compton emission (Björnsson & Fransson 2004; Sutaria et al. 2003). However, in most cases the X-ray observations are at a time when the optical light is not strong and the inverse Compton mechanism is not viable. This is especially true for *Chandra* observations of SN 1994I at an age of $6-7$ yr (Immler et al. 2002). In most cases, the extension of the observed radio synchrotron spectrum to X-ray energies falls below the observed X-ray fluxes. Chevalier & Fransson (2006) suggested that the relativistic electron spectrum produced in a cosmic ray dominated shock could have a flattening at high energies (e.g., Ellison et al. 2000) that allows the observed X-ray fluxes to be reproduced in a synchrotron model. More detailed observations are needed to check on this hypothesis.

For the velocities and densities that are present in the circumstellar interaction of SNe Ib/c, radiative cooling is not important for the shocked gas so that there is no cool gas present that could give optical emission. There is the possibility that the X-ray emission irradiates the ejecta, giving rise to observable effects, but that has yet to be established.

3. MASS LOSS VARIATIONS

While the general properties of the radio supernovae are consistent with interaction with a surrounding wind, there are some cases where there is evidence for structure within the wind.

3.1. *SN 2001ig and SN 2003bg*

As can be seen in Figure 1, SN 2001ig (Ryder et al. 2004) and SN 2003bg (Soderberg et al. 2006) have radio properties and inferred velocities that are in line with those expected for SNe Ib/c. As noted above, the high velocities are typical for those the explosions of relatively compact, Wolf-Rayet stars. The optical light curve of SN 2003bg (Hamuy private comm.) was consistent with the explosion of a relatively compact star. However, both SN 2001ig and SN 2003bg showed H lines in their spectra (Ryder et al. 2004; Hamuy et al. 2003), although SN 2003bg was initially classified as a Type Ic supernova of the broad-lined type (Filippenko & Chornock 2003). The H lines observed in SN 2003bg were very broad. Apparently, the supernovae exploded as Wolf-Rayet stars with a small amount of H, an amount insufficient to produce an extended envelope ($\lesssim 0.02\ M_\odot$).

Ryder et al. (2004) classified SN 2001ig as a Type IIb supernova, which is the same as SN 1993J. However, SN 1993J exploded as a red supergiant, with $\sim 0.1-0.2\ M_\odot$ of H at the time of the explosion. Compared to the other 2 supernovae, SN 1993J showed lower expansion velocities of the radio emitting region (Figure 1) and the interaction with the dense red supergiant wind produced a radiative reverse shock wave with strong optical signatures. A preferred explanation for the mass loss from the SN 1993J progenitor was a close binary companion (e.g., Woosley et al. 1994), and a likely binary companion was eventually found (Maund et al. 2004). The binary separation is determined by the fact that the binary interaction must drive mass loss when the progenitor star is a red supergiant; in the models of Woosley et al. (1994), the final separation is $6.4-14.3$ a.u. or $(0.96-2.1)\times 10^{14}$ cm. The corresponding range of binary periods is $5-15$ yr.

SN 2001ig and SN 2003bg were similar to each other not only in their basic radio properties, but also in detailed properties of their radio light curves: both showed a flux increase at around the time they were turning optically thin and later showed a flat section of light curve (Ryder et al. 2004; Soderberg et al. 2006). In the context of the interaction of freely expanding supernova ejecta with a surrounding wind, it is not plausible that the light curve features are due to structure in the supernova ejecta. The largest effect would be approximately constant velocity of the interaction region produced by a steep density gradient, but this would produce little change in the radio light curve compared to the normal case of slow deceleration.

The most likely reason for the flux variations is thus density variations in the circumstellar medium. A previous model of this type was for the regular flux variations in the radio light curve of SN 1979C over a time of 10 yr (Weiler et al. 1992); the amplitude of the variations was $\sim 20\%$. Weiler et al. (1992) attributed the variations to stellar pulsations or, more likely, to a binary companion. The binary would create a spiral pattern in the slow wind; Schwarz & Pringle (1996) showed how a binary companion with a velocity comparable to the wind velocity would create structure within the slow wind by gravitational effects. If there is a continual spiral structure and the emitting region is optically thin, the effect on the radio light curve should be steady and regular features in the light curve would not be expected. Thus, the suggestion is that the binary orbit is eccentric so that there is asymmetric structure in the spiral pattern (Weiler et al. 1992; Schwarz & Pringle 1996). The required binary period is $t_{\rm b} \approx t_{\rm per} v_{\rm sn}/v_{\rm w}$, where $t_{\rm per}$ is the timescale for the periodic structure in the light curve, $v_{\rm sn}$ is the average velocity of the supernova shock, and $v_{\rm w}$ is the wind velocity of the progenitor star. In the case of SN 1979C, $t_{\rm per} = 1575$ d (Weiler et al. 1992), $v_{\rm sn} \approx 10{,}000$ km s^{-1}, and $v_{\rm w} \approx 10$ km s^{-1}, so that $t_{\rm b} \approx 4300$ yr.

In the case of SN 2001ig, Ryder et al. (2004) also appealed to a companion in an eccentric orbit to produce the density structure. Ryder et al. (2006) in fact found a supergiant star at the position of the supernova that can plausibly be identified as the progenitor companion. The fact that SN 2001ig and SN 2003bg require similar binary parameters initially seems surprising, but becomes more plausible considering that the binary may play a crucial role in producing the mass loss leading to the Type IIb supernovae, as in the case of SN 1993J. The binary period needed for the flux variations is $t_{\rm b} \approx 13$ yr, based on $t_{\rm per} = 160$ d, $v_{\rm sn} \approx 30{,}000$ km s^{-1}, and $v_{\rm w} \approx 1000$ km s^{-1}. The approximate agreement between this binary period and the binary period needed to produce a SN 1993J type system is a point in favor of the binary hypothesis. If the binary in SN 1993J caused structure in the wind, the effect on the radio light curve would have a rapid timescale (days) because of the slow red supergiant wind velocity. On this timescale, asymmetric structure and inhomogeneities would be likely to wash out radio flux variations; the radio light curves of SN 1993J are, in fact, smooth (Van Dyk et al. 2005).

In the models for SN 1993J (Woosley et al. 1994), the binary interaction leaves $\sim 0.1 - 0.2\ M_\odot$ of envelope material on the supernova progenitor so there is the question of how SN 2001ig and SN 2003bg ended up with considerably less. At the time of explosion, the SN 1993J progenitor is thought to have been losing $\sim (3-4) \times 10^{-5}\ M_\odot$ yr^{-1} (for a wind velocity of 10 km s^{-1}) (Fransson et al. 1996), so if up to 10^4 yr pass between the binary interaction and the supernova, there is the possibility of most of the remaining H envelope being lost.

A possible problem is that if the binary goes through a phase where the binary separation is comparable to the stellar radius (of the red supergiant), the binary orbit should be circularized by tidal effects, giving rise to the question of how the asymmetric structure is created for the radio variations. A possibility is that, at early times, the interaction with only the spiral pattern in front of the supernova can be observed, because the radio emission from the back side is free-free absorbed by the supernova ejecta. In this case, the flux variations should become less marked with time as optical depth effects become less important. In fact, for both SN 2001ig and SN 2003bg the initial flux increase at ~ 160 d is approximately a factor of 2, whereas the next feature is simply a flattening of the light curve. These properties can be contrasted with the roughly steady undulations in the radio light curve of SN 1979C (Weiler et al. 1992).

Another issue is the physical mechanism for the regular density structure. In the scenario of gravitational effects discussed by Schwarz & Pringle (1996), the gravitational radius ($2GM_{\rm com}/v_{\rm w}^2$ where $M_{\rm com}$ is the companion star mass) is large because $v_{\rm w} =$ 10 km s^{-1}. When $v_{\rm w} = 1000$ km s^{-1}, as is the case here, the gravitational radius is much smaller and only a small fraction of the progenitor wind is affected by the companion star. Ryder et al. (2004) note that spiral dust patterns have been observed around some Wolf-Rayet stars as a result of binary interaction (e.g., Tuthill et al. 1999, 2006) and suggest that such a structure results in the radio light curve variations. The initial cases of this phenomenon that were discovered had a binary period < 1 yr, but Tuthill et al. (2006) find evidence for periods up to ~ 2.5 yr. However, this spiral structure is the likely result of wind-wind interaction and the companion star must be an O or early B star to have a strong enough wind to produce structure in the Wolf-Rayet wind. In the case of SN 2001ig, the apparent companion star is a late B through early F supergiant (Ryder et al. 2006) and it is questionable whether it has a sufficiently strong wind to produce the needed structure.

There is thus some degree of uncertainty in the binary hypothesis and single star possibilities should also be considered. Kotak & Vink (2006) suggested that the progenitor is an S Doradus star, which is related to the luminous blue variables (LBVs). The lower wind velocity in this case, $100 - 500$ km s^{-1}, would give a longer timescale for the structure in the wind, $26 - 100$ yr. Kotak & Vink (2006) suggest that this timescale is compatible with that observed during a "long-S Doradus" phase.

The two possibilities of S Dor or Wolf-Rayet star present progenitors with different properties. The properties of S Dor stars discussed by van Genderen (2001) indicate a radius range of $3 \times 10^{12} - 2 \times 10^{13}$ cm, much larger than a Wolf-Rayet star. Also, to have the requisite mass loss from a single star would require an initial mass $\gtrsim 30\ M_\odot$, whereas a lower mass is possible if there is mass loss driven by binary interaction. As mentioned above, the high expansion velocity indicated by the radio emission (Figure 1) implies a fairly compact progenitor, although some part of the S Dor range may be permitted. A better way to distinguish between the possibilities would be to compare information on the light curves and spectra of the supernovae with models for the explosions. This has yet to be carried out.

3.2. *SN 2001em*

SN 2001em was initially discovered as a Type Ib or Ic supernova, with Ic considered more likely (Filippenko & Chornock 2001). It was detected as a luminous radio source at an age of 767 days (Stockdale et al. 2004), which led to a detection of X-ray emission (Pooley & Lewin 2004) and the finding of a relatively narrow Hα line (Soderberg et al. 2004). The radio luminosity for the age is shown in Figure 1, which shows that its luminosity is comparable to those of the most luminous Type IIn supernovae at a comparable age. This supernova designation is also indicated by Hα line. The implication is that the supernova was transformed from a Type Ib/c, with relatively little circumstellar interaction, to a Type IIn, with strong interaction.

The large radiated luminosity implies that a significant fraction of the supernova energy (assuming it to be $\sim 10^{51}$ ergs) was thermalized, so that the supernova ejecta must interact with a surrounding mass that is comparable to the ejecta mass. The timescale for the interaction, coupled with the mean supernova velocity, suggests a radial scale $\sim 10^{17}$ cm (Chugai & Chevalier 2006). The presupernova mass loss timescale is then $\sim 3000(v_{\rm w}/10 \text{ km s}^{-1})^{-1}$ yr and the corresponding mass loss rate is $\sim 10^{-3}(v_{\rm w}/10 \text{ km s}^{-1})\ M_\odot \text{ yr}^{-1}$. Such a high rate of mass loss is unusual. One possible Galactic example is the eruptive phases of LBVs (Smith 2006).

4. THE CONNECTION TO LOW LUMINOSITY GRBS

Three Type Ic supernovae have been found in association with apparently low luminosity GRBs: SN 1998bw with GRB 980425 (Galama et al. 1998), SN 2003lw with GRB 031203 (Malesani et al. 2004), and SN 2006aj with GRB 060218 (Campana et al. 2006). The relative proximity of these events provides an excellent opportunity to examine the relationship between supernovae and GRBs. In all of these cases, the optical emission after about a day was dominated by the light from the supernova. SN 2006aj was also observed at very early times (Campana et al. 2006), when the issue is not clear; Campana et al. (2006) interpreted the early optical emission as shock breakout emission from the supernova. All 3 events were observed as radio and X-ray sources. It can be seen in Figure 1 that the 3 objects have radio properties that imply rapid (approximately relativistic) expansion of the radio emitting region. An important question is whether the emission can be attributed to supernova expansion and shock waves, as in the case of normal SNe Ib/c, or to the activity of a central engine, as is needed for a GRB.

4.1. *SN 1998bw and GRB 980425*

An especially good data set is the radio data set on SN 1998bw (Kulkarni et al. 1998). Li & Chevalier (1999) modeled the radio light curves and claimed that the emission was most likely related to a central engine and not to the outer supernova ejecta. There were several reasons for the claim: (i) there is insufficient energy at high velocity in the supernova to produce the radio emission; (ii) the flux rise observed around days $20-35$ requires the action of the central engine; and (iii) outside of the time of flux increase the evolution is consistent with a constant energy explosion, which is typical of GRB afterglows.

On (i), it is clear from § 2 that a supernova would not be able to produce the emission if the energy were comparable to that of a normal supernova ($\sim 10^{51}$ ergs). In this case, the shock acceleration would not attain sufficiently high velocities at the outer edge of the star to explain the radio emission (Li & Chevalier 1999). However, there have been estimates that the energy in SN 1998bw was as high as 5×10^{52} ergs in models that fit the early evolution (Nakamura et al. 2001). With the high energy, the breakout velocities can become relativistic and the density at a particular velocity in the outer steep part of the density profile is $\propto E^{3.59}$ (Chevalier & Fransson 2006). Tan et al. (2001) have carried out detailed calculations of the transrelativistic expansion expected for a high energy explosion, finding that the energetics required by the radio emission can be satisfied. Thus, the reason for the appearance of supernovae in the high velocity part of Figure 1 could be an usually high supernova energy.

The argument for the flux increase being due to a central engine as opposed to a circumstellar density feature was the behavior of the flux in the optically thick regime. However, that argument cannot be considered to be conclusive; the flux rise has a similar appearance to those seen in SN 2001ig and SN 2003bg. In the case of SN 1998bw, the shock radius when the flux rise occurs is $\sim (1-1.5)\times10^{17}$ cm (Li & Chevalier 1999). The inferred radius is

$2-3$ times larger than in the case of the other supernovae; this could simply reflect the time when the effect of the density structure was most noticeable. A difference in the objects is that SN 2001ig and SN 2003bg showed H lines in their spectra, whereas models for SN 1998bw indicate the explosion of the bare C/O core of a massive star (e.g., Nakamura et al. 2001). However, there have been suggestions that SN 1998bw-like explosions could contain some H (Branch et al. 2006).

The final argument involves the rate of decline of the radio emission, outside of the flux increase episode. Li & Chevalier (1999) took the relatively rapid decline to be indicative of a constant energy explosion, which is the typical assumption for GRB afterglows. However, assumptions about the evolution of the efficiency of magnetic field and relativistic electron production play a role in this interpretation, so the case is uncertain. Overall, there is not compelling evidence for either the central engine or supernova origin of the radio emission.

Over days $10-200$ (including the time of the flux increase), the optically thin radio flux from SN 1998bw declined by a factor of ~ 50, while the X-ray evolution was essentially flat (Pian et al. 2000; Kouveliotou et al. 2004). Waxman (2004) modeled the early X-ray emission as synchrotron emission from a shocked region driven by a supernova mass shell moving at constant velocity ($0.8c$); the shell mass was $\sim 1\times10^{29}$ gm. Waxman did not discuss the origin of the shell, but a shell can be formed at the time of supernova shock breakout because of the escape of the radiative energy. The shell mass is $M_{\rm s}=4\pi R^2\Delta R\rho=4\pi R^2\tau/\kappa$, where R is the radius at shock breakout, ΔR is the thickness of the region that collapses, ρ is the density, $\tau\approx c/3v$ is the optical depth at which radiation begins to leak out, v is the shock velocity, and κ is the opacity (Chevalier 1981). Allowing for shock breakout in an optically thick wind at $R=2\times10^{12}$ cm and opacity due to electron scattering, the shell mass is still orders of magnitude smaller than that needed for SN 1998bw. The implication is that the wind interaction is with the outer steep power law part of the supernova density distribution. The interaction shell produced in this way decelerates slowly, so there is not a large change from the constant velocity case; however, the steepening of the X-ray light curve at $100-200$ day, attributed by Waxman (2004) to the deceleration of the mass shell, is not produced in a natural way. However, the evidence for a break depends on just one X-ray point, that at day 200.

In the model of Waxman (2004), the radio and X-ray emission are both synchrotron emission from the interaction shell. Because the cooling frequency, $\nu_{\rm c}$, is between radio and X-ray wavelengths, the radio flux evolves as $t^{-1/2}$ while the X-ray evolution is flat. The observed radio decline is steeper than this. In addition, Waxman (2004) assumes a relativistic electron energy spectral index $p=2$, whereas the radio observations imply that $p=2.5$ (Kulkarni et al. 1998; Li & Chevalier 1999). An extrapolation of the radio spectrum on day 100 falls below the observed X-ray flux, even when the steepening of the spectrum due to synchrotron cooling is not taken into account. If the radio and X-ray emission are from the same region, there must be flattening of the particle spectrum toward high energies. Chevalier & Fransson (2006) discussed how this could be important for ordinary SNe Ib/c; the mechanism for the flattening was particle acceleration in a cosmic ray dominated shock. The mechanism needs to be examined for the case of a higher shock velocity, as is present in SN 1998bw.

4.2. *SN 2006aj and GRB 060218*

Figure 1 shows that the 3 SNe Ic associated with GRBs have radio properties implying unusually high velocities. In the case of SN 1998bw, the general radio properties could be attributed to a high energy explosion or to a central engine. However, SN 2006aj was observed to have optical properties similar to SN 2002ap, which was not very energetic. From modeling the light curve and spectra of SN 2006aj, Mazzali et al. (2006) estimate an energy of $E\sim2\times10^{51}$ ergs and an ejecta mass of $M_{\rm e}\sim2\ M_\odot$; these values can be compared to 4×10^{51} ergs and $3\ M_\odot$ deduced for SN 2002ap (Tomita et al. 2006), which seems to have had little high velocity ejecta (Berger et al. 2002). On the basis of the radio emission from SN 2006aj, Soderberg et al. (2006) deduced a minimum energy of $(1-2)\times10^{48}$ ergs in ejecta with a Lorentz factor of 2.3 (velocity of $270,000$ km s^{-1}). For the above values of E and $M_{\rm e}$ and the density profile for a SN Ib/c given in Berger et al. (2002), the energy above a velocity of $200,000$ km s^{-1} is $\sim10^{46}$ ergs. The implication is that the radio emission is related to the central engine that also produced the GRB.

Taking $F_\nu\propto\nu^\beta t^\alpha$ gives $\alpha=-0.8$ and $\beta=-0.55$ for the radio emission from SN 2006aj (Soderberg et al. 2006). Except for SN 2002ap, the normal SNe Ib/c have $\alpha=-(1.2-2)$, with an average of -1.5; the typical value of β is -1 (Chevalier & Fransson 2006). SN 2002ap, which is the normal SN Ib/c with the highest velocities has $\alpha=-0.8$, although this may be due to the importance of inverse Compton losses for the radiating particles (Björnsson & Fransson 2004). In the case of SN 2006aj, estimates of inverse Compton effects indicate that they are not important, which is supported by the relatively flat spectral index. In fitting a standard GRB afterglow model to the radio emission from SN 2006aj, Soderberg et al. (2006) found that the best model was expansion into a constant density medium with $n = 5$ cm^{-3}. This result, which is typical of GRB afterglow models, is at odds with the expected wind medium expected around a Wolf-Rayet star and with the medium deduced for normal SNe Ib/c.

The X-ray emission from SN 2006aj, with a steep spectrum $\beta = -2$, cannot be considered an extension of the radio synchrotron emission in any straightforward way (Soderberg et al. 2006). The steep spectrum, together with the moderate rate of decline ($\alpha = -1$), is suggestive of continued power input, and Soderberg et al. (2006) suggest that the power is provided by a central magnetar.

An additional component in SN 2006aj/GRB 060218 is an early thermal X-ray component, which Campana et al. (2006) interpreted as the shock breakout emission from the supernova. However, the radiated energy in this component, $\gtrsim 10^{49}$ ergs (Campana et al. 2006; Li 2006), is greater than that produced in a plausible Wolf-Rayet explosion model by a factor $\gtrsim 100$ (Li 2006). In addition, the duration of the thermal component, ~ 2700 s, is larger than can be accomodated in a Wolf-Rayet explosion model, even allowing for an emitting region out in an optically thick progenitor wind (Campana et al. 2006; Li 2006). The implication is that the thermal component is formed by a flow from a central engine, as well as the nonthermal emission.

5. DISCUSSION

The radio emission from normal SNe Ib/c is consistent with synchrotron radiation produced by the outer supernova ejecta interacting with the wind from the progenitor star. Early absorption is generally due to synchrotron self-absorption. Consistency with the wind densities expected around Wolf-Rayet stars requires a high efficiency of production of relativistic electrons and magnetic fields. Hydrodynamic instabilities in the decelerating interaction region may not be sufficient to produce the magnetic field and shock wave instabilities might play a role. The X-ray emission from SNe Ib/c requires a nonthermal mechanism if the surrounding densities are typical of the winds from Wolf-Rayet stars. A synchrotron origin for late X-ray emission requires a flattening of the particle spectrum to high energies, as might occur as a result of particle acceleration in a cosmic ray dominated shock wave.

Beyond the standard wind interaction model, there are deviations from the expected smooth radio evolution in some SNe Ib/c. In SN 2001ig and SN 2003bg, there are density variations that might be produced by a binary companion that is also responsible for loss of the H envelope of the progenitor star. A more dramatic radio (and X-ray) brightening occurred in SN 2001em, indicating that the exploding star was interacting with a substantial part of the lost H envelope. Such extreme mass loss is rare for Galactic stars; one example is perhaps the eruptive phase of luminous blue variables.

There is good evidence that long duration GRBs are associated with SNe Ib/c, but it has not been possible to relate the interaction properties to the circumstellar environment of Wolf-Rayet stars, as in the case of normal SNe Ib/c. Even for the nearby, low luminosity GRBs associated with well-studied supernovae, the type of circumstellar interaction is unclear. In the case of SN 1998bw/GRB 980425, there is uncertainty whether the radio and X-ray emission is powered by the outer supernova ejecta or by an inner engine as in GRBs. In the case of SN 2006aj/GRB 060218, except for the optical supernova emission the properties are most likely due to a relativistic flow from a central engine.

I am grateful to Nikolai Chugai, Claes Fransson, Zhi-Yun Li, and Alicia Soderberg for their collaboration on various aspects of this research. The research was supported in part by NASA grant NNG06GJ33G and NSF grant AST-0307366.

REFERENCES

Bell, A. R. 2004, MNRAS, 353, 550
Berger, E., Kulkarni, S. R., & Chevalier, R. A. 2002, ApJ, 577, L5
Björnsson, C.-I., & Fransson, C. 2004, ApJ, 605, 823
Branch, D., Jeffery, D. J., Young, T. R., & Baron, E. 2006, PASP, 118, 791
Campana, S., et al. 2006, Nature, 442, 1008
Chevalier, R. A. 1981, Fundam. Cosmic Phys., 7, 1
__________. 1998, ApJ, 499, 810
Chevalier, R. A., & Fransson, C. 2006, ApJ, 651, 381
Chugai, N. N., & Chevalier, R. A. 2006, ApJ, 641, 1051
Ellison, D. C., Berezhko, E. G., & Baring, M. G. 2000, ApJ, 540, 292
Filippenko, A. V., & Chornock, R. 2001, IAU Circ., 7737, 3
Filippenko, A. V., & Chornock, R. 2003, IAU Circ., 8084, 2

Fransson, C., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 461, 993
Galama, T. J., et al. 1998, Nature, 395, 670
Hamuy, M., Phillips, M., & Thomas-Osip, J. 2003, IAU Circ., 8088, 3
Immler, S., Wilson, A. S., & Terashima, Y. 2002, ApJ, 573, L27
Jun, B.-I., & Norman, M. L. 1996, ApJ, 465, 800
Kotak, R., & Vink, J. S. 2006, A&A, 460, L5
Kouveliotou, C., et al. 2004, ApJ, 608, 872
Kulkarni, S. R., et al. 1998, Nature, 395, 663
Li, L.-X. 2007, MNRAS, 375, 240
Li, Z.-Y., & Chevalier, R. A. 1999, ApJ, 526, 716
Malesani, D., et al. 2004, ApJ, 609, L5
Maund, J. R., Smartt, S. J., Kudritzki, R. P., Podsiadlowski, P., & Gilmore, G. F. 2004, Nature, 427, 129
Mazzali, P. A., et al. 2006, Nature, 442, 1018
Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001, ApJ, 550, 991
Pian, E., et al. 2000, ApJ, 536, 778
Pooley, D., & Lewin, W. H. G. 2004, IAU Circ., 8323, 2
Ryder, S. D., Murrowood, C. E., & Stathakis, R. A. 2006, MNRAS, 369, L32
Ryder, S. D., Sadler, E. M., Subrahmanyan, R., Weiler, K. W., Panagia, N., & Stockdale, C. 2004, MNRAS, 349, 1093
Schwarz, D. H., & Pringle, J. E. 1996, MNRAS, 282, 1018
Smith, N. 2006, in Mass Loss from Massive Stars and Stellar Clusters, in press (astro-ph/0609422)
Soderberg, A. M., Chevalier, R. A., Kulkarni, S. R., & Frail, D. A. 2006, ApJ, 651, 1005
Soderberg, A. M., Gal-Yam, A., & Kulkarni, S. R. 2004, GCN Circ. 2586, http://gcn.gsfc.nasa.gov/gcn/gcn3/2586.gcn3
Soderberg, A. M., Kulkarni, S. R., Berger, E., Chevalier, R. A., Frail, D. A., Fox, D. B., & Walker, R. C. 2005, ApJ, 621, 908
Sramek, R. A., Weiler, K. W., & Panagia, N. 2005, in IAU Coll. 192, Cosmic Explosions, ed. J. M. Marcaide & K. W. Weiler (Berlin: Springer), 137
Stockdale, C. J., Van Dyk, S. D., Sramek, R. A., Weiler, K. W., Panagia, N., Rupen, M. P., & Paczynski, B. 2004, IAU Circ., 8282, 2
Sutaria, F. K., Chandra, P., Bhatnagar, S., & Ray, A. 2003, A&A, 397, 1011
Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, ApJ, 551, 946
Tomita, H., et al. 2006, ApJ, 644, 400
Tuthill, P. G., Monnier, J. D., & Danchi, W. C. 1999, Nature, 398, 487
Tuthill, P., Monnier, J., Tanner, A., Figer, D., Ghez, A., & Danchik, W. 2006, Science, 313, 935
van Dyk, S. D., et al. 2005, in IAU Coll. 192, Cosmic Explosions, ed. J. M. Marcaide & K. W. Weiler (Berlin: Springer), 3
van Genderen, A. M. 2001, A&A, 366, 508
Waxman, E. 2004, ApJ, 605, L97
Weiler, K. W., van Dyk, S. D., Pringle, J. E., & Panagia, N. 1992, ApJ, 399, 672
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300