**ABSTRACT**

The post-burst evolution of fireballs that produce γ-ray bursts (GRBs) is studied, assuming the expansion of fireballs to be adiabatic and relativistic. Numerical results as well as an approximate analytic solution for the evolution are presented. Owing to the adoption of a new relation between $t$, $R$ and $\gamma$, our results differ markedly from previous studies. Synchrotron radiation from the shocked interstellar medium is carefully calculated, using a conventional set of equations. The observed X-ray flux of GRB afterglows can be reproduced easily. Although the optical afterglows seem much more complicated, our results can still present a rather satisfactory agreement with observations. We also find that the expansion will no longer be highly relativistic about 4 d after the main GRB. We thus suggest that the marginally relativistic phase of the expansion should be investigated so as to check the afterglows observed a week or more later.

**Key words:** relativity – shock waves – gamma-rays: bursts.

**1 INTRODUCTION**

Since their discovery nearly 30 years ago (Klebesadel, Strong & Olson 1973), γ-ray bursts (GRBs) have been one of the biggest mysteries in astrophysics (Fishman & Meegan 1995), primarily because they have remained invisible at longer wavelengths. The situation started to change drastically in 1997 because of the Italian–Dutch BeppoSAX satellite (Piro et al. 1995), whose prominent observations led to the discoveries of multi-wavelength counterparts of several GRBs: GRB 970111 (Costa et al. 1997a), GRB 970228 (Costa et al. 1997b), GRB 970402 (Feroci et al. 1997; Heise et al. 1997) and GRB 970508 (Costa et al. 1997d). The corresponding afterglows in X-rays (GRB 970228: Costa et al. 1997c; GRB 970402: Piro et al. 1997a; GRB 970508: Piro et al. 1997b), in the optical band (GRB 970228: Groot et al. 1997; van Paradijs et al. 1997; Sahu et al. 1997; Galama et al. 1997; GRB 970508: Bond 1997), and in radio band (GRB 970508: Frail et al. 1997) were observed with unprecedented enthusiasm and collaboration, and the results are exciting. GRB 970228 seems to be associated with a faint galaxy (van Paradijs et al. 1997), and the redshift of the optical counterpart of GRB 970508 was even determined to be between 0.835 and 2 (Metzger et al. 1997). Very recently it has also been reported that X-ray afterglows of GRB 970616 (Marshall et al. 1997a; Murakami et al. 1997a), GRB 970828 (Remillard et al. 1997) and possibly GRB 970815 (Smith et al. 1997) have been observed as a result of cooperation between the Compton Gamma-Ray Observatory and the Rossi X-ray Timing Explorer. These observations strongly suggest that GRBs originate from cosmological distances. The fireball model (Goodman 1986; Paczyński 1986; Rees & Mészáros 1992, 1994; Mészáros & Rees 1992; Mészáros, Laguna & Rees 1993; Mészáros, Rees & Papanastassiou 1994; Katz 1994; Sari, Narayan & Piran 1996) has become the most popular and successful model for GRBs, although other models, such as a hypernova scenario proposed by Paczyński (1998), cannot be eliminated at present.

After producing the main GRB, the cooling fireball is expected to expand as a thin shell into the interstellar medium (ISM) and generate a relativistic blast wave, although whether the expansion is highly radiative (Vietri 1997a,b) or adiabatic is still controversial. Afterglows at longer wavelengths are produced by the shocked ISM (Mészáros & Rees 1997). Much analytical work on GRB afterglows has been done (Waxman 1997a,b; Tavani 1997; Sari 1998), and it has been found that, for adiabatic expression, $R \propto t^{1/3}$, $\gamma \propto t^{-3/8}$, where $R$ is the shock radius measured in the static frame of the burst, $\gamma$ is the Lorentz factor of the shocked ISM measured in the frame of the observer and $t$ is the observed time. These scaling laws are valid only at the ultranegative expansion stage ($\gamma \gg 1$).

The purpose of this work is to study numerically the evolution of adiabatic fireballs from the ultrarelativistic expansion stage to the mildly relativistic expansion stage. We show that, although the scaling law between $\gamma$ and $t$ at the ultrarelativistic expansion stage obtained in this work is the same as above, our coefficient for $\gamma$ differs dramatically from that of Waxman (1997a,b). A detailed set of equations is presented to calculate synchrotron radiation from the shocked ISM. We see that radiation during the mildly relativistic phase ($2 < \gamma < 5$), which was obviously neglected in previous studies, is quite important.

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The structure of this paper is as follows. In Section 2 we calculate the dynamical evolution of the relativistic shock. The difference between our results and those of Waxman is stressed. Synchrotron radiation from the shocked ISM is calculated and compared with observations in Section 3, and a brief discussion is given in the final section.

2 DYNAMICAL EVOLUTION OF FIREBALLS

A fireball with total initial energy \( E_0 \) and initial bulk Lorentz factor \( \eta = E_0/M_0c^2 \), where \( M_0 \) is the initial baryon mass and \( c \) the velocity of light, is expected to radiate half of its energy in \( \gamma \)-rays during the GRB phase (Sari & Piran 1995), as a result either of an internal shock or of an external shock mechanism (Paczynski & Xu 1994; Vietri 1997b, and references therein). Subsequently the fireball will continue to expand as a thin shell into the ISM, generating an ultrarelativistic shock.

The jump conditions for the shock can be described as (Blandford & McKee 1976)

\[
n' = (4\gamma + 3)n, \quad e' = (4\gamma + 3)\gamma nm_p c^2, \quad \Gamma^2 = \frac{(\gamma + 1)(4\gamma - 1)^2}{8\gamma + 10},
\]

where \( n \) is the number density of the unshocked ISM, \( n' \) and \( e' \) are the number density and energy density of the shocked ISM in the frame comoving with the shell, \( m_p \) is the proton mass and \( \Gamma \) is the Lorentz factor of the shock in the frame of the observer. These equations are valid for describing ultrarelativistic shocks as well as mildly relativistic shocks (Blandford & McKee 1976). For \( \gamma \gg 1 \), we have \( e' = 4\gamma^2 nm_p c^2 \) and \( \Gamma = \sqrt{2}\gamma \). We will assume that the shocked ISM in the shell is homogeneous.

As usual, the expansion of the fireball is thought to be adiabatic, during which energy is conserved, so we have

\[
4\pi R^2 \left(1 - \frac{v}{c}\right) \frac{2}{\gamma} e' = \frac{E_0}{2} + \beta M_0 c^2,
\]

where \( v \) is the observed velocity of the shock and \( R(1 - v/c)\gamma \) is the thickness of the shocked ISM in the comoving frame. \( \beta \) is defined as \( \beta = 4\pi R^2 nm_p/(3M_0) \). Using equation (1), equation (4) can be further expressed as

\[
3\gamma^3(1 - \sqrt{1 - \Gamma^2})/(4\gamma + 3)\beta = \frac{\eta}{2} + \beta.
\]

Figure 1. Evolution of the shock radius. The solid line is our numerical result and the dashed line our approximate analytic solution (equation 10). Waxman’s result is plotted by the dotted line. Only the dot–dashed line corresponds to \( M_0 = 10^{-5} M_\odot \); the other lines correspond to \( M_0 = 2 \times 10^{-5} M_\odot \).

Figure 2. Evolution of \( \gamma \). The solid line is our numerical result and the dashed line our approximate solution (equation 10). Waxman’s result is plotted by the dotted line. Only the dot–dashed line corresponds to \( M_0 = 10^{-5} M_\odot \); the other lines correspond to \( M_0 = 2 \times 10^{-5} M_\odot \).

\[ \gamma(t) \] can be evaluated numerically. We take \( E_0 = 10^{52} \) erg, \( n = 1 \) cm\(^{-3} \), and \( M_0 = 10^{-5} \) and \( 2 \times 10^{-5} M_\odot \). Using these equations, we numerically study the evolution of \( \gamma \) and \( R \) as functions of observed time. Our results are plotted in Figs 1 and 2, where the dot–dashed line corresponds to \( M_0 = 10^{-5} M_\odot \), and the other lines to \( M_0 = 2 \times 10^{-5} M_\odot \). It can be seen that \( M_0 \) only influences the early-time evolution of the fireball.

Under the assumption that \( \gamma \gg 1 \), we can derive a simple analytic solution,

\[
R^3 \approx R_0^3 + 4Kr,
\]

\[
\gamma = \left(\frac{K}{2cR^3}\right)^{1/2},
\]

where \( K \) is the initial value of \( R \). In Figs 1 and 2, we also plot the results of equations (9) and (10). It is clear that at early times, when \( \gamma \gg 1 \), the analytic solution is quite a good approximation for the numerical results.
If \( R \gg R_0 \), that is, \( t \gg \tau \), where \( \tau \) refers to the duration of the main GRB, then we can rewrite equations (9) and (10) as

\[
R = 8.93 \times 10^{15} \frac{E_{51}^{1/4} n_1^{1/4}}{c} \text{ cm},
\]

(11)

\[
\gamma = 193 E_{51}^{1/8} n_1^{-1/8} t^{-3/8},
\]

(12)

where \( E_0 = 10^{51} E_{51} \) erg, \( n_1 \) cm\(^{-3} \) and \( t \) is in units of seconds. We find that, when \( \gamma \gg 1 \) and \( t \gg \tau \), equations (11) and (12) also fit the numerical results very well. Equations (11) and (12) are the scaling laws for \( R \) and \( \gamma \) mentioned in the Introduction.

We next compare equation (12) with previous studies. The scaling law for \( \gamma \) is quite simple, but the coefficient should be treated with great caution, since it may affect synchrotron radiation and observational behaviour significantly (Sari 1997). Waxman (1997a,b) derived a result with a larger coefficient: \( \gamma = 332 E_{51}^{1/8} n_1^{-1/8} t^{-3/8} \). As shown in the next section, this will result in very strong radiation in both X-ray and optical bands. We have plotted his results for \( R(t) \) and \( \gamma(t) \) in Figs 1 and 2. The discrepancy is noticeable. The difference between his and our results is due to the fact that he has used a relation between \( t \) and \( \gamma \) of \( t = R/(2\gamma^2 c) \), which may be incorrect for the evolution of ultra-relativistic adiabatic fireballs (Sari 1997), and we have adopted another relation: \( t = R/(8\gamma^2 c) \), which is obtained by integrating equations (7) and (8).

We want to emphasize that the equations in this section are correct only for ultra-relativistic blast waves (\( \gamma \gg 1 \)) and mildly relativistic blast waves (\( 2 < \gamma < 5 \)). This means that after about 3\( 0 \) our numerical results for the parameters used in the above might be spurious. Of course, our calculation can be prolonged considerably by adjusting the parameter (\( E_5/n_1 \)).

### 3 X-RAY AND OPTICAL AFTERGLOWS

#### 3.1 Synchrotron radiation

Electrons in the shocked ISM are highly relativistic. Inverse Compton cooling of the electrons may not contribute to emission in the X-ray and optical bands in which we are interested. We will consider only synchrotron radiation below. The electron distribution in the shocked ISM is assumed to be a power-law function of electron energy, as expected for shock acceleration:

\[
\frac{dn_e}{d\gamma} \propto \gamma^{-p} \quad (\gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}}),
\]

(13)

where \( \gamma_{\text{min}} \) and \( \gamma_{\text{max}} \) are the minimum and maximum Lorentz factors, and \( p \) is the index, varying between 2 and 3. We suppose that the magnetic field energy density (in the comoving frame) is a fraction \( \xi_0^2 \) of the energy density, \( B^2/8\pi = \xi_0^2 \epsilon_0 \), and that the electrons carry a fraction \( \xi_0 \) of the energy. \( \gamma_{\text{min}} \) is determined by

\[
\gamma_{\text{min}} = \frac{\xi_0 \epsilon_0}{m_e} \left( \frac{p - 2}{p - 1} \right). \tag{14}
\]

We estimate \( \gamma_{\text{max}} \) by equating, as usual, the electron acceleration time-scale with the synchrotron cooling time-scale, and find (Mészáros et al. 1993; Vietri 1997a)

\[
\gamma_{\text{max}} \approx 10^8 B^{-1/2}, \tag{15}
\]

The spectral property of synchrotron radiation is clear (Rybicki & Lightman 1979). In the comoving frame, the characteristic photon frequency is \( \nu_s = eB \gamma_{\text{min}}^2/(2\pi m_e c) \), where \( e \) is the electron charge. The spectrum peaks at \( \nu_{\text{max}} = 0.29 \nu_m \). For frequency \( \nu \gg \nu_{\text{max}} \), the flux density scales as \( S_c \propto \nu^{-\alpha} \), where \( \alpha = (p - 1)/2 \), and, for \( \nu < \nu_{\text{max}} \), \( S_c \propto \nu^{1/2} \). Below we derive a formula for synchrotron radiation. First, using equation (1), we further express equation (13) as

\[
\frac{dr_c}{d\gamma_e} = C' \gamma_e^p, \tag{16}
\]

where

\[
C' = (p - 1) \gamma_{\text{min}}^{-1} (4 \gamma + 3).n. \tag{17}
\]

Secondly, the synchrotron radiation power emitted per unit volume is

\[
j(\nu) = \frac{\nu}{m_e c^2} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \gamma q \epsilon \nu^2 F\left( \frac{\nu}{\nu_c} \right) d\gamma_e, \tag{18}
\]

with

\[
F(x) = \frac{1}{2} \int_{x}^{\infty} K_{5/2}(t) dt, \tag{19}
\]

and

\[
\nu_c = \frac{\gamma_e^2 e B}{2 \pi m_e c}, \tag{20}
\]

where \( K_{5/2}(t) \) is the Bessel function. The specific intensity at frequency \( \nu \) in the comoving frame is thus written as

\[
I_{\nu, c} = \frac{1}{4\pi} j(\nu) R \left( 1 - \frac{v}{c} R \right) \gamma. \tag{21}
\]

The observed frequency \( \nu_0 \) and specific intensity \( I_{\nu_0, o} \) are related to \( \nu \) and \( I_{\nu, c} \) via the following relativistic translations (Rybicki & Lightman 1979):

\[
\nu_0 = (1 + v/c) \nu, \tag{22}
\]

\[
I_{\nu_0, o} = (1 + v/c)^3 \gamma I_{\nu, c}. \tag{23}
\]

In previous work, it has been customary in analytic derivations to consider that at a given time \( t \) the emitting surfaces is located at \( 2\gamma^2 c t \) and that the disc seen by the observer has a radius \( \gamma c t \), as it would in the absence of the deceleration (i.e. an ellipsoid). Then the relativistic fireball expanding isotropically will produce an observed flux \( S_{\nu_0, o} = \pi(\gamma c t)^2 I_{\nu_0, o}/D^2 \), where \( D \) is the distance from the source to the Earth (Rees 1966). However, the deceleration dynamics was recently investigated in more detail and it was found that, owing to the deceleration, the emitting surfaces become distorted ellipsoids, and, at sufficiently late times, most of the light (either bolometric or in a given band) comes from a ring-like surface (Waxman 1997c; Panaitescu & Mészáros 1998). For a given observed frequency band, as the shocked fluid is decelerated, the peak frequency \( \nu_{\text{peak}} = \gamma \nu_{\text{max}} \) crosses the observed band, and the region radiating in that band shrinks from the full disc to a narrow ring. According to Panaitescu & Mészáros (1998), at energies far below or above \( \nu_{\text{peak}} \), the ratios of the equivalent radii of the emitting surfaces to \( \gamma c t \) are approximately constant in time. For example, these ratios are 2.8 and 3.3 respectively, by assuming a homogeneous ISM and an adiabatic expansion. We use the following equation to evaluate the observed flux density:

\[
S_{\nu_0, o} = \frac{\pi(\gamma c t)^2 I_{\nu_0, o}}{D^2}. \tag{24}
\]

where \( k = 2.8 \) for \( \nu_0 < \nu_{\text{peak}} \) and \( k = 3.3 \) for \( \nu_0 > \nu_{\text{peak}} \). Since \( \nu_{\text{peak}} \) enters the X-ray and optical bands very quickly, the ‘visible’ zone acts as a narrow ring for most of the time and equation (24) should
be accurate enough for our calculations. So we obtain the observed flux density

$$S_{\nu_0} = \frac{1}{4} \left(1 + \frac{v}{c}\right)^3 \left(1 - \frac{v}{c}\right) \frac{R(kc)^2}{D^2} \ln \left(\frac{\nu_1}{\nu_u}\right),$$

(25)

This equation shows that $S_{\nu_0}$ strongly depends on $\gamma$, so that the coefficient in equation (12) should be treated carefully (Sari 1997).

The flux observed by a detector is an integral of $S_{\nu_0}$:

$$F_{\nu_0} = \int_{\nu_u}^{\nu_1} S_{\nu_0} \, d\nu_0,$$

(26)

where $\nu_u$ and $\nu_1$ are the upper and lower frequency limits of the detector.

3.2 Comparison with observations

Following the numerical solution in Section 2, we continue to calculate the afterglow in the X-ray and optical bands, using equation (26). Some of the parameters are taken as follows:

\[ p = 2.5, \xi_0 = 0.5 \text{ and } \xi_R = 0.1, \]

which are required by the spectral and temporal properties of GRBs (Sari et al. 1998; Wijers, Rees & Mészáros 1997). The distance $D$ is set to be 3 Gpc. In order to get an X-ray flux, we integrate equation (26) from 0.1 to 10 keV, since BeppoSAX and ASCA work approximately in this band. For the optical flux, we use equation (25) to calculate the $R$-band flux density ($S_{\nu_0}$). Our numerical results for the X-ray flux ($F_X$) and $S_R$ are illustrated in Figs 3 and 4.

Also plotted in Figs 3 and 4 are some observational data, which will make it possible for us to see to what extent the model could agree with observations. The X-ray data are quoted from Wijers et al. (1997), Frontera et al. (1997), Costa et al. (1997a), Butler et al. (1997), Feroci et al. (1997), Piro et al. (1997a), Costa et al. (1997d), Piro et al. (1997b), Marshall et al. (1997a), Murakami et al. (1997a), Remillard et al. (1997), Marshall et al. (1997b), Murakami et al. (1997b) and Greiner et al. (1997). Please note that, since different detectors work in different bands and here we have converted their flux data into the 0.1–10 keV band linearly, errors of up to a factor of 2 are thus possible.

In Fig. 4 the observed $R$-band flux densities are quoted from Wijers et al. (1997), Galama et al. (1997) and Fruchter et al. (1997).

Although the observed GRBs are expected to reside at different distances and their intrinsic parameters such as $E_0$, $n$, $p$, $\xi_e$ and $\xi_R$ may vary markedly, it can be seen from Fig. 3 that the observed X-ray data are really quite easily reproduced by our model. The optical afterglow from GRB 970228 can be fitted quite well for $t \leq 3 \text{ d}$. However, after about 3 d the theoretical light curve shows too sharp a decline. As mentioned in Section 2, this might be spurious, since our calculations are reliable only before about 3 d. Because the X-ray afterglow of GRB 970228 was observed 11.6 d later and the optical afterglow was observed more than 6 months later, we suggest that a marginally relativistic ($1 < \gamma < 2$) afterglow model should be considered so as to provide a perfect description for the afterglow. We noticed that Wijers et al. (1997) have pointed out that when the GRB remnant becomes non-relativistic and enters the Sedov–Taylor phase, the optical flux declines as $F_{\nu} \propto t^{(1-1.5a)/2}$, decaying faster than at earlier times.

On 1997 September 4 the Hubble Space Telescope observed the afterglow of GRB 970228 for the third time and found that the optical transient has faded to $V \approx 28.0$ mag (Fruchter et al. 1997), which corresponds to an $R$-band magnitude $\approx 27.0$, being well consistent with the power-law extrapolation of earlier data. This suggests that the radiation during the whole period may be emitted via one mechanism. Although this seems to have confirmed the fireball model, we argue below that it may be a puzzle. If we suppose that $\gamma$ decays as $\gamma(t) = (200–300)(E_{51}/m_1)^{0.8} t^{-3/8}$, the relativistic condition $\gamma > 2$ for $t = 6.25 \text{ months}$ will require $(E_{51}/m_1) > 10^5 – 10^7$, which seems quite unlikely. This difficulty may be overcome by assuming that the ISM is not homogeneous, so that the shock can stay relativistic for more than 6 months. Another possibility is that $\gamma$ does fall below 2 several days after the main GRB, but the radiation during the marginally relativistic phase could account for the long-term optical afterglow. This point should be investigated in more detail.

The optical afterglow of GRB 970508 shows a first-rising-then-decreasing behaviour (Castro-Tirado et al. 1997; Vietri 1997b; Djorgovski et al. 1997). The light curve peaks at about $t = 2 \text{ d}$. This behaviour cannot be explained by the simple shock model described here, which only predicts a peak at $t = 10^3 – 10^4 \text{ s}$. We suggest that an inhomogeneous ISM with some clumps might account for it.
We have shown in this paper that a relativistic fireball expanding adiabatically into the uniform ISM can roughly explain the afterglows of five observed GRBs, especially their X-ray fluxes. We would like to stress that extensive observational and theoretical investigations on GRB afterglows should be helpful in providing much more important clues to the origin of GRBs.

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