SHOCK BREAKOUT IN DENSE MASS LOSS: LUMINOUS SUPERNOVAE

ROGER A. CHEVALIER AND CHRISTOPHER M. IRWIN
Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904-4325, USA; rac5x@virginia.edu
Received 2010 December 27; accepted 2011 January 22; published 2011 February 8

ABSTRACT

We examine the case where a circumstellar medium around a supernova is sufficiently opaque that a radiation-dominated shock propagates in the circumstellar region. The initial propagation of the shock front into the circumstellar region can be approximated by a self-similar solution that determines the radiative energy in a shocked shell; the eventual escape of this energy gives the maximum luminosity of the supernova. If the circumstellar density is described by \( \rho = D r^{-2} \) out to a radius \( R_w \), where \( D \) is a constant, the properties of the shock breakout radiation depend on \( R_w \) and \( R_d \equiv \kappa D v_{sh}/c \), where \( \kappa \) is the opacity and \( v_{sh} \) is the shock velocity. If \( R_w > R_d \), the rise to maximum light begins at \(~R_w/v_{sh}\); the duration of the rise is also \(~R_d/v_{sh}\); the outer parts of the opaque medium are extended at low velocity at the time of peak luminosity; and a dense shell forms whose continued interaction with the dense mass loss gives a characteristic flatter portion of the declining light curve. If \( R_w < R_d \), the rise to maximum light begins at \(~R_w/v_{sh}\); the duration of the rise is \(~R^2_w/v_{sh} R_d\); the outer parts of the opaque medium are not extended and are accelerated to high velocity by radiation pressure at the time of maximum luminosity; and a dense shell forms but does not affect the light curve near maximum. We argue that SN 2006gy is an example of the first kind of event, while SN 2010gx and related supernovae are examples of the second.

Key words: circumstellar matter – shock waves – supernovae: general – supernovae: individual (SN 2006gy)

1. INTRODUCTION

Supernova shock breakouts from normal massive stars typically give rise to X-ray/ultraviolet bursts with a timescale \( \lesssim 10^3 \) s (Klein & Chevalier 1978; Falk 1978; Enssman & Burrows 1992; Matzner & McKee 1999; Nakar & Sari 2010). The timescale is generally determined by \( R_\infty /c \), where \( R_\infty \) is the stellar radius, because the radiative diffusion time at breakout is less than the light travel time across the star. The largest red supergiants have a radius of \(~10^{14} \) cm (Levesque et al. 2005) so that the longest time of the breakout event is about 1 hr. The short timescale of the bursts makes it difficult to detect them, other than with a wide-field X-ray telescope. The breakout detection of SN 2008D with Swift (Soderberg et al. 2008) was fortunate.

The situation changes if there is dense mass loss prior to the supernova that creates an optically thick region. Calculations of this case go back to early computer simulations of supernova light curves. Model 5 of Grassberg et al. (1971) and Model B of Falk & Arnett (1977) include a dense circumstellar shell with radius \(~10^{15} \) cm that determines the properties of the shock breakout. The peak luminosity occurs on a timescale of \(~15 \) days in the model of Grassberg et al. (1971). Grasberg & Nadyozhin (1987) considered a steady wind of limited duration just before the supernova. Chugai et al. (2004) calculated a model for SN 1994W which allows for dense mass loss around the supernova, leading to a peak luminosity at an age of \(~20 \) days. A systematic numerical study of such events has recently been carried out by Moriya et al. (2010). Because of the high surrounding density, the supernova can be especially bright and this type of model has been invoked for luminous supernovae. In addition to SN 1994W (Chugai et al. 2004), the application of the dense mass-loss model has been made to SN 2006gy (Smith & McCray 2007), PTF 09uj (Ofek et al. 2010), and SN 2009kf (Moriya et al. 2010) among others.

The aim here is to give an analytical description of the shock breakout process for the case where a radiation-dominated shock propagates into the mass-loss region. Progress on this front has been made by Ofek et al. (2010). The model is presented in Section 2 and compared to observations in Section 3.

2. INTERACTION WITH DENSE MASS LOSS

We assume that the dense mass loss can be described by a steady wind acting for some time \( t_{ml} \) before the supernova explosion; the extent is \( R_w = v_w t_{ml} \), where \( v_w \) is the wind velocity. The actual case may be more complex, but is not well determined; the wind assumption has been made in other work (Grasberg & Nadyozhin 1987; Ofek et al. 2010; Moriya et al. 2010). If the mass loss is in a steady wind, the density \( \rho_w = M/4\pi r^2 v_w \equiv Dr^{-2} \) can be specified by a density parameter, \( D_w \), scaled to a \( M = 10^{-2} M_\odot \) yr\(^{-1} \) and \( v_w = 10 \) km s\(^{-1} \) so that \( \rho_w = 5.0 \times 10^{16} D_{10} r^{-2} \) in cgs units. For typical supernova parameters, the explosion drives a radiation-dominated shock through the star. A radiation-dominated shock in a uniform medium has a characteristic thickness described by an optical depth \( \tau_{sh} \approx c/v_{sh} \), where \( v_{sh} \) is the shock velocity (Weaver 1976). If the wind optical depth \( \tau_w < c/v_{sh} \), then a radiation-dominated shock does not form in the wind and the radiation diffuses out through an optically thick wind (e.g., Nakar & Sari 2010). In the case that \( \tau_w > c/v_{sh} \), the radiation-dominated shock front propagates into the mass-loss region. This is the case considered here.

After the shock wave passes through the star and the supernova ejecta tend toward free expansion, a shocked layer develops in the wind that is bounded by forward and reverse shock waves at \( R_{fs} \) and \( R_{rs} \), respectively. The shock waves are initially energy conserving. Once the forward shock front reaches a place where the diffusion time equals the expansion time or, equivalently, \( \tau_w \approx c/v_{sh} \), radiation diffusion becomes important. We have \( \tau_w = (R_{fs}^{-1} - R_{rs}^{-1}) \kappa D \), so the diffusion condition can be written as \( R_{fs}^{-1} \approx R_{rs}^{-1} - R_w^{-1} \), where \( R_d \equiv \kappa D v_{sh}/c = 5.7 \times 10^{14} v_{sh} k D \) cm, where \( v_{sh} \) is the shock velocity in units of \( 10^4 \) km s\(^{-1} \) and \( k \) is the opacity \( \kappa \) in units of 0.34 cm\(^2\) g\(^{-1}\). Two cases are of interest: \( R_w > R_d \) so that...
$R_{\text{sh}} \approx R_d$ when diffusion becomes important and $R_w < R_d$ so that $R_{\text{sh}} \approx R_w$ at that time.

In the wind, for diffusion over a distance $\Delta R$, the diffusion time is $t_d = \Delta R^2 / c_x = \kappa \rho_w \Delta R^2 / c$. Taking $\Delta R \approx R$ and noting $\rho_w = D r^{-2}$, we have $t_d = \kappa D / c$, independent of radius (see also Ofek et al. 2010). If the extent of the optically thick region (to $R_{\text{ph}} = \min(R_w, \kappa D)$) is not much beyond $R_d$, then $\kappa D / c$ provides an estimate of the diffusion time for the radiation to escape. The time is longer if $R_{\text{ph}} > R_d$. If the diffusion is assumed to proceed in steps with size $\Delta r \ll R$, we can increase by a term that is logarithmic in $\Delta r$.\)

The interaction between this power-law density distribution and a surrounding wind, with a finite density gives a radiation temperature $T_{\text{rad}} = 6.4 \times 10^4 k^{0.25} T_{d,0.25}^{-0.25} = 7.1 \times 10^4 k^{-0.5} D_{*}^{-0.25} \text{ K}$, (7)

where we have used $R_{sh}/R_{cd} = 1.208$ and $R_{sh}/R_{cd} = 0.978$ (Chevalier 1983), and $t_{d,1}$ is in units of 10 days. Another estimate of $T_{\text{rad}}$ can be obtained from the forward shock condition on the pressure: $a T_{\text{sh}}^3 / 3 = (6/7) \rho_w v_{sh}^2$ for a $a = 4 / 3$ gas, where $a$ is the radiation constant (see also Ofek et al. 2010). In this case, the temperature coefficient in Equation (7) is 7% higher; the difference is due to the fact that there is a drop in the pressure behind the forward shock front in the shocked region. The results assume a smooth wind with an $r^{-2}$ density profile, but the temperature of the breakout shell is not strongly dependent on this assumption. More generally, if $\Delta R$ is the size of the breakout region, the optical depth through the region is $\rho w \Delta R \approx c / v_{sh}$ and the shock crosses the shell in the diffusion time, or $\Delta R \approx v_{sh} t_d$. The resulting density $\rho_w = c / (\kappa v_{sh}^2 t_d)$, when combined with the shock jump condition for the radiation pressure, gives a temperature comparable to that in Equation (7).

These results can be compared to the numerical results of Moriya et al. (2010). Taking their model s13w2r20m2e3 with $E_{51} = 3$, $M_{\text{ej}} = 1.3$, and $D_s = 1$, the breakout radius in our model is $R_d = 5.9 \times 10^{14}$ cm, which is inside the outer radius of $2 \times 10^{15}$ cm in the numerical model. Substituting the parameters into Equation (5), the radiated energy is $E_{\text{rad}} = 1.4 \times 10^{50}$ erg, which is close to the $2.0 \times 10^{50}$ erg found in the numerical model (Moriya et al. 2010). The numerical result may be larger, in part, because the shock wave generates power in the more extended circumstellar medium. We also examined the scaling of $E_{\text{rad}}$ with the parameters and found reasonable agreement with the numerical results. The scaling depends on the supernova density gradient, which is only approximately treated here.

Estimates of the observable color temperature of the radiation require considerations of whether radiation equilibrium is attained in the emitting region. Following Nakar & Sari (2010), we define a thermal coupling coefficient $\eta = n_{\text{BB}} / (n_{\text{ph}} (T_{\text{BB}}))$, where $n_{\text{BB}} \approx a T_{\text{BB}}^4 / 3 k_B T_{\text{BB}}$ is the photon number density in thermal equilibrium, $k_B$ is Boltzmann’s constant, and $n_{\text{ph}} (T_{\text{BB}}) = 3.5 \times 10^{30} \rho_w T_{\text{BB}}^{-1/2} s^{-1}$ cm$^{-3}$ is the production rate of photons by the free–free process. If sufficient photons are produced to maintain the blackbody number density, or $\eta \lesssim 1$, thermal equilibrium is achieved. Using Equations (1) and (7) for $t_d$ and $T_{\text{BB}}$, and $\rho = 7 \rho_w (R_{\text{sh}})$ (taking into account the factor 7 compression in the shock wave), we estimate $\eta$ for the breakout shell:

$$\eta_0 \approx 0.4 k^{0.45} E_{51}^{1.6} M_{\text{ej}}^{-0.8} D_{*}^{-1.48}.$$ (8)

For the standard parameters, the breakout shell is marginally in thermal equilibrium. As the radiation propagates into the unshocked mass-loss region, the lower density results in a deviation from thermal equilibrium. The frequency dependence of the opacity can play a role (Moriya et al. 2010) and we do not treat the details of spectrum production here.

The loss of radiative energy from the shocked region results in the formation of a dense shell at radius $R$, as seen in numerical simulations (Grassberg et al. 1971; Falk & Arnett 1977). The expansion of the shell into additional mass loss produces continuing power for the supernova, $L = 2 \pi R^2 \rho_w (v_{\text{sh}} - v_w)^2$, where the wind velocity $v_w$ may be affected by preshock radiative acceleration. The simulations of Moriya et al. (2010)
show some evidence for acceleration, but it is only significant near the breakout radius because of the $r^{-2}$ dependence of the radiative flux, and we neglect it here. The expansion of $R$ can be described by the thin shell approximation (Chevalier 1982), yielding $R = 0.94R_{cd}$. The resulting power is

$$L = 7.1 \times 10^{43} E_{51}^{1.2} M_{e1}^{-0.6} D_{*}^{0.4} t_{1}^{-0.6} \text{ erg s}^{-1}. \quad (9)$$

The magnitude of the luminosity is similar to that produced by the initial breakout radiation, as is seen in numerical simulations (Grasberg & Nadyozhin 1987; Moriya et al. 2010). The luminosity lasts until the shock wave at $R$ reaches the edge of the dense wind, $R_{w}$, at $t_{w} = 1.1 E_{51}^{-0.5} M_{e1}^{0.25} D_{*}^{0.25} R_{w}^{1.25} 15 \text{ yr}$, where $R_{w,16}$ is in units of $10^{16} \text{ cm}$. Figure 1(a) illustrates the luminosity evolution with the late flattening from the shell interaction.

In the case of shock breakout from a red supergiant, the shock front takes ~1 day to traverse the star and the time for shock breakout is $\sim 10^3 \text{ s}$ (Klein & Chevalier 1978). The shock breakout timescale is much less than the time since explosion. In the dense mass-loss case considered here, the time for the shock front to move to the breakout region is $\sim R_{d}/v_{sh}$, which is also the timescale for the breakout event. This property of the luminosity evolution can be seen in simulations of such events (Grassberg et al. 1971; Falk & Arnett 1977; Chugai et al. 2004; Moriya et al. 2010). The rise to maximum light can have complications due to variations in the gas opacity. At the high circumstellar densities considered here, it is likely that the gas is initially neutral and that most of the opacity is due to dust in the presupernova environment. The radiation-dominated shock wave from the supernova has a precursor in the mass-loss region that is expected to heat the circumstellar dust. As the temperature rises through 1000–2000 K, the dust evaporates, giving a decrease in the opacity and the photospheric radius drops to where there is a sharp gradient in the opacity as the gas becomes ionized.

In Type IIP supernovae, this property of the opacity causes a recombination wave to back into the expanding envelope with a constant photospheric temperature $T \sim 5000–6000 \text{ K}$. Here, the process is inverted and the photosphere is expected to follow the ionization wave moving out through the dense circumstellar gas. This phase of approximately constant temperature can be seen in simulations (Grassberg et al. 1971). Once the circumstellar mass is ionized, the photospheric expansion slows and the temperature rises. The light curve rises fairly sharply due to the temperature rise until the maximum temperature, and luminosity, is reached.

We now consider the case that $R_{w} < R_{d}$. The shock breakout process begins at $t_{b} \approx R_{w}/v_{sh}$. The rise time for the light curve is $t_{r} \approx \delta R/v_{sh}$, where $\delta R$ is the distance in from $R_{w}$, across which the diffusion time equals the shock crossing time. We thus have $(\delta R)^2/k D_{*} R_{w}^{-2}/c = \delta R/v_{sh}$, leading to $t_{r} \approx (R_{w}/v_{sh})(R_{w}/R_{d})$. This case, the rise time can be considerably shorter than the time for initial heating of the envelope (Figure 1(b)). Since $\delta R/R_{w} < 1$, the region involved in shock breakout is not radially extended, so the pressure of the escaping radiation can accelerate the gas out to $R_{w}$ (Ensmann 1994). High gas velocities are expected around the time of maximum luminosity. A dense shell forms when the radiation can escape, but does not produce continuing high luminosity because the dense gas does not extend far beyond the breakout point and it has been radiatively accelerated.

For our specific supernova model, the shock breakout begins when the forward shock ($R_{sh}$) reaches $R_{w}$, which occurs at $t_{w} = 16 R_{w,15}^{0.25} E_{51}^{-0.5} M_{e1}^{0.25} D_{*}^{0.25} \text{ days}$, where $R_{w,15}$ is $R_{w}$ in units of $10^{15} \text{ cm}$. The free expansion velocity at the reverse shock is $v_{0} = 5.7 \times 10^{3} E_{51}^{-0.25} E_{51}^{0.5} M_{e1}^{0.25} D_{*}^{-0.25} \text{ km s}^{-1}$, which leads to a radiated energy of $E_{\text{rad}} = 0.65 \times 10^{50} R_{w,15}^{0.5} E_{51} M_{e1}^{-0.5} D_{*}^{0.5} \text{ erg}$. The rise time for the light curve is $t_{r} = t_{w} R_{w}/R_{d} = 41 k^{-0.8} R_{w,15}^{0.8} E_{51}^{0.8} M_{e1}^{0.45} D_{*}^{0.35} \text{ days}$, so that $L \approx E_{\text{rad}}/t_{r} = 1.8 \times 10^{43} k^{0.8} R_{w,15}^{1.75} E_{51}^{0.8} M_{e1}^{-0.95} D_{*}^{0.8} \text{ erg s}^{-1}$. The temperature in the shocked shell is like that given in the first part of Equation (7) except that $t_{b}$ is replaced by $t_{w}$. The temperature is lowered in the escape out to the photosphere if there is sufficient photon production in this region (Nakar & Sari 2010).

3. COMPARISON WITH OBSERVATIONS

The radiated energy from SN 2006gy from the initial optical rise to around the peak is $\sim 1 \times 10^{52} \text{ erg}$ (Ofek et al. 2007; Smith et al. 2007), which makes it a good candidate for the physical situation described here (with wind optical depth $\tau_{w} > c/v_{sh}$). In this case, the observed rise time gives an estimate of $t_{b}$, the diffusion time. The observations indicate a rise time of 60 days. Using Equation (1), the indicated wind density is $D_{*} \approx 10$. The observed peak luminosity has sensitivity to the supernova energy. At maximum light, the observed luminosity was $4 \times 10^{44} \text{ erg s}^{-1}$ (Smith et al. 2010),
which implies $E_{51} \approx 3$ for the other standard parameters. With these parameters, Equation (3) gives $R_d = 2.5 \times 10^{15} M_{\odot}^{-0.2}$ cm while the dense medium may extend to $\sim 1 \times 10^{16}$ cm (Smith et al. 2010), so that $R_d > R_{sh}$. We attribute the flattening of the observed light curve (Smith et al. 2010) to the continuing interaction in the extended region. With $R_w = 10^{16}$ cm, the implied circumstellar mass is $\sim 30 M_{\odot}$. These parameters are close to those found by Smith & McCray (2007) and Smith et al. (2010), which is expected because the basic physical picture is similar in the two cases. Depending on the ejecta mass, the condition that $v_t < v_{sh}$ may be violated, but we do not expect the results to be strongly affected.

Smith et al. (2007, 2010) estimated an explosion date of 2006 August 20 for SN 2006gy; this time is just before the beginning of a rise in optical luminosity from $0.01 L_{\text{max}}$ to $L_{\text{max}}$, where $L_{\text{max}}$ is the maximum optical luminosity. In the shock breakout view, the sharp rise of optical radiation occurs after a time $R_d/v_{sh}$ during which the shock is traveling in the optically thick region (Figure 1). The explosion date is thus $\sim 60$ days earlier than the estimate of Smith et al. (2007, 2010), and mean velocities of uniformly expanding ejecta are lower than the estimates of Smith et al.

Another aspect of the rise to maximum in shock breakout is that the increasing temperature as the shock breaks out is an important component of the rising luminosity. In the case of SN 2006gy, Smith et al. (2010) find a temperature $T \approx 11,000$ K on days 65 and 71 (from 2006 August 20; their Figure 4), which is close to the time of optical maximum light. On day 36, Smith et al. (2010) estimate $T \approx 9500$ K, using the same extinction value as that used for other epochs (their Figure 4). However, they find that with an assumed larger extinction, a photosphere with $T \approx 15,000$ K provides a better fit to the observed spectrum. The higher temperature would bring the temperature evolution more in line with that observed in other supernovae, i.e., a decreasing temperature with time, and is advocated by Smith et al. (2010). However, in the shock breakout view, the increasing temperature is expected and there is no need for a time-dependent extinction.

In our model, the dense shell and shock wave are deep within the circumstellar envelope, outside of which is the last equilibrium shell where the spectrum is formed. The radius of this shell is not the blackbody radius $R_{sh}$ because of the nonequilibrium conditions in the medium. Outside of the shell is an electron-scattering region of moderate optical depth (between $c/v_{sh}$ and 1) where the peaked Hα profile with a broad base can be formed (Chugai 2001; Smith et al. 2010); the broadening is due to scattering in the thermal gas as opposed to the Doppler effect.

An example of a different type of luminous supernova is SN 2010gx and related objects (Pastorello et al. 2010; Quimby et al. 2009). In this case, there is a sharp drop from peak luminosity without a flattening, broad lines of O II are present at maximum light, and the narrow H or He lines often observed in Type II supernovae are not present. The evidence points to an explosion in a more compact circumstellar medium for this class of objects. The rise time, $\sim 50$ days, and peak luminosity, $(3-4) \times 10^{44}$ erg s$^{-1}$, are comparable to the case of SN 2006gy, while the temperature is higher, 15,000 K. The rise time suggests that $R_e$ is not much less than $R_d$, so $R_e \approx R_d$. The density is comparable to SN 2006gy. The higher temperature in this case can be attributed to the lower opacity due to the lack of H and He, and the smaller extent of the opaque circumstellar medium.

Although the case for dense mass-loss years before the supernova appears good, the cause of the mass loss is not known. Woosley et al. (2007) suggested that SN 2006gy was the result of pair instability eruption before the supernova. Since the radiated energy produced in this case is $\sim 10^{50}$ erg and the radiated energy in observed luminous supernovae is $\gtrsim 10^{51}$ erg, we have not specifically treated that case here, although if the energy were larger similar physical arguments would presumably apply. The dense mass loss is typically attributed to luminous blue variable eruptions (Smith & McCray 2007), although such eruptions are not understood in the context of stellar evolution. An eruption was observed two years before the explosion of SN 2006jc, which was an H-poor, Type Ib supernova (Pastorello et al. 2007; Foley et al. 2007). The mass loss in this case was too weak to produce the high density phenomena discussed here, but it does show the possibility of a presupernova outburst, even in the H-poor case.

We thank Claes Fransson for discussions. This research was supported in part by NSF grant AST-0807727.

Note added in proof. A model similar to that developed here was presented by Balberg & Loeb (2011) and applied to the Type Ib SN 2008D.

REFERENCES

Balberg, S., & Loeb, A. 2011, MNRAS, submitted (arXiv:1101.1489)
Chevalier, R. A. 1982, ApJ, 259, 302
Chevalier, R. A. 1983, ApJ, 272, 765
Chevalier, R. A., & Fransson, C. 1994, ApJ, 420, 268
Chugai, N. N. 2001, MNRAS, 326, 1448
Chugai, N. N., et al. 2004, MNRAS, 352, 1213
Enslow, L. 1994, ApJ, 424, 275
Enslow, L., & Burrows, A. 1992, ApJ, 393, 742
Falk, S. W. 1977, ApJ, 225, L133
Falk, S. W., & Arnett, W. D. 1977, ApJS, 33, 515
Foley, R. J., Smith, N., Ganeshalingam, M., Li, W., Chornock, R., & Filippenko, A. V. 2007, ApJ, 657, L105
Grassberg, E. K., Imshennik, V. S., & Nadyozhin, D. K. 1971, Ap&SS, 10, 28
Grasberg, E. K., & Nadyozhin, D. K. 1987, AZh, 64, 1199
Klein, R. I., & Chevalier, R. A. 1978, ApJ, 223, L109
Levesque, E. M., Massey, P., Olsen, K. A. G., Plez, B., Josselin, E., Maeder, A., & Meynet, G. 2005, ApJ, 628, 971
Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379
Moriya, T., Tomimaga, N., Blinnikov, S. I., Baklanov, P. V., & Sorokina, E. I. 2010, MNRAS, submitted (arXiv:1009.5799)
Nakar, E., & Sari, R. 2010, ApJ, 725, 904
Olek, E. O., et al. 2007, ApJ, 659, L13
Olek, E. O., et al. 2010, ApJ, 724, 1396
Pastorello, A., et al. 2007, Nature, 447, 829
Pastorello, A., et al. 2010, ApJ, 724, L16
Quimby, R. M., et al. 2009, Nature, submitted (arXiv:0910.0059)
Smith, N., Chornock, R., Silverman, J. M., Filippenko, A. V., & Foley, R. J. 2010, ApJ, 709, 856
Smith, N., & McCray, R. 2007, ApJ, 671, L17
Smith, N., et al. 2007, ApJ, 666, 1116
Soderberg, A. M., et al. 2008, Nature, 453, 469
Weaver, T. A. 1976, ApJS, 32, 233
Woosley, S. E., Blinnikov, S., & Heger, A. 2007, Nature, 450, 390