

SHOCK BREAKOUT EMISSION FROM A TYPE Ib/c SUPERNOVA: XRT 080109/SN 2008D

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Received 2008 April 30; accepted 2008 July 3; published 2008 July 31

ABSTRACT

The X-ray transient 080109, associated with SN 2008D, can be attributed to the shock breakout emission from a normal Type Ib/c supernova. If the observed emission is interpreted as thermal emission, the temperature and radiated energy are close to expectations, considering that scattering dominates absorption processes so that spectrum formation occurs deep within the photosphere. The X-ray emission observed at ~ 10 days is attributed to inverse Compton scattering of photospheric photons with relativistic electrons produced in the interaction of the supernova with the progenitor wind. A simple model for the optical/ultraviolet emission from shock breakout is developed and applied to SN 1987A, SN 1999ex, SN 2008D, and SN 2006aj, all of which have optical emission observed at $t \sim 1$ day. The emission from the first three can plausibly be attributed to shock breakout emission. The photospheric temperature is most sensitive to the radius of the progenitor star core and the radii in these cases are in line with expectations from stellar evolution. The early optical/ultraviolet observations of SN 2006aj cannot be accommodated by a nonrelativistic shock breakout model in a straightforward way.

Subject headings: shock waves — supernovae: general — supernovae: individual (SN 2008D)

1. INTRODUCTION

The shock wave generated by the central explosion in a supernova accelerates through the outer layers of the star, giving rise to the peak photospheric temperature at the time of shock breakout. The resulting X-ray/ultraviolet flash was predicted long ago (Klein & Chevalier 1978; Falk 1978; Matzner & McKee 1999). GRB 060218, discovered by its X-ray radiation (Campana et al. 2006), was associated with the fairly normal Type Ic SN 2006aj (Mazzali et al. 2006), and its early emission has been interpreted as due to shock breakout (Campana et al. 2006; Waxman et al. 2007). However, mildly relativistic motion is needed and it is likely that a central engine played a role in the emission.

The X-ray transient XRT 080109 was serendipitously discovered during *Swift* observations of SN 2007uy in NGC 2770 (Soderberg et al. 2008). The supernova associated with the burst, SN 2008D, was found to be spectroscopically similar to the Type Ib SN 2005hg (Modjaz et al. 2008). Early radio emission was detected, but not at the high luminosity that would suggest relativistic motion, and no gamma-ray burst emission was detected by *Swift* (Soderberg et al. 2008). In view of these properties, we further examine the possibility that the early ($\lesssim 1$ day) emission from SN 2008D was entirely due to the supernova. This view was advocated by Soderberg et al. (2008), but Xu et al. (2008) and Li (2008) find that a central engine flow is needed. We treat the X-ray emission in § 2 and the optical/ultraviolet emission in § 3. We take the distance to NGC 2770 to be 27 Mpc.

2. EARLY X-RAY EMISSION

The early X-ray emission from a supernova depends on the properties of the shock wave generated by the central explosion. The shock wave moving through the star is strongly radiation dominated, giving rise to a burst of radiation when the shock wave reaches an optical depth $\sim c/u$, where c is the speed of light and u is the shock velocity. The radiation accelerates the

gas ahead of the shock wave, so that the shock wave disappears; a gas-dominated shock wave then forms in the surrounding medium when the supernova radius has roughly doubled (Epstein 1981; Fransson 1982). This evolution is shown well in the simulation by Ensman (1994) which has parameters intended for SN 1987A. The shock breakout begins at $t \approx 5.8 \times 10^3$ s when the radiation shock starts to spread, and reaches a peak luminosity at $t \approx 1.0 \times 10^4$ s when no shock is present. The gas shock starts to develop at $t \approx 1.1 \times 10^4$ s, when the luminosity is down by a factor of 3 from its peak value, and is well developed by $t \approx 1.7 \times 10^4$ s, when the luminosity is down by another factor of 3. The simulation assumes pure absorption and an r^{-7} density power law for the preshock atmosphere, but these properties do not appear to be crucial for the shock evolution. Particle acceleration at the gas-dominated shock gives rise to the radio synchrotron radiation emission that is observed from Type Ib/c supernovae, including SN 2008D. Chevalier & Fransson (2006) found that for the conditions typically found in SNe Ib/c, the X-ray emission from the later interaction is dominated by nonthermal mechanisms (inverse Compton and synchrotron) as opposed to thermal emission.

Swift and *Chandra* observations of the XRT 080109 showed an early bright phase lasting ~ 600 s, followed by a slow, fainter decline (Soderberg et al. 2008). We identify the early bright phase with the breakout of the radiation-dominated shock and the later emission with the interaction with the circumstellar medium. An important issue is the spectrum of the initial burst. There is general agreement that a power-law spectrum (with photon index $\Gamma = 2.3$) provides a better fit than a blackbody (with $kT = 0.73$ keV) (Xu et al. 2008; Soderberg et al. 2008; Li 2008; Modjaz et al. 2008), although a blackbody fit may still be acceptable (Xu et al. 2008; Modjaz et al. 2008). Soderberg et al. (2008) find an absorption-corrected fluence of 1.7×10^{46} ergs for the power-law spectral fit.

Previous studies of shock breakout (Klein & Chevalier 1978; Falk 1978; Matzner & McKee 1999) assumed that the initial breakout radiation has a blackbody or dilute blackbody spectrum. The fits to the observed spectrum of SN 2008D show a preference for a power-law spectrum, and photon Fermi acceleration is invoked by Soderberg et al. (2008) to explain the

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observations of SN 2008D, based on calculations by Wang et al. (2007). In this scenario, the photons gain energy by scattering across a semirelativistic shock front. The authors assume that an infinitesimally thin shock front is present, apparently from the time that the radiation-dominated shock front breaks down at an optical depth of c/u . As discussed above, the breakout radiation is capable of accelerating the matter ahead of the shock front so that the formation of the gas-dominated shock is delayed; the viscous shock starts to form only when the breakout luminosity is dropping from its peak value and the optical depth at the shock is decreasing.

In view of the possible difficulty with producing a power-law spectrum, we consider the thermal interpretation of the spectrum. Matzner & McKee (1999) estimated the breakout radiation expected from a relatively compact star with a radiative envelope; they determine the temperature by setting the postshock pressure $= \frac{1}{3}aT^4$, where a is the radiation constant. For the explosion parameters, we use the energy $E_{51} = 3$, where E_{51} is the energy in units of 10^{51} ergs, and ejecta mass $M = 4 M_{\odot}$, determined by Soderberg et al. (2008) from the supernova light curve and spectra. Taking the opacity, κ , of the He-rich gas to be $0.2 \text{ cm}^2 \text{ g}^{-1}$, the radius of the progenitor star required to produce $kT = 0.73 \text{ keV}$ at shock breakout is $R = 1.5 \times 10^{11} \text{ cm}$. With these values of E , M , and R , the expected radiated energy at shock breakout is 1.7×10^{45} ergs. However, Klein & Chevalier (1978) and Ensman & Burrows (1992) find that the observed color temperature can be 2–3 times the effective temperature if a blackbody were assumed because the spectrum is formed at a relatively deep layer in the scattering atmosphere. If the effective temperature is reduced by a factor of 2 to 0.36 keV, the radius is increased to $R = 6.4 \times 10^{11} \text{ cm} = 9 R_{\odot}$, which corresponds to a breakout energy of 1.9×10^{46} ergs. Woosley et al. (1995) find that a He star with initial mass $4 M_{\odot}$ has a radius of $9 R_{\odot}$ at the time of carbon ignition; a He star can become extended in its late burning phases. With this radius, the peak shock velocity has $\beta\gamma \approx 0.6$, a high, but nonrelativistic, velocity.

Although the thermal shock breakout model can reproduce the temperature and radiated energy of the observed burst, it falls short on the timescale. The expected timescale is $\approx R/c = 5\text{--}20 \text{ s}$, but the observed timescale is $\sim 100 \text{ s}$ (taken as the time with flux above half the peak flux). One possibility is that the photosphere is actually in a dense stellar wind around the Wolf-Rayet star (Soderberg et al. 2008). Assuming a constant wind velocity, the optical depth to electron scattering in the wind is $\tau_e = 0.2\mu_e \dot{M}_{-5}/(r_{12}v_3)$, where the mean molecular weight $\mu_e \approx 0.5$ for a non-hydrogenic gas, r_{12} is the radius in units of 10^{12} cm , \dot{M}_{-5} is the wind mass-loss rate in $10^{-5} M_{\odot} \text{ yr}^{-1}$, and v_3 is the wind velocity in 10^3 km s^{-1} , normalized to a typical value for Wolf-Rayet stars. From the observed radio emission, Chevalier & Fransson (2006) estimated $\dot{M}_{-5}v_3^{-1} = 2.8$ for SN 1994I for an efficiency of magnetic field production in the shock front of 10%; a lower efficiency would increase the wind density. A similar estimate for SN 2008D, using radio data from Soderberg et al. (2008), gives $\dot{M}_{-5}v_3^{-1} = 1.5$. For these parameters, we have $\tau_e = 1$ at $r_{12} = 0.15$, which is smaller than the estimated stellar radius, indicating that the freely expanding wind is not optically thick.

However, the wind structure in the immediate vicinity of the star is likely to be more complicated than a $\rho \propto r^{-2}$ wind. The radiative acceleration thought to be responsible for the high velocity occurs over a region of several stellar radii (e.g., Gräfener & Hamann 2005; Li 2007), leading to an enhanced density. Gräfener & Hamann (2005) find that the acceleration up

to $\sim 1000 \text{ km s}^{-1}$ takes place over a factor of 2 in radius, while the final velocity of $\sim 2000 \text{ km s}^{-1}$ was only reached at more than 10 stellar radii. Another important, but less understood, effect is connected to pulsational instabilities. Fadeyev & Novikova (2003) find that for He core masses below $10 M_{\odot}$ and $L/M \geq 7 \times 10^3 L_{\odot}/M_{\odot}$ the star is pulsationally unstable. Hydrodynamical calculations show that these pulsations steepen to shock waves at the surface, which levitates the outer regions. For a $10 M_{\odot}$ He core and a luminosity of $2 \times 10^5 L_{\odot}$ they find that the radius of the star expands by a factor of 2, and the scale height at the surface increases from $6 \times 10^{-3} R_{\text{ph}}$ to $\sim 0.23 R_{\text{ph}}$. There is observational evidence for transient mass loss before some Type Ib/c and IIIn supernovae, e.g., SN 2006jc (Foley et al. 2007), on a scale of $\sim 10^{16} \text{ cm}$. In view of these issues and the uncertainty in the nonequilibrium radiation field, the difference between the model and observed timescales may not be significant.

A crucial aspect of our scenario is that the spectral formation and thermalization occurs at a considerable depth in the supernova, so that the photons just scatter in the mass-loss region. The place of thermalization is characterized by $\tau_{\text{scatt}}\tau_{\text{abs}} \approx 1$, where τ_{scatt} is the scattering optical depth and τ_{abs} is the absorption optical depth. We have $\tau_{\text{abs}}/\tau_{\text{scatt}} \approx \kappa_{\text{ff}}/\kappa_{\text{T}}$, where the absorption is dominated by the free-free opacity $\kappa_{\text{ff}} = 1.77 \times 10^{-23} \bar{g} n^2 T^{-1.5} \nu^{-2}$ in cgs units, κ_{T} is the Thomson opacity, and n is the density. The probability for absorption becomes $\tau_{\text{abs}}/\tau_{\text{scatt}} \approx 1.46 \times 10^{-23} \bar{g} n T_7^{-1.5} E_{\text{keV}}^{-2}$, where T_7 is the temperature in units of 10^7 K , E_{keV} is the photon energy in keV, and cgs units are used. At 1 keV thermalization requires $n \geq 6.8 \times 10^{22}/\tau_{\text{scatt}}^2 \text{ cm}^{-3}$; photons will only scatter at lower densities and thermalization occurs in the steep density region. We thus find that it is plausible that the temperature and energy can be reproduced, although detailed hydrodynamic, radiative transfer calculations are needed to show this definitively. Xu et al. (2008) and Li (2008) argued against a thermal model for the emission based on the small radiating area derived from the luminosity and temperature. Here we argue that the spectrum is diluted in the scattering atmosphere, so that a larger radiating region can be accommodated.

In a model intended for SN 1994I, Chevalier & Fransson (2006) found that inverse Compton emission dominates over days 1–20, with an X-ray luminosity on day 1 of $\nu L_{\nu} \sim 1 \times 10^{39} \text{ ergs s}^{-1}$. The model luminosity evolves slowly because of the balance between the shock wave expansion and the increasing optical luminosity, and on day 10 is $\sim 4 \times 10^{38} \text{ ergs s}^{-1}$. The observed X-ray emission from SN 2008D by *Chandra* on day 10 had a luminosity (0.5–10 keV) of $\sim 10^{39} \text{ ergs s}^{-1}$ (Soderberg et al. 2008), which corresponds to $\nu L_{\nu} \sim 3 \times 10^{38} \text{ ergs s}^{-1}$ for a $L_{\nu} \propto \nu^{-1}$ spectrum. There is reasonable agreement with the model expectations; the radio and X-ray emission suggest wind conditions similar to those in SN 1994I on a scale $\sim (2\text{--}3) \times 10^{15} \text{ cm}$. Soderberg et al. (2008) also advocate an inverse Compton origin for this emission. The Chevalier & Fransson (2006) model predicts a drop in X-ray luminosity after day 10 when the photospheric luminosity drops. However, the supernova was close to the detection limit of *Chandra* on day 10 (Soderberg et al. 2008), making it difficult to check this prediction.

3. EARLY OPTICAL EMISSION

As the supernova photosphere expands and cools, the emission at lower frequencies, including optical, increases. Optical emission related to shock breakout thus peaks at a later time,

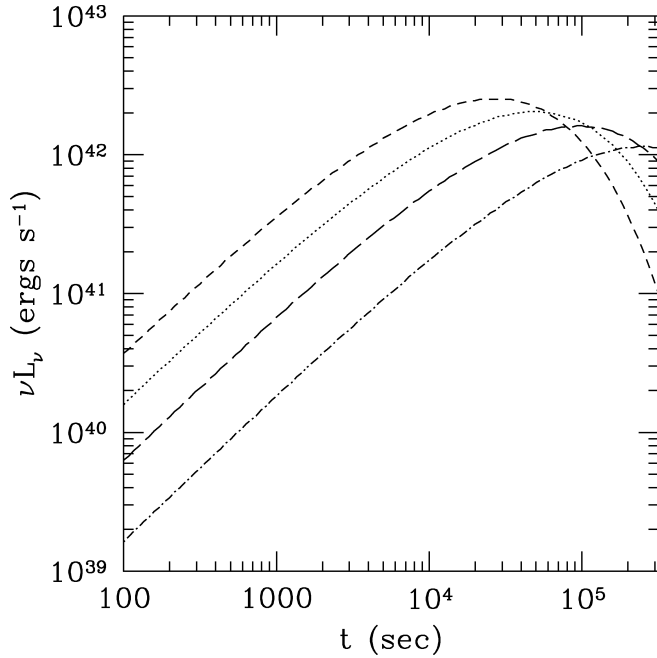


FIG. 1.—Model predictions for the photospheric spectral luminosity in the shock breakout phase. The curves are for 1880 Å (dashed curve), 2510 Å (dotted curve), 3450 Å (long-dashed curve), and 5440 Å (dash-dotted curve). The model assumes reference values of the physical parameters, but can be scaled to other values, as described in the text.

~ a day or days. Such emission was seen in the early observations of SN 1987A (Hamuy et al. 1988), and Chevalier (1992) developed an analytical theory to describe the emission. The main approximation in this approach was that the supernova be well into its free expansion phase, which requires a relatively small radius progenitor star. The model should thus be applicable to Type Ib/c supernovae and we consider the Type Ic's SN 1999ex (Stritzinger et al. 2002) and SN 2006aj (Campana et al. 2006; Modjaz et al. 2006), as well as SN 2008D. In all these cases, there are observations at an age ~1 day. Here the theory of Chevalier (1992) is extended so it can be compared to detailed observations.

After correcting for a typographical error, equation (2.8) in Chevalier (1992) for the density of outer freely expanding gas at velocity v becomes

$$\rho = 1.4 \times 10^{98} E_{51}^{3.59} M_0^{-2.59} F_1^{7.18} t^{-3} v^{-10.18} \text{ g cm}^{-3}, \quad (1)$$

where M_0 is the ejecta mass in units of M_\odot and F_1 is a factor that describes by how much the velocity of an element of gas increases after it has first been shocked. This expression was derived for the case of SN 1987A, which had a progenitor with a radiative envelope, like SNe Ib/c. In a planar blow off $F_1 = 1.81$, but is reduced in a spherical expansion. Taking $F_1 = 1.35$ leads to density and pressure profiles that agree with results of Matzner & McKee (1999, their eqs. [46] and [47]) for the outer parts of an exploded star with a radiative envelope, and we use that as a reference value.

Given the density structure, the photospheric radius can be found by integrating $\kappa\rho$ in to the point where $\tau = 1$. Taking $\kappa = 0.2 \text{ g cm}^{-2}$, the photospheric radius is then

$$r_{\text{ph}} = 3.0 \times 10^{14} E_{51}^{0.39} M_0^{-0.28} (F_1/1.35)^{0.78} t_d^{0.78} \text{ cm}, \quad (2)$$

where t_d is the age in days. The velocity of freely expanding gas at the photosphere is

$$v_{\text{ph}} = 3.4 \times 10^4 E_{51}^{0.39} M_0^{-0.28} (F_1/1.35)^{0.78} t_d^{-0.22} \text{ km s}^{-1}. \quad (3)$$

The luminosity at the photosphere can be found by allowing for a diffusion wave to move back into the exploded star (Chevalier 1992),

$$L_c = 3.3 \times 10^{42} E_{51}^{0.91} M_0^{-0.74} R_{12} (F_1/1.35)^{-0.17} t_d^{-0.34} \text{ ergs s}^{-1}, \quad (4)$$

where R_{12} is the radius of the progenitor star in units of 10^{12} cm. Because the inner layers are shocked at a lower velocity and are observed at a later time than the X-ray observations, the radiation field in this case can be approximated by a black-body. Using $L_c = 4\pi r_{\text{ph}}^2 \sigma T_e^4$, where σ is Stefan-Boltzmann's constant and T_e is the effective temperature of the photosphere, we have from equations (2) and (4)

$$T_e = 1.4 \times 10^4 E_{51}^{0.03} M_0^{-0.04} R_{12}^{0.25} (F_1/1.35)^{-0.43} t_d^{-0.48} \text{ K}. \quad (5)$$

These results can be compared with those of Waxman et al. (2007) who also assumed that the photosphere is in the outer shock-accelerated part of the supernova density profile, but otherwise used a different method. The scaling with parameters is similar, although not exactly that found here, and, for the same reference values, Waxman et al. (2007) obtain $r_{\text{ph}} = 3.2 \times 10^{14}$ cm and $T_e = 2.6 \times 10^4$ K. The agreement with the r_{ph} found here is good, but the value of T_e found here is smaller by a factor of 1.9, or the luminosity is smaller by 12. The method of Waxman et al. (2007) does not include radiative diffusion, whereas that of Chevalier (1992) used here does. We find that the luminosity decreases by 1.9 because of diffusion, for the standard parameters at $t_d = 1$, a relatively small effect.

The photospheric radius and temperature determine the spectral luminosity evolution, as shown in Figure 1 for four wavelengths relevant to the *Swift* UVOT bands. The results in Figure 1 assume the reference values for the physical parameters ($E_{51} = 1$, $M = 1 M_\odot$, $R_{12} = 1$), but can be used for other values by scaling the luminosity by a factor $E_{51}^{0.88} M_0^{-0.68} R_{12}^{0.81}$ and the time by a factor $E_{51}^{-0.06} M_0^{0.08} R_{12}^{-0.52}$. When the wavelength is in the Rayleigh-Jeans part of the spectrum, we have $L_\nu \propto t^{1.1}$.

For the theory described here to be applicable, the photosphere must be within the steep power part of the supernova density profile. If there is no surrounding medium, the limitation at the high-velocity end is the maximum velocity at shock breakout, which is $v_{\text{max}} \approx 129,000 E_{51}^{0.58} M_0^{-0.42} R_{12}^{-0.32} \text{ km s}^{-1}$ (Matzner & McKee 1999). Using equation (3) and the reference values, this velocity corresponds to the velocity at the photosphere at an age of 0.002 days. If the supernova is surrounded by a dense, optically thick wind, the time at which the theory becomes applicable is after the shock wave has broken out from the wind. Also, because the density distribution at small radii becomes flatter than the steep power law, the actual value of r_{ph} should gradually become smaller than the value estimated here. To estimate this effect, we used the harmonic mean density profile of Matzner & McKee (1999) (their eq. [46]) to estimate the value of r_{ph} more accurately. For the reference parameters and an age of 1 day, the value of r_{ph} is 20% smaller with the more accurate density distribution.

Another requirement of the applicability of the simple model

is that the opacity remain constant. Recombination of He^{++} to He^+ occurs at a temperature of a few 10^4 K at the densities of interest; this results in a decrease in the opacity by a factor of 2. A larger decrease in opacity occurs when the gas becomes neutral, which occurs at $T \sim 1.6 \times 10^4$ K. The recombination adds internal energy to the gas, which can help power the light curve. These considerations show that the simple model for the early light curve starts to break down at an age ~ 1 day.

The earliest observations of SN 1987A by Hamuy et al. (1988) are on day 1.14 when $L = 4.9 \times 10^{41}$ ergs s^{-1} , $r_{\text{ph}} = 1.4 \times 10^{14}$ cm, and $T_e = 13,600$ K. To apply the model developed here, we use the parameters $\kappa = 0.34$ cm^2 g^{-1} (to account for a H and He composition), $E_{51} = 1$, $M_0 = 16$, and $R_{12} = 2.1$ with the result $L = 5.5 \times 10^{41}$ ergs s^{-1} , $r_{\text{ph}} = 1.6 \times 10^{14}$ cm, and $T_e = 13,100$ K. In this case, the parameters are fairly well determined by extensive modeling (e.g., Imshennik & Nadezhin 1989) and it appears that the model presented here can approximately represent the early evolution.

There are good early limits on the brightness of the Type Ic SN 1999ex because of the occurrence of another supernova, SN 1999ee, in the galaxy, implying that the age of the supernova was $\lesssim 1.05$ days when first observed. At that time, $L = 2.8 \times 10^{41}$ ergs s^{-1} , $r_{\text{ph}} = 1.2 \times 10^{14}$ cm, and $T_e = 12,900 \pm 1400$ K (Stritzinger et al. 2002). Stritzinger et al. (2002) compare the light curve of SN 1999ex to models of Woosley et al. (1987) with $M = 6.2 M_{\odot}$; with $E_{51} = 1$, our model then gives $r_{\text{ph}} \approx 1.8 \times 10^{14} t_d^{0.78}$ cm, which is in adequate agreement with the observations. The corresponding model value of T_e is $13,000 R_{12}^{0.25} t_d^{-0.48}$ K.

From *Swift* UVOT observations of SN 2008D, Soderberg et al. (2008) estimate that $r_{\text{ph}} \approx 3 \times 10^{14}$ cm and $T \approx 10^4$ K at an age of ~ 1 day; the closest time of observation is 1.7 days, so these values must be regarded as estimates. For $E_{51} = 3$, $M = 4 M_{\odot}$, and $R = 9 R_{\odot}$, our model gives $r_{\text{ph}} = 3.1 \times 10^{14}$ and $T = 1.2 \times 10^4$, in reasonable agreement with the observed values. We note that the radius R refers to the outer star layers where shock acceleration and a steep density gradient occur. There is the expectation in the model that the supernova should be cooling at this age, which is consistent with the optical/ultraviolet observations (Soderberg et al. 2008).

For SN 2006aj, Campana et al. (2006) estimate $r_{\text{ph}} \approx 3 \times 10^{14}$ cm and a temperature of 3 eV at $t = 10^5$ s = 1.16 days, corresponding to $T_e \approx 35,000$ K and $L \approx 1 \times 10^{44}$ ergs s^{-1} , far more luminous than either SN 1987A or SN 1999ex at a com-

parable age. To compare the observations with models, we use $E_{51} = 2$ and $M_0 = 2$ (Mazzali et al. 2006). The model reference properties on day 1.16 values are then $r_{\text{ph}} = 3.6 \times 10^{14}$ cm and $T_e = 13,000$ K, corresponding to $L = 2.6 \times 10^{42}$ ergs s^{-1} . The value of r_{ph} is in reasonable agreement with observations, but the model T_e is low, leading to a significantly lower luminosity than is observed. The critical parameter for T_e is the radius of the progenitor star. The required radius to produce the temperature is $R \approx 5 \times 10^{13}$ cm, which is the radius of an extended red supergiant star and much larger than that expected for a Wolf-Rayet star. As noted above, a helium star can become more extended in the evolution leading up to the explosion if its initial mass is low (Woosley et al. 1995), but the effect does not appear to be sufficient to explain the radius needed here.

In addition, the evolution leading up to 10^5 s can be considered. The *Swift* UVOT light curves for GRB 060218 (Campana et al. 2006; see also Ghisellini et al. 2007) can be compared to the model curves in Figure 1. The cooling indicated by the evolution of the 1880 and 2510 Å model light curves matches that seen in the observations fairly well. However, between 10^4 and 10^5 s, the observations show a turnover at the longer wavelengths (3450 and 5440 Å) that is not in the model curves and cannot be attributed to the expected cooling of the photosphere. The turnover indicates a decrease in the emitting area that is not expected if the emission is from the outer part of the exploding star. In addition, it can be seen that, although there is a roughly power law increase in the fluxes at early times, the observed slope is shallower than the $t^{1.1}$ dependence expected in the model. For these reasons, the problem of underproduction of flux in the model at 10^5 s is even more severe at early times (see Ghisellini et al. 2007). Although the early *Swift* UVOT observations of GRB 060218 show a tantalizing similarity to expectations for early supernova emission, a shock breakout model does not reproduce the observations in a straightforward way, indicating that a central engine plays a role in the emission.

We are grateful to P. Chandra and A. Soderberg for discussions and information, and to C. Matzner and the referee for comments. This research was supported in part by NASA grant NNG06GJ33G, the Swedish Research Council, and Swedish National Space Board.

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