 DOES THE DETECTION OF X-RAY EMISSION FROM SN 1998bw SUPPORT ITS ASSOCIATION WITH GRB 980425?

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ABSTRACT

We show that the recent identification of X-ray emission from SN 1998bw is naturally explained as synchrotron emission from a shock driven into the wind surrounding the progenitor by a mildly relativistic shell ejected by the supernova, the existence of which was inferred earlier from radio observations. X-ray observations imply a shell energy $E \approx 10^{57.7}$ ergs and constrain the initial shell velocity $\beta c$ and normalized wind mass-loss rate, $m = (M/10^{-13} M/yr)/(v_0/10^3 \text{ km s}^{-1})$, to satisfy $\beta m \approx 10^{-12.5}$. The inferred energy is consistent with energy estimates based on radio observations provided $m \approx 0.04$, in which case radio observations imply $\beta \approx 0.8$, consistent with the X-ray constraint $\beta m \approx 10^{-1.5}$. While X-ray observations allow us to determine the parameters characterizing the preexplosion wind and the mildly relativistic shell ejected by SN 1998bw, they do not provide evidence for existence of an off-axis “standard” gamma-ray burst (GRB) jet associated with SN 1998bw, which may have produced GRB 980425. The lack of observational signatures, typically expected to be produced by such an off-axis jet on a 1 yr timescale, may be due to the low $m \leq 0.1$, which implies that an off-axis jet will become observable only on a $\geq 10$ yr timescale.

Subject headings: gamma rays: bursts — gamma rays: theory — supernovae: general — supernovae: individual (SN 1998bw) — X-rays: general

1. INTRODUCTION

Recent Chandra observations of SN 1998bw (Kouveliotou et al. 2004) have allowed us to identify one of the X-ray sources detected earlier by BeppoSAX (Pian et al. 2000) as associated with the supernova. We discuss here the implications of the detected X-ray emission, in particular to the suggested association of SN 1998bw with GRB 980425.

The association of gamma-ray bursts (GRBs) with Type Ib/c supernovae (SNe Ib/c) is motivated by the coincidence of GRB 980425 and SN 1998bw (Galama 1998) and by the identification of an SN 1998bw-like spectrum in the optical afterglow of GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003). The gamma-ray luminosity of GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003). The gamma-ray luminosity of GRB 980425,51 of GRB 0303292 (Stanek et al. 2003; Hjorth et al. 2003). The cation of an SN 1998bw–like spectrum in the optical afterglow 980425 and SN 1998bw (Galama 1998) and by the identification of SNe Ib/c-like spectra in the optical afterglow of GRB 980425 and SN 1998bw (Galama 1998) and by the identification of an SN 1998bw-like spectrum in the optical afterglow of GRB 030329. The gamma-ray luminosity of GRB 980425, inferred from the redshift $z = 0.1685$ of its host galaxy, lies within the range of typical cosmological GRBs, $L_{\gamma, iso} \approx 10^{52.6}$ ergs s$^{-1}$ (e.g., Schmidt 2001). The subscript “iso” indicates luminosity derived assuming isotropic emission. The association of GRB 980425 with SN 1998bw sets the distance to this burst to 38 Mpc (for $H_0 = 65$ km s$^{-1}$ Mpc), implying that its luminosity is nearly 5 orders of magnitude lower than that typical for cosmological GRBs (Pian et al. 2000).

Two hypotheses are commonly discussed that may account for the orders of magnitude difference in luminosity. First, it may be that SNe Ib/c produce two different classes of GRBs, with two different characteristic luminosities. It is now commonly believed that long-duration, $T > 2$ s, cosmological, $L_{\gamma, iso} \approx 10^{52}$ ergs s$^{-1}$ GRBs are produced by the collapse of SN Ib/c progenitor stars. It is assumed that the stellar core collapses to a black hole, which accretes mass over a long period, $\sim T$, driving a relativistic jet that penetrates the mantle/envelope and then produces the observed GRB (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999). This scenario is supported by the association of GRB 030329 with SN 2003dh

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2 See, however, Katz (1994), who suggests that a supernova-like emission may result from the impact of the relativistic GRB debris on a nearby dense gas cloud.

and by additional evidence for optical supernova emission in several GRB afterglows (Bloom 2004). The origin of a second low-luminosity class is unknown. It may be due to, e.g., supernova shock break-out (Colgate 1968; Woosley & Weaver 1986; Matzner & McKee 1999; Tan et al. 2001).

A second possibility is that GRB 980425 was a typical cosmological GRB jet viewed off-axis (Nakamura 1998; Eichler & Levinson 1999; Woosley, Eastman, & Schmidt 1999; Granot et al. 2002; Yamazaki, Yonetoku, & Nakamura 2003). Because of the relativistic expansion of jet plasma, with Lorentz factor $\Gamma \approx 100$ during gamma-ray emission (Krolik & Pier 1991; Baring 1993), gamma rays are concentrated into a cone of opening angle comparable to the jet opening angle $\theta_j$ (assuming $\theta_j > 1/\Gamma$). Thus, if the jet is viewed from a direction making an angle larger than $\theta_j$ with the jet axis, the gamma-ray flux may be strongly suppressed. In this scenario, strong radio emission, $L_v \approx 10^{37} \text{ ergs s}^{-1}$ Hz, is expected at $\approx 1$ yr delay (Frail, Waxman, & Kulkarni 2000; Livio & Waxman 2000) as the jet decelerates to subrelativistic speed and its emission becomes nearly isotropic (for a more detailed discussion, see Waxman 2004 and references therein).

We have recently shown (Waxman 2004) that the low radio luminosity of SN 1998bw, compared to that expected from a decelerated GRB jet at $\approx 1$ yr delay, may be consistent with the off-axis jet interpretation of GRB 980425 provided that either the magnetic field energy fraction behind the shock driven by the jet into the wind is atypically low, $\epsilon_B \leq 10^{-5}$, or the density of the wind surrounding the progenitor is lower than typically expected, $\bar{m} = (M/10^{-13} M/yr)/(v_0/10^3 \text{ km s}^{-1}) \approx 0.1$. Lower values of $\bar{m}$ and $\epsilon_B$ reduce the specific luminosity at the transition to subrelativistic expansion. A low value of $\bar{m} \ll 1$ further delays the time at which the flow approaches subrelativistic expansion. We consider the low $\epsilon_B$ scenario less likely, since we expect $\epsilon_B$, which is determined by the shock microphysics, to be similar for different bursts, and $\epsilon_B$ close to equipartition is inferred from radio observations of other bursts. The latter scenario, $\bar{m} \approx 0.1$, is consistent with the constraints imposed on $\bar{m}$ by the observed radio emission from the supernova (Kulkarni et al. 1998), which is interpreted as due to synchrotron emission.
from a shock driven into the wind by a mildly relativistic shell ejected by the supernova explosion (Kulkarni et al. 1998; Waxman & Loeb 1999; Chevalier & Li 1999). In this scenario, transition to subrelativistic expansion is expected over a ~10 yr timescale (Waxman 2004).

The recent identification of the X-ray emission of SN 1998bw was argued to support the interpretation that GRB 980425 was an off-axis “standard” GRB jet associated with SN 1998bw (Kouveliotou et al. 2004). We show here that the observed X-ray emission may be naturally explained as synchrotron emission from a shock driven into the wind surrounding the SN 1998bw progenitor by the mildly relativistic shell that was inferred to exist from earlier radio observations. In §2 we construct a simple model that describes the emission from a shock driven into the wind by a subrelativistic shell, based on the analysis of Waxman (2004). In §3 we show that the model can account for both X-ray and radio observations. While X-ray observations or radio observations alone do not allow us to determine all model parameters, combined X-ray and radio data overconstrain the model and therefore enhance our confidence in its validity. Our conclusions are summarized in §4.

2. MODEL

2.1. Dynamics

Let us consider a subrelativistic shell ejected by the supernova explosion, with mass $M$, total energy $E$, and initial velocity $v = \beta c$. We assume that the shell’s thermal energy is dominated by its kinetic energy, since the thermal energy deposited in the shell by the passage of the supernova shock leads to expansion and postshock acceleration that converts the thermal energy to kinetic energy (as pointed out by Matzner & McKee 1999, this postshock acceleration is essential for achieving mildly relativistic shell velocity). The shell is assumed to propagate into an $r^{-2}$ density profile created by stellar mass loss. We assume a density profile

$$\rho = Knr^{-1/2}, \quad K = \frac{\dot{M}}{4\pi v_w},$$

(1)

where $\dot{M}$ is the mass-loss rate and $v_w$ is the wind velocity.

As the shell expands, it drives a shock wave into the surrounding wind, and a reverse shock is driven backward (in the shell frame) into the shell. It is straightforward to show that as long as the mass of shocked wind plasma, $M_{sw}(r) = 4\pi Kr^2$, is small compared to the shell’s mass, the shock driven backward into the shell does not lead to significant deceleration. Denoting by $u < v$ the velocity of shocked wind (and shell) plasma, pressure balance between the forward and reverse shocks implies $\rho_u u^2 = \rho_v (v - u)^2$, where $\rho_v = M_v/4\pi r^4$ and $\rho_u = \eta M/4\pi r^3$ denote wind and shell density, respectively. Here $r/\eta$ is the thickness of the ejected shell. For $M_{sw} \ll M$ we find $(v - u)/v = (M_{sw}/\eta_M)^{1/2}$. Thus, at small radii, where $M_{sw} \ll M$, the shell expands with a time-independent velocity, $v = \beta c$. At this stage, the velocity of the shock propagating into the wind is also time independent and given by $\dot{v}/(\dot{v} + 1)u/2$, where $\dot{v}$ is the adiabatic index of the wind plasma.

Significant deceleration of the shell begins at a radius where the shocked wind mass, $M_{sw}(r)$, is similar to the shell’s mass $M$. At larger radii the flow approaches the Sedov–von Neumann–Taylor solution describing expansion of a spherical strong shock wave into a $r^{-2}$ density profile (e.g., Zel’dovich & Raizer 2002, p. 93). In these solutions, the shock radius is given by

$$R = \frac{\xi(\dot{v}) (E/K)}{(\dot{v})^{1/3}}.$$

(2)

Here $\xi(\dot{v})$ is a dimensionless parameter of the order of unity, which may be approximated by $\xi(\dot{v}) = (3/2)(\dot{v} + 1)^2(\dot{v} - 1)/2\pi(2\dot{v} - 3)^{1/3}$ (Waxman 2004). For $\dot{v} = 5/3$, appropriate for subrelativistic flow, we have $\xi = 0.73$. At the radius where $M_{sw}(r) \sim M$, the velocity given by the Sedov–von Neumann–Taylor solution for the appropriate energy $E$ is similar to the initial shell velocity $v$. We therefore define the deceleration radius, $R_{dec}$, as the radius at which the Sedov–von Neumann–Taylor postshock fluid velocity equals $v$, $2R/(\dot{v} + 1) = v$,

$$R_{dec} = \frac{16\pi}{9} \xi^3 \frac{E[(\dot{v} + 1)/2]^2}{Mv_w} = 2.1 \times 10^{15} \frac{E_{49}}{\beta^2 m} \text{ cm},$$

(3)

where $E = 10^{49}E_{49}$ ergs. The deceleration time, $t_{dec}$, is defined as

$$t_{dec} \equiv \frac{R_{dec}}{(\dot{v} + 1)v/2} = 0.62 \frac{E_{49}}{\beta^2 m} \text{ days}.$$

(4)

For $t \ll t_{dec}$ we therefore expect shell expansion at constant velocity, $v$, and a shock driven into the wind at a constant speed, $(\dot{v} + 1)v/2$. For $t \gg t_{dec}$, we expect the expansion to follow the Sedov–von Neumann–Taylor solution, equation (2), with shock velocity $R \propto t^{-1/3}$.

2.2. Synchrotron Emission

Let us consider synchrotron emission from electrons accelerated to relativistic energies by the collisionless shock driven into the wind. We assume that a constant fraction $\epsilon_e$ ($\epsilon_B$) of the postshock thermal energy is carried by relativistic electrons (magnetic field) and that the electron distribution function follows a power law, $d\ln n_{ee}/d\ln v_{ee} = -p$, for $\gamma \geq \gamma_{cr}$. In what follows, we assume $p = 2$, as observed for nonrelativistic (Blandford & Eichler 1987) as well as for relativistic shocks (Waxman 1997). This power law is produced by Fermi acceleration in collisionless shocks (Blandford & Eichler 1987; Bednarz & Ostrowski 1998; Achterberg et al. 2001), although a first principles understanding of the process is not yet available.

At times $t \gg t_{dec}$ the flow is well described by the spherical nonrelativistic self-similar solution, where the shock radius is given by equation (2). For simplicity, we assume that at this stage the shocked plasma is concentrated into a thin shell behind the shock, $R/\eta \ll R$, within which the plasma conditions are uniform (the Chernyi-Kompaneets approximation). This implies, in particular, $\eta = (\dot{v} + 1)/(\dot{v} - 1)$. The synchrotron emission obtained under the above assumptions was derived in Waxman (2004). The scaling of magnetic field amplitude $B$ and of $\gamma_{cr}$ with time, at $t \gg t_{dec}$, is (Waxman 2004)

$$B \propto t^{-1}, \quad \gamma_{cr} \propto t^{-2/3},$$

(5)
and for $p = 2$ the specific luminosity $L_\nu$ is

$$
nL_\nu \approx 10^{42}(3\epsilon_e)(3\epsilon_B)^{3/4}m^{5/4}E_{49}\left(\frac{h\nu}{1\text{ keV}}\right)^{1/2} \times \left(\frac{t}{100 \text{ days}}\right)^{-3/2} \text{ergs s}^{-1}.
$$

(6)

Equation (6) holds at frequencies well above the characteristic synchrotron frequency of the lowest energy electrons ($\gamma_e = \gamma_m$) and below the cooling frequency, $\nu_c$. Here $\nu_c$, the characteristic synchrotron frequency of electrons for which the synchrotron cooling time is comparable to the shock expansion time, $t$, is

$$
\nu_c \approx 2 \times 10^{15}(3\epsilon_B)^{3/2}m^{3/2}t^{-3/2}/100 \text{ days Hz}.
$$

(7)

Let us now consider synchrotron emission from the shock driven into the wind at times $t \ll t_{dec}$. At frequencies $\nu > \nu_c$, the specific luminosity (for $p = 2$) is given by $L_\nu = L_{\nu_c}(\nu_c/\nu)^{-3/2}(\nu/\nu_c)^{-1} = L_{\nu_c}(\nu_c/\nu)^{3/2}/\nu_c$. Here $L_{\nu_c}$ is the specific intensity at $\nu = \nu_c$, the characteristic synchrotron frequency of the lowest energy electrons ($\gamma_e = \gamma_m$). In order to determine the time dependence of $L_{\nu_c}$, we first note that $L_{\nu_c}$ is proportional to the product of the number of radiating electrons, $N_e$, and the magnetic field strength, $B$. $L_{\nu_c} \propto N_eB$. And that $\nu_c \propto \gamma_m^2B$. The Lorentz factor $\gamma_c$ of electrons that cool on a time $t$ is given by comparing the synchrotron cooling time, $t_{syn} \propto 1/\gamma_c^2B^2$, to $t$, yielding $\gamma_c \propto 1/tB^2$ and $\nu_c \propto B^2 \propto r^{-2}$. The dependence of $\nu_c$, $\nu$, and $L_{\nu_c}$ on time is now obtained by noting that the time-independent shock velocity implies time-independent thermal energy per shocked particle, i.e., $\gamma_m \propto t^0$, thermal energy density proportional to $r^{-2} \propto r^{-2} \propto r^{-2} (\text{since the density drops as } 1/r^3, i.e., B \propto r^{-1} \text{ and } N_e \propto t)$. Thus, $L_{\nu_c} \propto t^0$, $\nu_c \propto \gamma_m^2B \propto r^{-1}$, $\nu \propto t$, and $L_{\nu_c} \propto t^0$ for $\nu > \nu_c$. Synchrotron emission at times $t \ll t_{dec}$ is therefore described by

$$
nL_\nu \propto \left(\frac{\nu^{1/2}t^{-1/2}}{\nu_0^{1/2}t^{-1/2}}, \nu < \nu_c(t)\right; \left(\frac{\nu_c^{1/2}t^{-1/2}}{\nu_c^{1/2}t^{-1/2}}, \nu > \nu_c(t)\right).
$$

(8)

with $\nu_c$ given by equation (7). Combined with equations (4) and (6), this determines the synchrotron emission predicted by the model at $t < t_{dec}$.

The following line of arguments shows that synchrotron emission from the shock driven backward into the expanding shell, which exists at $t < t_{dec}$, is dominated by the emission from the shock driven into the wind, under the assumption that $\epsilon_e$ and $\epsilon_B$ are similar for the postshock plasma behind the two shocks. Since the thermal energy density is the same in the shocked wind and shell plasmas (pressure equilibrium), the magnetic field is the same in the two regions (assuming similar $\epsilon_B$ for both shocks) and the product of the electron number density and their minimum Lorentz factor, $n_e\gamma_m$, which is proportional to the thermal energy density, is the same in the shocked wind and shell plasmas. Similar $B$ implies similar $\nu_c$ for both shocks and hence the ratio of the specific synchrotron luminosity of the shocked shell plasma and shocked wind plasma, $L_{\nu_c}/L_{\nu_c}$, is $L_{\nu_c}/L_{\nu_c} = L_{\nu_c}/L_{\nu_c} = N_e/\gamma_m$. Thus, $L_{\nu_c} \propto \Delta/\Delta$, where the subscript $s$ denotes quantities related to the shocked shell plasma, and $\Delta (\Delta_s)$ is the width of shocked wind (shell) plasma. The thickness of the region of shocked wind/shell plasma is proportional to the velocity of the shock propagating into the wind/shell plasma, measured in the shocked plasma rest frame, $\Delta/\Delta = (v - u)/u$ (see discussion following eq. [1]). Thus, for $M_s \ll M$ we find $L_{\nu_c}/L_{\nu_c} = (M_s/\eta M)^{1/2} \ll 1$.

The following point should be emphasized here. The model described above is highly simplified. For example, the wind density is assumed to follow a pure $1/r^2$ law and to be free of inhomogeneities, and the expanding shell is assumed uniform with no internal (density, velocity) gradients. In comparing model predictions with observations one should therefore expect an approximate, rather than exact, agreement. Construction of a more detailed, and more accurate, model requires a more detailed knowledge of, for example, the wind density distribution and its inhomogeneities and of the internal structure of the shell. We find that such a more detailed analysis is not warranted by the present data, since the number of free parameters in a more detailed model would be larger than the observational constraints.

3. IMPLICATIONS TO SN 1998bw

The luminosity of the X-ray source associated with SN 1998bw, given in Figure 3 of Kouveliotou et al. (2004), may be approximately described as

$$
L_X \approx 6 \times 10^{40} \text{ ergs s}^{-1}\left(\frac{t}{110 \text{ days}}\right)^{-3/2}, \text{otherwise}.
$$

(9)

The $t^{-3/2}$ decline at late times is consistent with the prediction of equation (6), describing synchrotron emission from the shock driven into the wind at the self-similar stage of expansion, $t > t_{dec}$ (see eq. [4]), at frequencies lower than the cooling frequency, given by equation (7). The time-independent flux at earlier time is consistent with synchrotron emission from the shock driven into the wind at the stage of expansion at constant speed, $t < t_{dec}$, at frequencies higher than the cooling frequency (see eq. [8]). The observed X-ray luminosity may therefore be interpreted as due to the shock driven by a subrelativistic shell into the wind, for which deceleration starts at $t_{dec} \approx 110$ days and the cooling frequency passes through the X-ray band at $t \sim t_{dec}$, i.e., $h\nu_c(t = 110 \text{ days}) \approx 1 \text{ keV}$.

Using equation (7), the requirement $h\nu_c(t = 110 \text{ days}) \simeq 1 \text{ keV}$ implies

$$
(3\epsilon_Bm)^{3/4} \approx 10^{-2}.
$$

(10)

Using this result in equation (6), the observed luminosity at $t = t_{dec} \approx 110$ days implies

$$
3\epsilon_eE_{49} \approx 6.
$$

(11)

Using this result in equation (4), the requirement $t_{dec} \approx 110$ days implies

$$
\beta^2m \approx 0.03/(3\epsilon_e).
$$

(12)

Our model for the X-ray emission of SN 1998bw is consistent with its radio emission, which is also interpreted as synchrotron emission from a shock wave driven into the wind by a mildly relativistic shell ejected by the supernova explosion. Within the framework of this model, radio observations imply electron energy fraction close to equipartition, $3\epsilon_e \approx 1$ (see eq. [17] of Waxman & Loeb 1999). A near-equipartition value
of $\epsilon_\gamma$ is also inferred from radio observations of GRB 970508
for the shock driven by the fireball into surrounding plasma at late stages, where the shock becomes mildly relativistic (Frail, Waxman, & Kulkarni 2000). We therefore adopt $3\epsilon_\gamma \sim 1$, which implies, using equation (11), $E_{10} \approx 6$.

Radio observations further allow us to determine the values of $\epsilon_\gamma$, $\beta$, and $E$ as functions of $\dot{m}$. The lowest allowed value of $\dot{m}$ (and of $E$) is that corresponding to magnetic field equipartition, with larger values of $\dot{m}$ implying lower values of $\epsilon_\gamma$ (and larger values of $E$). Model predictions were shown (Kulkarni et al. 1998; Waxman & Loeb 1999; Chevalier & Li 1999) to be consistent with radio observations for, e.g., \( \{ \dot{m} = 0.04, \epsilon_\gamma \approx 0.1, E_{10} \approx 5, \beta \approx 0.8 \} \) and for \( \{ \dot{m} = 6, E_{10} \approx 50, \epsilon_\gamma \approx 10^{-6}, \beta \approx 0.6 \} \). The energy inferred from X-ray observations, equation (10), implies that the former choice of parameters, \( \{ \dot{m} = 0.04, \epsilon_\gamma \approx 0.1, E_{10} \approx 3 \} \) with $\beta \approx 0.8$, should be chosen for consistency with observations.

X-ray and radio observations therefore overconstrain the model: All model parameters are determined from radio observations with the additional X-ray constraint given by equation (11). The inferred parameter values are consistent with the two additional independent X-ray constraints, equations (10) and (12).

4. DISCUSSION

Simple analytic expressions are given in § 2 for the specific luminosity emitted by a shock wave driven into a wind surrounding a supernova progenitor by a subrelativistic shell ejected by the supernova explosion. We have shown in § 3 that the observed X-ray and radio emission from SN 1998bw are consistent with such a model. In particular, the approximately time-independent X-ray flux at early time, $t < 100$ day, and the $t^{-3/2}$ decline of the flux at late time (see eq. [9]) are characteristic for the emission from a shock driven into a wind by a shell that suffers significant deceleration at $t \approx 100$ day (see eqs. [6] and [8]). Combined X-ray and radio data allow us to determine all model parameters: The shell kinetic energy is $E \approx 10^{49.7}$ ergs, and its initial velocity is $\beta \approx 0.8$. The normalized mass-loss rate\( \approx \frac{M}{10^{-5} M_{\odot} \text{ yr}^{-1}}/(v_\infty/10^3 \text{ km s}^{-1}) \), is $\dot{m} \approx 0.04$. The postshock magnetic field is not far below equipartition, $\epsilon_\gamma \approx 0.1$. Combined X-ray and radio data overconstrain the model and therefore enhance our confidence in its validity. We note that the inferred energy in mildly relativistic ejecta, $\Gamma \beta > 1$ where $\Gamma \equiv (1 - \beta^2)^{-1/2}$, is an order of magnitude higher than the value obtained from analyses of shock emergence from the assumed progenitor of SN 1998bw, $\sim 10^{48.5}$ ergs (Tan et al. 2001).

X-ray observations do not provide, therefore, evidence for existence of an off-axis standard GRB jet associated with SN 1998bw, which may have produced GRB 980425. The lack of observational signatures typically expected to be produced by such an off-axis jet on a 1 yr timescale may be due, however, to the low value of $\dot{m}$, $\dot{m} \lesssim 0.1$, which implies that an off-axis jet will become observable only on a $\approx 10$ yr timescale (Waxman 2004).

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