Supernova Explosions with Close Massive Companion: SN 1998bw/GRB 980425

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Abstract

Some gamma ray bursts may be produced by supernovae exploding in close massive binary systems (type Ib/c supernovae) as suggested by the recent observation of SN 1998bw/GRB 980425. We propose that high energy radiation observed in such gamma ray bursts may be produced by synchrotron radiation of electrons accelerated by 1st order Fermi acceleration at a quasi-stationary shock in the high velocity SN ejecta colliding with the companion star or some other nearby massive object. Nuclei would also be accelerated, and could give rise to an observable fluence of high energy neutrinos at Earth.

1 Introduction:

GRB 980425 was observed in low energy γ-rays by the OSSE and Beppo-SAX detectors (Kippen et al. 1998, Soffitta et al. 1998). It was rather a weak burst with the spectrum being well described by a power law with a steepening at ~ 150 keV, essentially a cut-off. During the burst which lasted ~ 40 s (Kippen et al., 1998), the average index below the break was ~ -1.9 consistent with that expected for synchrotron cooling of an E^{-2} electron spectrum at production by shock acceleration. The burst was identified with Supernova 1998bw (type Ib/c) at a redshift 0.0085 (Galama et al. 1998). This identification gives a peak burst luminosity $\sim (5.5 \pm 0.7) \times 10^{46}$ erg s^{-1}. GRB 980425 belongs to the class of long duration GRB (Kouveliotou et al. 1993) with no hard γ-ray emission, and so the arguments requiring highly relativistic motion of the emission region do not apply to this object. Its energy budget in X-rays/hard X-rays is relatively low, and the radio emission from SN 1998bw had a low level of polarization suggesting that the explosion was rather spherical, and did not involve highly collimated outflows.

Berezinsky et al. (1996) described a model in which a type Ia supernova of a white dwarf in a binary system with a red giant caused a GRB. Supernovae exploding in close massive binaries probably produce type Ib/c supernovae (Nomoto et al. 1990). We suggest that electrons and nuclei may be accelerated at a stationary shock which could occur as a result of the interaction of the high velocity component of the SN ejecta with a massive companion such as an OB star. Very collimated high energy radiation may then be produced, for example, as a result of a highly anisotropic distribution of accelerated particles accelerated at a relativistic shock, or by the magnetic field and shock topology in the acceleration region. See Protheroe and Bednarek (1999) for full details and additional references.

2 Model Parameters

For an initially exponentially declining density profile, the density, ρ (g cm^{-3}) and Lorentz factors of the ejecta at radius r (cm) are related by $Q \approx \Gamma\beta(\rho r^3)^{0.2}$, where $Q \approx 3.5 \times 10^5$ g$^{0.2}$ and Γ is the Lorentz factor of matter moving with velocity βc (Woosley et al. 1999). This allows us to obtain the density at the distance of the companion star $R_{\rm sep}$ as a function of time t measured from the explosion, and we use this density to obtain the radius of the photosphere which corresponds to unit Thomson optical depth from this radius to infinity ($\tau_T = 1$ for 5.1 g cm^{-2} for fully ionized carbon). In Fig. 1 we show the photosphere radius, $R_{\rm photo}$, as a function of time since the explosion. The bolometric luminosity of SN 1998bw was $\sim 1.7 \times 10^{42}$ erg s^{-1} shortly after the explosion (see fig. 3 of Woosley et al. 1999), giving $T_{\rm photo}$ as shown in Fig. 1 which is seen to be below 1.5×10^5 K for $t > t_0 \equiv R_{\rm sep}/c \approx 113$ s. However, the light received at the companion star at time $t_{\rm rec}$ was emitted at an earlier time when the photosphere was hotter, and the solid angle subtended by

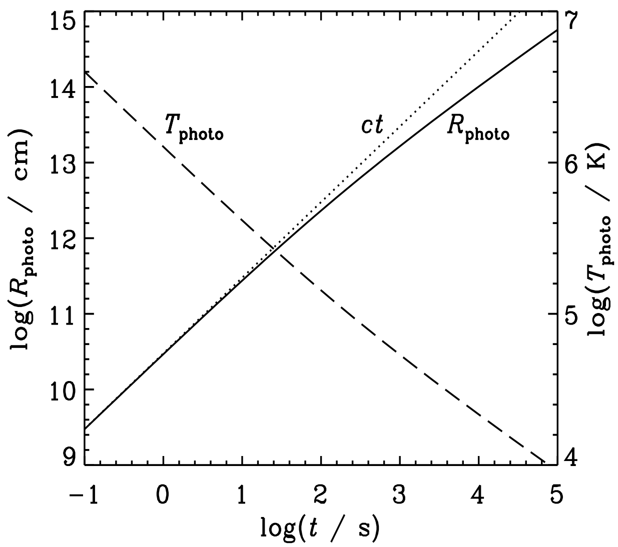

Figure 1: *Radius and temperature of the photosphere as a function of time after the explosion.*

In our model, the GRB is produced near the companion star, and the arrival of the photosphere determines the end of the GRB emission because at that time the optical depth of escaping X-rays/hard X-rays to Compton scattering is 1, and subsequently rapidly increases. For the model to be viable, the separation must be greater than the radius of the companion star. Solving $[t - R_{\rm photo}(t)/c] = 40$ s gives a separation of 3.4×10^{12} cm which is greater than an OB star's radius, unlike short-duration bursts. This distance is also of the same magnitude as close binary separations.

We assume the photosphere emits black-body radiation, and so its temperature is given by $T_{\rm photo} = 1.94 \times 10^5 L_{42}^{1/4} R_{\rm photo,\,12}^{-1/2}$ where $L = 10^{42} L_{42}$ erg s^{-1} is the bolometric luminosity and $R_{\rm photo} = 10^{12} R_{\rm photo,\,12}$ cm.

the photosphere was smaller. We therefore include the light propagation times when calculating the radiation field.

We shall next consider the likely location of the shock in relation to the companion star, and this will depend on the ram pressure of the arriving SN ejecta, $p_{\rm ram} = (\rho\gamma\beta c)(\beta c)$. The density and ram pressure are plotted in Fig. 2(a). The ram pressure plotted far exceeds those present in the stellar wind of a typical OB star, and also exceeds a magnetic pressure of $\sim 4 \times 10^4$ erg cm^{-3} corresponding to a stellar surface magnetic field of 10^3 G. The SN ejecta will compress the star's dipole magnetic field until its magnetic pressure balances the ram pressure. Taking $R_{\rm star} \sim 10^{12}$ cm and $B_{\rm star} \sim 10^3$ G as reasonable values for OB stars, at $(t - t_0) = 1$ s, 10 s, and 100 s, the shock height would be $h_{\rm shock} \sim 1.6 \times 10^{-2} R_{\rm star}$, $1.6 \times 10^{-3} R_{\rm star}$, and $1.5 \times 10^{-4} R_{\rm star}$, respectively.

2.1 Acceleration parameters We assume acceleration of electrons and protons occurs at a shock created by the interaction of the SN ejecta and the binary companion star at a rate $dE/dt = \eta E c / r_g \approx 9 \times 10^3 \eta B$ GeV s^{-1} where η is the acceleration rate parameter, r_g is the gyroradius, and B is in Gauss. The acceleration rate paramenter η can be determined from the assumption that the maximum electron energy is determined by a balance between energy gains and synchrotron losses. The maximum Lorentz factor of electrons accelerated in magnetic field B is $\gamma_{\rm e,max} \approx 1.2 \times 10^6 \eta^{1/2} B^{-1/2}$. The break energy is then $\epsilon_{\rm max} = m_{\rm e} c^2 (B/B_{\rm cr}^e) \gamma_{\rm e,max}^2 \approx 300 m_{\rm e} c^2 \eta$ where $B_{\rm cr}^e = 4.4 \times 10^{13}$ G, and from this we can uniquely estimate the acceleration rate parameter. For $\epsilon_{\rm max} \sim 150$ keV, we obtain $\eta \approx 10^{-3}$, independent of the assumed magnetic field.

2.2 Energetics and beaming Fig. 2(b) shows the kinetic energy flux at $r = R_{\rm sep}$. For $(t - t_0) < 100$ s the shock is relativistic, and the distribution of accelerated particles will be highly anisotropic. Typical angles of particles returning from upstream to the shock are $\sim \sqrt{2}/\Gamma$ as measured in the upstream frame (Gallant and Achterberg 1999) which is also the frame of the SN ejecta at the shock. Transforming to the shock frame (observer's frame) we find typical angles $\theta_{\rm beam} \sim 1/\sqrt{2}\Gamma^2$. Hence the beaming solid angle will be

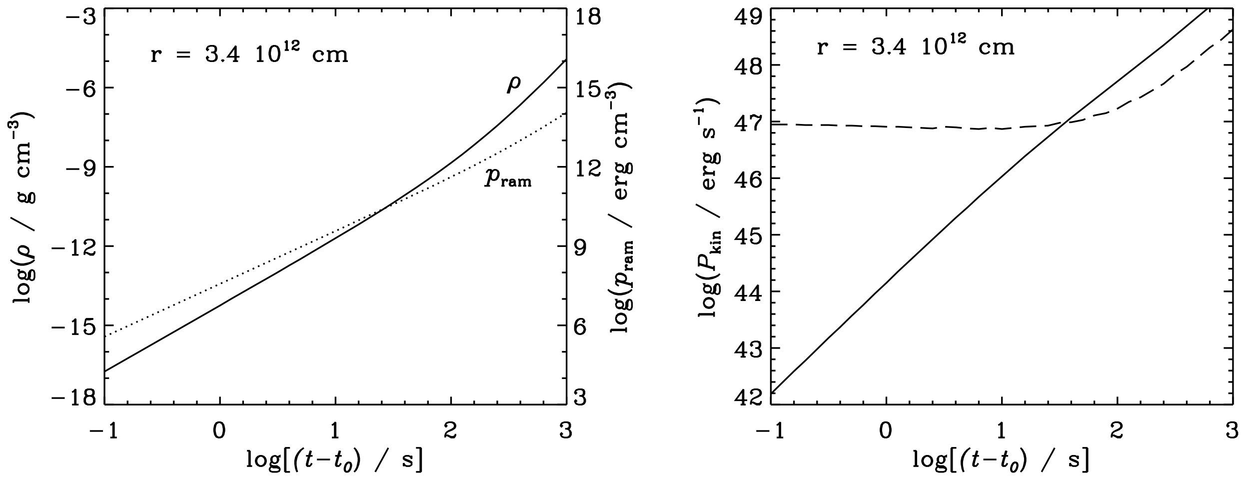

Figure 2: *(a) Density and ram pressure of matter arriving at distance* $r = 3.4 \times 10^{12}$ *cm as a function of time delay following arrival of fastest matter. (b) Kinetic energy flux of matter arriving at distance* $r = 3.4 \times 10^{12}$ *cm as a function of time delay following arrival of fastest matter (solid curve). The dashed curve shows the effect multiplying by the fraction* $k \approx 0.2$ *intercepted by area* $\pi R_{\rm star}^2$ *for* $R_{\rm star} = 10^{12}$ *cm, and multiplying by the beaming factor.*

$\Omega_{\rm beam} = 2\pi(1 - \cos\theta_{\rm beam}) \sim \pi/2\Gamma^4$.

We have added to Fig. 2(b) the product of the kinetic energy flux, the fraction of the SN ejecta intercepted by the shock at the companion star, and the beaming factor $4\pi/\Omega_{\rm beam} \sim 8\Gamma^4$. We see that the resulting 'apparent kinetic energy flux' available (dashed curve) is approximately constant at $\sim 10^{47}$ erg s^{-1} while the shock is relativistic, and then increases with time. This is interestingly of the right order of magnitude, and implies a very high acceleration efficiency. Nevertheless, we find it encouraging, and will assume that the apparent kinetic energy flux available has the time dependence as given by the dashed curve in Fig. 2(b), and is normalized such that for $(t - t_0) < 100$ s it is equal to twice the estimated peak luminosity of GRB 980425 assuming an electron to proton ratio of one.

Table 1: *Magnetic field, maximum energies (GeV) of electrons (due to synchroton loss) and protons, cause of proton spectrum cut-off, and proton interaction processes (energy range in GeV, time of emission in s) for* $B^2/8\pi = p_{\rm ram}$ *and* $\eta = 10^{-3}$ *at distance* $r = 3.4 \times 10^{12}$ *cm.*

$t - t_0$ (s)	B (G)	$E^e_{\rm max}$	$E^p_{\rm max}$	Cause	Process (energy range, time)
1.0	3.2×10^4	10	2.5×10^5	Time	pN ($<10^5$, $\sim$ 32); Syn. ($>10^5$, $\sim$ 32)
10.0	3.2×10^5	3	10^7	Syn.	pN ($<10^5$, $\sim$ 32); Syn. ($>10^5$, $\sim$ 32)
100	3.2×10^6	1	3×10^6	Syn.	pN ($<3\times10^5$, 100); Syn. ($>3\times10^5$, 100)
1000	5×10^7	0.25	10^5	pN	pN ($<10^5$, 1000)

3 Results and Discussion

We find interactions with matter to be more important than interactions with photons of the companion star or supernova. The maximum energies, the loss processes responsible for the cut-offs, and the emission processes of the accelerated electron and proton populations are summarized in Table 1. We show in Fig. 3(a) the $(\nu_\mu + \bar\nu_\mu)$ flux at Earth for E^{-2} proton spectra by pion production interactions as given in Table 1.

We estimate the muon signal expected in a 1 km^2 detector using the $P_{\nu\to\mu}(E_\nu, E_\mu^{\rm min})$ function given in fig. 2 of Gaisser et al. (1995) for $E_\mu^{\rm min} = 1$ GeV, modified for other $E_\mu^{\rm min}$ values in a way consistent with that given for $E_\mu^{\rm min} = 1$ TeV. The effects of shadowing for vertically upward-going neutrinos have been included using the shadow factor $S(E_\nu)$ given in fig. 20 of Gandhi et al. (1998). The expected neutrino induced muon signal for the horizontal and vertical directions corresponding to the time-integrated neutrino fluxes shown in Fig. 3(a) are shown in Fig. 3(b). We see that for GRB 980425 we would expect ~ 3 muons above 1 TeV. For nearer or more powerful GRB—SN Ib/c associations, the signal expected would be higher.

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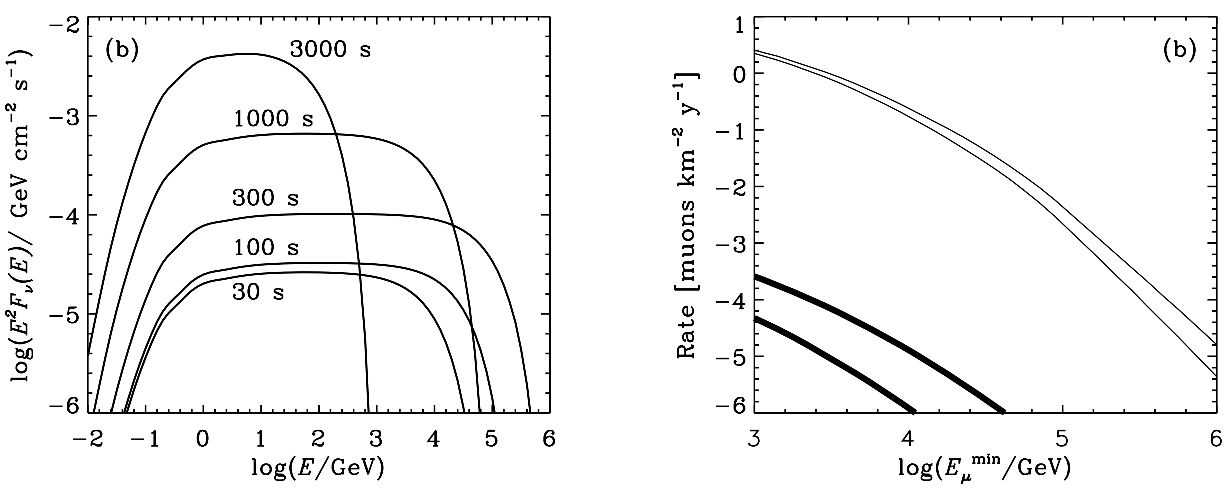

Figure 3: *(a) Predicted $(\nu_\mu + \bar{\nu}_\mu)$ flux at various times. (b) Time-integrated muon signal corresponding to the fluxes given in part (a) together with the atmospheric background during 100 s arriving within 5° of the GRB direction (thick solid curves). Upper curves give signal expected if source direction is horizontal, lower curves apply if source direction is vertically down.*