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A Sub-Relativistic Shock Model for the Radio Emission of SN1998bw

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ABSTRACT

SN1998bw is the most luminous radio supernova ever observed. Previous discussions argued that its exceptional radio luminosity, $\sim 4 \times 10^{38} \text{ erg s}^{-1}$, must originate from a highly relativistic shock which is fully decoupled from the supernova ejecta. Here we present an alternative model in which the radio emission originates from a sub-relativistic shock with a velocity $\simeq 0.3c$, generated in the surrounding gas by the expanding ejecta. In this model, thermal electrons heated by the shock to a relativistic temperature of $\sim 60 \text{ MeV}$, emit synchrotron self-absorbed radiation in the post-shock magnetic field. This model provides an excellent fit to the observed spectra provided that the thermal electrons are in equipartition with the ions behind the shock. The required magnetic field is much weaker than its equipartition value and could have been carried out by the progenitor's wind prior to the supernova explosion. According to this model, the radio emission from SN1998bw is unrelated to the highly relativistic blast wave that produced the γ -ray burst GRB980425.

Subject headings: supernovae: individual (SN1998bw) – radio continuum: general – gamma rays: bursts

1. Introduction

The optical emission spectrum of SN1998bw classifies this event as a Type Ib/Ic supernova (Lidman et al. 1998; Sadler et al. 1998; Patat & Piemonte 1998; Galama et al. 1998), suggesting that it resulted from a core collapse of a massive star which lost its hydrogen and helium envelope. Radio monitoring of the source revealed an exceptionally bright emission which peaked after 12 ± 2 days (Kulkarni et al. 1998). The inferred radio luminosity at the source redshift of 0.0083, $\sim 4 \times 10^{38} \text{ erg s}^{-1}$, is the highest ever observed for a supernova. Multi-frequency measurements around the peak of the lightcurve showed a strong suppression of the emitted flux below a frequency of a few GHz.

Aside from being associated with a rare class of supernovae, SN1998bw also occurred inside the 8 arcminute error circle of the Gamma-Ray Burst GRB980425 which was detected by the

Beppo-SAX satellite at about the same time (Soffitta et al. 1998). The small likelihood for a chance overlap between the two events, $\sim 10^{-4}$, led to the suggestion that the two might be associated (Galama et al. 1998) and to the conjecture that perhaps all SN Ib,c events lead to Gamma-Ray Bursts (Wang & Wheeler 1998; Woosley, Eastman, & Schmidt 1998). However, the non-Euclidean number-count statistics, the event rate, and the temporal and spectral properties of most GRBs imply that SN1998bw-like events could only be associated with a minority fraction, $\lesssim 10\%$ of the GRB population (Bloom et al. 1998). Indeed, the lack of an X-ray afterglow at the position of SN1998bw makes its potential GRB counterpart rare, since all but one of the other 11 GRBs detected so far by Beppo-SAX showed an X-ray afterglow. In fact, a separate X-ray transient source, 1SAXJ1935.3-5252, was identified inside the Beppo-SAX error circle, with a flux comparable to that of the X-ray afterglows of other GRBs. This source provides an alternative to the SN-GRB association. A chance overlap between the error circle of GRB980425 and SN1998bw would fit better theoretical expectations, since supernova models have difficulties accounting for the highly-relativistic shock required to produce a GRB (Woosley et al. 1998). Hence, in gauging the likelihood of an association between SN1998bw and GRB980425 it is of fundamental importance to understand whether the bright radio emission from SN1998bw requires a relativistic shock by itself. If it does, then a more relativistic incarnation of the same shock at earlier times would serve as a plausible source for GRB980425 and hence strengthen the case for an association between the two events.

The velocity of the supernova ejecta was measured from the blue wing of the Ca II line to be $\sim 60,000 \text{ km s}^{-1} = 0.2c$ about a week after the explosion (Stathakis et al. 1998; Kulkarni et al. 1998). Kulkarni et al. (1998) argued that the radio emission must have originated from a shock which was fully decoupled from the main supernova ejecta and expanded at a relativistic speed. They based their assertion on two arguments:

1. If the radio source expanded at the measured ejecta velocity, then the brightness temperature of the source exceeded the threshold temperature for the so-called “inverse Compton catastrophe” (Kellerman & Pauliny-Toth 1969, Readhead 1994). Under these conditions, Compton scattering of the radio photons to higher energies would have dominated the luminosity and violated upper limits on the X-ray flux of SN1998bw (Pian et al. 1998a,b). Relativistic expansion alleviates this problem.
2. The lack of a strong variability at low frequencies implies that the source size exceeded the refractive scintillation scale of $\sim 10^{16} \text{ cm}$ at the peak of the lightcurve, and therefore expanded at a speed $\gtrsim 0.3c$.

In order to put these constraints in a concrete physical context, we have constructed the simplest model for synchrotron emission due to the sub-relativistic ejecta of SN1998bw. In this model, the ejecta push as a piston and generate a strong forward shock in the surrounding gas (the latter being a remnant of the progenitor’s wind prior to the supernova explosion). The shock front heats electrons to a relativistic temperature, and these emit incoherent synchrotron radiation

in the post-shock magnetic field. To our surprise, we had found this model to be consistent with all observational data. In particular, the two constraints mentioned above are satisfied for the following reasons:

1. The relativistic electrons responsible for the observed synchrotron radiation have a typical Lorentz factor of only ~ 360 , and hence scatter the radio photons up in energy only into the optical regime but not into the X-ray band. Hence, the upper limit set by Beppo-SAX on the X-ray luminosity of SN1998bw is not in conflict with this model. In fact, the X-ray luminosity is dominated by scattering of the optical supernova photons by the relativistic electrons. This flux is consistent with the BeppoSAX bound for an expansion speed $\gtrsim 0.3c$ or a corresponding bulk Lorentz factor of only $\gtrsim 1.05$.
2. We find that a shock velocity of $\simeq 0.3c$ is sufficient for explaining the radio properties of SN1998bw. This velocity is $\sim 50\%$ higher than the measured velocity shift of the CaII line. However, since the energy ($\sim 10^{49}$ erg) and mass ($\sim 10^{-4}M_{\odot}$) associated with the radio emitting plasma are small fractions of the total energy and mass of the ejecta, the required shock can be produced by a small amount of material preceding the bulk of the ejecta. In fact, our results are consistent with the modeling of the optical emission from SN1998bw by Woosley et al. (1998, see their §3.2), who suggested that the outer $10^{-3}M_{\odot}$ of the supernova ejecta might have moved at a speed of $\sim c/3$ and carried $\sim 10^{50}$ ergs.

In section §2 we describe our model and derive the expected emission spectrum. In §3 we compare model predictions with the radio data, and derive the physical properties of the emitting electrons. The implications of our results are discussed in §4. Throughout the discussion, we adopt a distance of $d = 38$ Mpc to SN1998bw, assuming that it is located in the galaxy ESO 184-G82 at a redshift $z = 0.0083$ (Lidman et al. 1998; Tinney et al. 1998) and that the Hubble constant is $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Model

In our model, the radio luminosity of SN1998bw is emitted by the material behind a forward shock, which is generated by the expanding ejecta in the medium surrounding the supernova progenitor. Since the ejecta expand at a sub-relativistic velocity, we assume to leading order that the radio flux observed at any given time is emitted by a static spherical shell of radius r . The compressed material behind the shock is expected to occupy a thin shell of width r/η , with $\eta \approx 10$. We denote the mean number density of electrons inside this shell by n .

The energy distribution of radiating electrons can be constrained from the observed synchrotron spectrum of the source. Kulkarni et al. (1998) have assumed that the radiating electrons have a power-law energy distribution. The synchrotron self-absorption spectrum of such an electron population is expected to show a spectral flux index of 2.5 at low photon frequencies (Rybicki & Lightman 1979). However, as noted by Kulkarni et al. (1998), the observed spectral

index is closer to ~ 2 . This indicates that the electron distribution is truncated at low energies, as would be the case if they were thermal. For simplicity, we assume a mono-energetic electron population which should mimic closely the emission properties of thermal electrons. As shown below (see Figs. 1 and 2), our simple model provides an excellent fit to the observed spectra.

The synchrotron power per unit frequency ν emitted by a single electron of Lorentz factor γ is given by (Rybicki & Lightman 1979),

$$P(\nu, \gamma) = \frac{e^3 B}{m_e c^2} F\left[\frac{\nu}{\nu_c(B, \gamma)}\right], \quad (1)$$

where e and m_e are the electron charge and mass, B is the post-shock magnetic field strength and

$$\nu_c \equiv \gamma^2 \left(\frac{eB}{2\pi m_e c} \right). \quad (2)$$

The function $F(x)$ describes the synchrotron power spectrum (Rybicki & Lightman 1979), averaged over an isotropic distribution of pitch angles. The total number of electrons in the radiating shell is $n \times (4\pi r^3/\eta)$, and so the total flux per unit frequency observed at a distance $d = 38$ Mpc is,

$$f_\nu \approx \left(\frac{1 - e^{-\tau_\nu}}{\tau_\nu} \right) \left(\frac{nr^3}{\eta d^2} \right) P(\nu, \gamma), \quad (3)$$

where $\tau_\nu = \alpha_\nu \times (r/\eta)$ is the optical depth per unit frequency for synchrotron self-absorption across the shell thickness. The self-absorption coefficient is given by (Rybicki & Lightman 1979),

$$\alpha_\nu = -\frac{1}{8\pi m_e \nu^2} \int d\gamma' P(\nu, \gamma') \gamma'^2 \frac{\partial}{\partial \gamma'} \left(\frac{1}{\gamma'^2} \frac{dn}{d\gamma'} \right). \quad (4)$$

For mono-energetic electrons of Lorentz factor γ , $dn/d\gamma' = n\delta(\gamma' - \gamma)$, and the absorption coefficient can be integrated by parts. We then get,

$$f_\nu = A \nu^2 \xi \left(\frac{\nu}{\nu_c} \right), \quad (5)$$

where the functions,

$$\xi(x) \equiv \frac{1 - e^{-\tau_\nu}}{1 - [d \ln F(x)/d \ln x]}, \quad (6)$$

$$\tau_\nu(x) \equiv \tau_c x^{-2} F(x) \left[1 - \frac{d \ln F(x)}{d \ln x} \right], \quad (7)$$

and the constants,

$$A \equiv 4\pi \gamma m_e \left(\frac{r}{d} \right)^2, \quad (8)$$

$$\tau_c \equiv \frac{1}{8\pi \nu_c^2} \left(\frac{2nr}{\eta \gamma m_e} \right) \left(\frac{e^3 B}{m_e c^2} \right). \quad (9)$$

The shape of the model spectrum, $\xi(\nu/\nu_c)$, is determined by a single dimensionless parameter, τ_c . The frequency and flux normalizations are determined by the dimensional parameters ν_c and A .

3. Comparison with Observations

The most stringent constraints on the model parameters are obtained, as shown below, from observations near the peak of the radio lightcurve, ~ 12 days after GRB980425. These constraints are derived in §3.1. Observations at later times are discussed in §3.2.

3.1. Observations Near the Peak of the Radio Lightcurve

Figure 1 shows the observational data from the first two epochs (12 and 15 days after GRB980425) when multi-frequency measurements were taken around the peak of the radio lightcurve (Kulkarni et al. 1998). Our simple model of emission from mono-energetic electrons (solid line) provides an excellent fit to the data. The spectral shapes at both epochs are consistent with the model spectral shape in equation (6) for $\tau_c = 0.6$. The frequency and flux normalizations are $\nu_c = 7.6$ GHz, $A = 3.3 \times 10^{-44}$ g at the first epoch, and $\nu_c = 6.2$ GHz, $A = 4.0 \times 10^{-44}$ g at the second epoch. For comparison, we also show the predicted spectra for a power-law population of electrons, $dn/d\gamma \propto \gamma^{-p}$, with $p = 2$ (dashed line) or $p = 3$ (dotted), which are not consistent with the data. Note that the shape of the low frequency tail is independent of all parameters in both models.

The free variables in our model are the density and temperature (Lorentz factor) of the radiating electrons, and the magnetic field strength behind the shock. The spectral constraints 12 days after GRB980425 can be parametrized in terms of the radius of the emitting shell, $r_{16} = (r/10^{16} \text{ cm})$, the synchrotron frequency, $\nu_8 \equiv (\nu_c/8) \text{ GHz}$, the flux amplitude, $A_3 \equiv (A/3 \times 10^{-44} \text{ g})$, and the optical depth coefficient $\tau_{6.6} \equiv (\tau_c/0.6)$. We adopt a value of $\eta = 10$, and note that $r_{16} = 1$ corresponds to an average expansion speed of $\simeq 0.3c$.

Equation (8) yields the electron Lorentz factor,

$$\gamma \approx 3.6 \times 10^2 A_3 r_{16}^{-2}, \quad (10)$$

which is equivalent to an electron temperature of $kT \equiv \frac{1}{3} \langle \gamma m_e v^2 \rangle \approx 60 A_3 r_{16}^{-2} \text{ MeV}$. The magnetic field strength can then be obtained from equation (2),

$$B \approx 2.2 \times 10^{-2} \nu_8 A_3^{-2} r_{16}^4 \text{ G}. \quad (11)$$

Substitution of these results into equation (9) yields,

$$n \approx 5.3 \times 10^4 \nu_8 \tau_{6.6} A_3^3 r_{16}^{-7} \text{ cm}^{-3}. \quad (12)$$

The inferred number density of radiating electrons is much higher than that of the interstellar medium and is likely to be associated with a wind that originated from the supernova progenitor before or during the explosion. The existence of a dense ambient medium is natural given that

the progenitor might have lost its hydrogen and helium envelope prior to the explosion (Patat & Piemonte 1998).

The mass of ions associated with the radiating electrons is small,

$$M_{\text{ion}} \approx 1.1 \times 10^{-4} \mu_2 \nu_8 \tau_{.6} A_3^3 r_{16}^{-4} M_{\odot}, \quad (13)$$

where $\mu = 2\mu_2$ is the atomic mass per free electron. For fully-ionized metal-rich material, $\mu_2 \sim 1$. The total shock energy associated with this mass at a post-shock fluid speed $V = 0.3V_3 \times c$ is given by

$$E_{\text{shock}} \approx M_{\text{ion}} V^2 = 1.7 \times 10^{49} \mu_2 V_3^2 \nu_8 \tau_{.6} A_3^3 r_{16}^{-4} \text{ ergs}. \quad (14)$$

This amounts to less than a percent of the total hydrodynamic energy carried by the supernova ejecta. The radiating shell contains a total electron energy of

$$E_e \approx n \gamma m_e c^2 \times \frac{4\pi r^3}{\eta} = 2.0 \times 10^{49} \nu_8 \tau_{.6} A_3^4 r_{16}^{-6} \text{ ergs}, \quad (15)$$

and a magnetic energy of

$$E_B \approx \frac{B^2}{8\pi} \times \frac{4\pi r^3}{\eta} = 2.5 \times 10^{43} \nu_8^2 A_3^{-4} r_{16}^{11} \text{ ergs}. \quad (16)$$

Our model predicts that the electrons and ions are nearly in *equipartition*,

$$\frac{E_e}{E_{\text{shock}}} \approx 1.2 \mu_2 A_3 V_3^{-2} r_{16}^{-2}. \quad (17)$$

This is consistent with our model assumption that the radio emission is produced by thermal electrons. The post-shock magnetic field is several orders of magnitude weaker than its equipartition amplitude.

Let us now consider the constraints imposed by the X-ray observations of BeppoSAX. The radio radiation energy inside the shell volume is

$$E_{\text{radio}} \approx \left(\frac{4L_{\text{radio}}}{c} \right) \left(\frac{r}{\eta} \right) = 5.3 \times 10^{43} r_{16} \text{ ergs}, \quad (18)$$

where the factor of 4 is due to the fact that synchrotron radiation is approximately isotropic in the shell. Thus, the ratio between the synchrotron luminosity and the inverse Compton luminosity due to scattering of radio photons is

$$\frac{L_{\text{IC-radio}}}{L_{\text{syn}}} = \frac{E_{\text{radio}}}{E_B} \approx 2.1 \nu_8^{-2} A_3^4 r_{16}^{-10}. \quad (19)$$

A single Compton scattering boosts the synchrotron photon frequency up to a value of $\sim (4/3)\gamma^2 \nu_c \approx 1.2 \times 10^{15} \nu_8 A_3^2 r_{16}^{-4} \text{ Hz}$, i.e. into the optical regime. The resulting optical luminosity due to the upscattered synchrotron radiation is well below the thermal supernova emission in this

band – which is ~ 4 orders of magnitude larger than the radio luminosity. The upper limit on the X-ray flux of SN1998bw in the 1–10 keV band (Pian et al. 1998a,b) is obviously in accordance with the negligible X-ray flux due to the scattering of radio photons.

Inverse-Compton scattering of optical supernova photons by the relativistic electrons yields a γ -ray flux which peaks at a photon energy of ~ 300 keV and has a low-energy tail extending into the soft X-ray range. For input radiation of flux F_0 at a frequency ν_0 , the low-energy tail of the inverse-Compton emission due to electrons with a Lorentz factor γ is given by (Rybicki & Lightman 1979), $f_\nu = 0.75\tau_T(\nu/\gamma^2\nu_0)F_0/\nu_0$, where τ_T is the Thomson optical depth of the shell. For the supernova optical emission we approximate F_0/ν_0 by the peak flux of ~ 10 mJy in the V-band ($\nu_0 = 5 \times 10^{14}$ Hz) and obtain

$$F_X \approx 10^{-13}\nu_8\tau_{6.6}A_3r_{16}^{-2} \text{ erg cm}^{-2} \text{ s}^{-1}, \quad (20)$$

for the 1–10keV flux. The predicted flux is consistent with the BeppoSAX upper limit, $\sim 10^{-13}\text{erg cm}^{-2} \text{ s}^{-1}$, for $r_{16} \gtrsim 1$. (Note that the BeppoSAX limit applies to day 8, when both the optical and the radio fluxes are smaller by a factor ~ 2 compared to the corresponding fluxes at day 12 considered here). Inverse-Compton scattering of far infrared photons with initial wavelength $\sim 30\mu\text{m}$, produces a flux that peaks in the X-ray band. However, since the supernova flux at low frequencies is roughly thermal, $f_\nu \propto \nu^2$, the low-frequency tail of the inverse-Compton scattering of optical photons dominates the X-ray flux.

Finally, we calculate the electron cooling time. The synchrotron cooling time is given by,

$$t_{\text{syn}} \equiv \frac{6\pi m_e c}{\gamma \sigma_T B^2} \approx 2 \times 10^2 \nu_8^{-2} A_3^3 r_{16}^{-6} \text{ yrs}, \quad (21)$$

where σ_T is the Thomson cross-section. The inverse-Compton cooling time equals,

$$t_{\text{IC}} = \left(\frac{E_B}{E_{\text{opt}}} \right) \times t_{\text{Syn}} \approx 5\nu_8^2 A_3^{-4} r_{16}^{10} \text{ days}, \quad (22)$$

where, $E_{\text{opt}} = L_{\text{opt}}r/\eta c$, is the optical radiation energy inside the shell volume, and we have used $L_{\text{opt}} = 10^{43}\text{erg s}^{-1}$. Inverse-Compton cooling might therefore be responsible for the decline of the radio lightcurve immediately following the first peak.

3.2. Observations After the Peak of the Radio Lightcurve

Figure 2 shows the observational data around the second, weaker, radio peak (33 days after GRB980425) and at the last observational epoch (58 days after GRB980425). At both epochs, the spectrum is well fitted by synchrotron emission of mono-energetic electrons, with a very small self-absorption optical depth, $\tau_c = 0.06$ and $\tau_c = 0$ at the earlier and later times, respectively. Since $\tau_c \ll 1$, the spectrum is essentially fitted by an unabsorbed synchrotron model and for a given r the observations provide only two constraints on the three model parameters n , γ and

B. Thus, the late time observations can not determine the model parameters in the same way as observations near the first peak do (see §3.1). The decline in the self-absorption optical depth with time may be due to a decrease in the ambient gas density with radius, as expected for a wind. Similarly, the complicated lightcurve structure might reflect clumpiness in the spatial distribution of the ambient gas.

4. Discussion

The emission spectrum predicted by our model for mono-energetic electrons provides an excellent fit to the observational radio data of SN1998bw (see Figs. 1 and 2). This agreement implies that most of the radiating electrons share the same energy, as expected if their distribution is thermal rather than power-law in energy. Comparison of model predictions to data around the peak of the radio lightcurve suggests that the total energy content of the radiating electrons is comparable to the kinetic energy carried by the ions in the forward shock, implying that the two species are in equipartition at a temperature of ~ 60 MeV. On the other hand, the inferred magnetic field is much weaker than its equipartition amplitude and could have originated from a frozen-in seed field that evolved adiabatically with the ambient gas and did not suffer any dynamo amplification behind the shock. The field is likely to have been carried-out with the wind that emerged from the progenitor’s envelope prior to the supernova. In fact, its predicted amplitude of ~ 20 mG [Eq. (11)] is only an order of magnitude higher than that expected from the adiabatic compression of the interstellar $\sim \mu$ G field as the interstellar medium density is increased by ~ 5 orders of magnitude to the value of the ambient gas density [Eq. (12)].

The source radius required in order that our model be consistent with X-ray observations near the peak of the radio emission, ~ 12 days after GRB980425, is only $\sim 10^{16}$ cm. This implies a shock velocity of $\sim 0.3c$ and a corresponding Lorentz factor of only 1.05. For these parameters, the mass and energy associated with the radio emitting plasma are $\sim 10^{-4}M_{\odot}$ and $\sim 10^{49}$ ergs, respectively. Our model is therefore consistent with the modeling of the optical emission by Woosley et al. (1998) who suggested that the outer $10^{-3}M_{\odot}$ of the ejecta in SN1998bw might have moved at a speed of $\sim c/3$ and carried $\sim 10^{50}$ ergs.

Based on these findings we conclude that the radio luminosity of 1998bw could have been produced by the sub-relativistic shock in front of the supernova ejecta. In our model, there is no need to invoke an ultra-relativistic shock that might have been related to GRB980425. This raises the possibility that GRB980425 was associated instead with the transient X-ray source 1SAXJ1935.3-5252.

The large scatter in the radio luminosities of Type Ib/Ic supernovae (for examples, see Weiler & Sramek 1988; van Dyk et al. 1993; and Weiler et al. 1998) is not surprising in view of the fact that the total energy and mass of the radio-emitting plasma are negligible fractions of the overall energy and mass budgets of the supernova ejecta. The scatter might also be enhanced by viewing

angle variations due to non-spherical explosion geometries (Höflich, Wheeler, & Wang 1998).

Our discussion ignored various effects, such as the increase in the self-absorption optical depth towards the limb of the source, the free-free absorption in the surrounding stellar wind, or the nonzero time delay due to the finite light crossing time across the source. Future work is necessary in order to refine the detailed predictions of this model.

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Fig. 1.— Emission spectrum from SN1998bw around the peak of the radio lightcurve. The data points from Kulkarni et al. (1998) are shown 12 days (squares) and 15 days (circles) after GRB980425 and are compared to theoretical predictions for a population of electrons which is either mono-energetic (solid line), or power-law in energy with a spectral index of $p = 2$ (dashed) and $p = 3$ (dotted). The frequency and flux of the second epoch observations (15 days after GRB980425) are renormalized so as to show that the spectra at both epochs have a similar shape (frequency multiplied by 1.23, flux by 1.24). The model parameters for mono-energetic electrons are $\tau_c = 0.56$, $A = 3.3 \times 10^{-44}$ g, $\nu_c = 7.6$ GHz [see Eq. (5)].

Fig. 2.— Emission spectrum from SN1998bw around the second radio peak (circles) and at the last observational epoch (squares), 33 and 58 days after GRB980425 respectively (Kulkarni et al. 1998). The data points are compared to the theoretical predictions for a mono-energetic electron distribution with $\tau_c = 0.06$ at the first epoch and $\tau_c = 0$ at the second epoch.