THE EVOLUTION OF GAMMA-RAY BURST REMNANTS

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ABSTRACT

The detection of the delayed emission in X-ray, optical, and radio bands, i.e., the afterglow of γ-ray bursts (GRBs), suggests that the sources of GRBs are likely to be at cosmological distances. Here we explore the interaction of a relativistic shell with a uniform interstellar medium (ISM) and obtain the exact solution of the evolution of γ-ray burst remnants, including the radiative losses. We show that in general the evolution of the bulk Lorentz factor, γ, satisfies γ ∝ t^{−αγ} when γ ≫ 1; here, αγ is mainly in the range 9/22–3/8, the latter corresponding to adiabatic expansion. So it is clear that adiabatic expansion is a good approximation even when radiative loss is considered. However, in fact, αγ is slightly larger than 3/8, which may have some effects on a detailed data analysis. Synchrotron self-absorption is also calculated, and it is demonstrated that the radio emission may become optically thin during the afterglow. Our solution can also apply to the nonrelativistic case (γ ∼ 1); at that time, the observed flux decreases more rapidly than that in the relativistic case.

Subject heading: gamma rays: bursts — radiation mechanisms: nonthermal

1. INTRODUCTION

Since the discovery of γ-ray bursts nearly 30 years ago, their origin and emission mechanisms have remained mysterious. A major reason for this is that their emissions other than X-ray and γ-ray have remained invisible. This situation has been changed dramatically since the launch of Italian-Dutch satellite BeppoSAX. The delayed emission at X-ray, optical, and radio wavelengths has been detected from several γ-ray bursts (GRBs) due to an accurate determination of their position (Costa et al. 1997a, 1997b). The very long-lasting afterglow (more than 1 month) strongly suggests that the sources of GRBs are at cosmological distances.

It is a natural prediction of the cosmological fireball model that γ-ray bursts should have an afterglow in X-ray, optical, and radio bands (Mészáros & Rees 1997; Paczyński & Rhoads 1993; Vietri 1997a). After the main GRB event occurs, the fireball continues to propagate into the interstellar medium (ISM), and thus relativistic electrons may be continuously accelerated to produce the delayed radiation on timescales of days to months. Several authors have discussed the radiation mechanisms of GRB afterglow, and the agreement between the fireball deceleration model and the measurements is good (Waxman 1997a, 1997b; Wijers, Rees, & Mészáros 1997). However, these authors simply assume that the fireball expansion is adiabatic. On the other hand, Vietri (1997a, 1997b) has assumed that the fireball expansion is highly radiative, and the surrounding matter is nonuniform. His results are also in agreement with the observations.

In this paper, we explore the interaction of a relativistic fireball with a uniform ISM. In § 2 we derive the exact solution of the evolution of the bulk Lorentz factor, γ, in the general case, without assuming expansion that is adiabatic or highly radiative. Our solution can also extend to the nonrelativistic case. In § 3 we discuss the emission features for adiabatic expansion and nonadiabatic expansion. The evolution of the synchrotron self-absorption frequency is also calculated. Finally, we summarize our results and give some implications for future observations in § 4.

2. THE EVOLUTION OF GRB REMNANTS

Whatever the sources of GRBs are, the observations suggest the following scenario. A very large energy burst (E ∼ 10^{51} ergs for cosmological distances) is suddenly released (T < 100 s) in a small region of space, so the initial energy density is so large that an opaque fireball forms (Paczynski 1986; Goodman 1986; Shemi & Piran 1990); then, the fireball expands outward relativistically. After an initial acceleration phase, the fireball energy is converted to proton kinetic energy. When the fireball is decelerated by the swept-up external matter, a strong shock can be created, and electrons may be accelerated to very high energy. Then a GRB is produced through synchrotron radiation or possible inverse Compton emission of these electrons. This occurs at decelerating radius (Mészáros, Rees, & Papathe3nassion 1994):

\[ r_d = \left( \frac{2E}{\eta n_1 m_p c^2} \right)^{1/3} = 5 \times 10^{16} \left( \frac{E_{51}}{n_1} \right)^{1/3} \left( \frac{\gamma_0}{100} \right)^{-2/3} \text{ cm}, \]  

where \( E = 10^{51} E_{51} \) is the total burst energy, \( n_1 \) is the density of ISM, \( \eta \) is the ratio of fireball energy to the initial rest mass energy of baryons, \( M_p \) is the total mass of polluting baryons initially mixed with the fireball, and \( \gamma_0 \) is the Lorentz factor of the blast wave at radius \( r_d \). It should be noted that at this time, the shell thickness is similar to that of the heated ISM region, so the heated ISM and shell carry similar energy (Sari & Piran 1995; Waxman 1997a). Therefore, it is easy to show that \( \gamma_0 = \eta/2 \), and the ISM mass swept up by the forward blast wave at this time is \( 2/\eta \) of the shell’s mass, i.e., \( M_0/M_b = 2/\eta \)
Sari & Piran (1995) pointed out that the fireball energy dissipation may occur at two different places. They defined a radius, $r_E$, where the reverse shock becomes relativistic. If $r_d < r_E$, a relativistic reverse shock cannot be formed, and the shell loses its energy to the heated ISM at $r_d$. Otherwise, if $r_d > r_E$, then most of the shell kinetic energy is converted into thermal energy once the reverse shock crosses the shell (see also Waxman 1997a). This conclusion is valid only if the shell propagates with a constant width, $\Delta$. However, if the shell is expanding, then the shell width, $\Delta = r/\gamma^2$, will not be a constant. According to the definition of Sari & Piran (1995), the parameter $f(r) = n_l n_b = \gamma t^4/m^3$, where $l = (E/n_l m_p c^2)^{1/3}$, is the Sedov length. Then, when the reverse shock becomes relativistic, i.e., $\gamma^2 f(r_g) = 1$, we can obtain

$$r_E = \left(\frac{E}{\gamma n_l m_p c^2}\right)^{1/3}. \quad (2)$$

Comparing with equation (1), we find that $r_E \approx r_d$. So it is clear that when the fireball is expanding, the density ratio, $\rho$, decreases with time. Initially $\gamma^2 f \ll 1$, and the reverse shock is Newtonian. When $r \sim r_d(r_g)$, the fireball is decelerated by ISM, and at the same time, the reverse shock becomes mildly relativistic.

After the GRB occurs, the fireball decelerates, and a relativistic blast wave continues to propagate into the ISM to produce the relativistic electrons that may produce the delayed emission on timescales of days to months. The light curves of the afterglow are controlled by the deceleration of the bulk Lorentz factor, $\gamma$, and the intrinsic intensity, $I_0$. In previous studies, some authors (Waxman 1997a; 1997b; Wijers et al. 1997) assume that the fireball expansion is adiabatic, i.e., the radiative energy loss can be negligible. However, some other people (Vietri 1997a, 1997b) assume that the expansion is highly radiative, i.e., the internal energy of the system is instantaneously radiated out. It is obvious that these are two extreme cases. In fact, the fireball should expand between these two cases, some fraction (not all) of the internal energy being radiated and lost from the system. So it is important to calculate the evolution of the bulk Lorentz factor, $\gamma$, when including radiative energy loss. We define $e_\gamma$ to be the fraction of the internal energy emitted; then the total energy radiated per unit swept mass is given by (Blandford & McKee 1976)

$$dE = -\gamma(\gamma - 1)e_\gamma c^2 dM,$$  \hspace{1cm} (3)

where $M = (4/3)\pi r^3 n_l m_p$ is the swept-up ISM mass. For simplicity, we assume that the energy loss of the swept-up matter is small; then, the total kinetic energy can be written as $E = (\gamma^2 - 1)MC^2$. Thus we obtain

$$\frac{d\gamma}{dM} = -\frac{(1 + e_\gamma)^2 - e_\gamma \gamma - 1}{2M\gamma}, \quad (4)$$

which has the solution

$$\frac{(\gamma - 1)(\gamma + 1)}{(\gamma_0 - 1)(\gamma_0 + 1)} = \left(\frac{M}{M_0}\right)^{-\gamma(1+\gamma)/2}, \quad (5)$$

where $\gamma = 1 + e_\gamma$, and $\gamma_0$ and $M_0$ are the initial values of the Lorentz factor and the mass of swept-up matter at the radius $r_0$, where the deceleration begins ($a_0 \approx r_0$). When the expansion is highly relativistic ($\gamma \gg 1$), $\gamma/\gamma_0 = (M/M_0)^{-\gamma/2} = (r/r_0)^{-3/2}$. If expansion is adiabatic ($e_\gamma = 0$, $\gamma = 1$), $\gamma/\gamma_0 = (r/r_0)^{-3/2}$. Otherwise, if expansion is extremely radiative ($e_\gamma = 1$, $\gamma = 2$), then $\gamma/\gamma_0 = (r/r_0)^{-3}$. However, it should be pointed out that in the above calculation, we have taken the value of $e_\gamma$ as a constant. This is appropriate for describing the adiabatic and nonadiabatic limits ($e_\gamma = 0$, 1), but for intermediate values, the value of $e_\gamma$ is almost certain not to be a constant and in fact probably depends on gas parameters which depend on radius.

3. THE EMISSION FROM THE GRB REMNANT

The variation of the bulk Lorentz factor, $\gamma$, with observer time, $t$, can be obtained by combining relation $dt = [(1 + z)dr]/(2\gamma^2 \beta c)$ and equation (5), where $z$ is the cosmological redshift of the GRB source. For $\gamma \gg 1$ ($\beta \approx 1$), it is given by

$$\frac{\gamma}{\gamma_0} = \left(\frac{r}{r_0}\right)^{-a_\gamma}, \quad (6)$$

where $t_0 = (1 + z)r_0/(2 + 3y)\gamma_0 c$ is the typical duration of a GRB event, and $a_\gamma = 3y/2(1 + 3y)$. The fraction of the energy radiated can be estimated as $e_\gamma = e_\gamma e_{\gamma \text{syn}}$, where $e_{\gamma \text{syn}}$ represents the fraction of the energy of the electron that is occupied by electrons, and the typical Lorentz factor of electrons in the comoving frame can usually be expressed as $\gamma_\text{syn} = \xi_\text{e}(m_\text{e}m_p)$ ($\gamma - 1$), so $e_\gamma \approx \xi_\text{e}/(1 + \xi_\text{e})$. $\xi_\text{e} = 1(e_\gamma = 1/2)$ represents the energy equipartition between electrons and protons. The synchrotron radiation efficiency can be expressed as $e_{\gamma \text{syn}} = t^{-1}(s_{\gamma \text{syn}} + t^{-1})$ (we assume that synchrotron radiation is the main mechanism for GRB afterglow), where $t_{\gamma \text{syn}} = 6\sigma T_\text{s}m_\text{e}c^2/\gamma_\text{syn}^2 B^2$ and $t_{\text{ex}} = r/\gamma \beta c$ are the synchrotron cooling time and expansion time in comoving frame, respectively, $B = \xi_\text{B} B_{\text{g}}(\gamma - 1)n_l m_p c^2$ is the comoving magnetic field, $m_\text{e}(m_p)$ is the mass of electron (proton), and $\sigma_T$ is Thomson cross section. Therefore, we expect $e_\gamma$ to lie in the range $0–1/2$ and $y$ in the range $1–3/2$, so $a_\gamma$ should be between $3/8$ (adiabatic expansion) and $9/22$. Thus, it is somewhat surprising that $a_\gamma$ lies in a very narrow range; for the general case, $a_\gamma$ is only slightly larger than $3/8$ (adiabatic case), so it is reasonable to think that adiabatic expansion is a good approximation, and the radiative energy loss could be treated as a small correction. Therefore, in the following, we first consider the emission features at adiabatic expansion.

3.1. Adiabatic Case

From equation (5), we see that for the adiabatic case ($y = 1$), the bulk Lorentz factor, $\gamma$, can be expressed as

$$\gamma = \left[1 + (\gamma_0^2 - 1) \frac{r_0^3}{r^3}\right]^{1/2}, \quad (7)$$

without any assumption. Here, $r_0$ is the initial value of the deceleration phase, so $r_\gamma = r_0$. From equation (1), $r_\gamma^3 = 2E/n_l m_p c^2 = E/(2\gamma_0^2 n_l m_p c^2)\beta^2 r_0^3$, so $\gamma_\gamma r_\gamma^3 = \beta^3 r_0^3$. Thus, for $\gamma_0 \gg 1$, we have

$$\gamma = \left(1 + \frac{\beta^3}{2x}\right)^{1/2} = \left(1 + \frac{1}{x^3}\right)^{1/2}, \quad (8)$$

where $x = r/r_\gamma$, and $r_\gamma = (l/2)^{1/3}$. For $\gamma \gg 1$ from equation (6), we obtain

$$\gamma = 278(1 + 2)^{1/8} E_{51}^{1/8} n_l^{-1/8} t^{-3/8}. \quad (9)$$

This expression is valid only for relativistic expansion; it breaks down for $\gamma \approx 1$. The time through which the blast wave remains relativistic is about 1 month.
If synchrotron radiation is the main mechanism that produces the GRB afterglow, we can estimate the time delay between the beginning of the afterglow and the onset of the optical flash. The observed photon energy of synchrotron emission from typical electrons is ($\gamma \gg 1$)

$$\epsilon_m = \frac{3m_e c^2 B^2 \gamma^2}{2 (1 + z) B_c} = 5.2 \times 10^{-5} \frac{\gamma^{1/2} n_1^{1/2} z^{2.5} \epsilon_0^{-1/2}}{(1 + z)} \text{eV}, \quad (10)$$

where $B_c = 4.413 \times 10^{13}$ G is the critical magnetic field. Then, combining this equation with equation (9), we have

$$t_m \approx 1.1(1 + z)^{1/3} B_c^{2/3} \left(\frac{\epsilon_m}{1 \text{ eV}}\right)^{-2/3} \epsilon_0^{4/3} \epsilon_b^{2/3} \text{(days)}. \quad (11)$$

Thus, considering the uncertainty of the parameters, the value of $t_m$ (optical flash) could range from a few hours to about 3 days.

It can easily be seen from equation (10) that the typical photon energy cannot possibly enter the radio region when $\gamma \gg 1$, so we expect that until the fireball expansion is moderately relativistic does the synchrotron emission peak at the radio band. It is interesting to note that our solution (eq. [8]) can be extended to the nonrelativistic case. From equation (8), the shell velocity is $\beta = 1/(1 + x^2)$; then, the relation between observer time and radial distance is $t = \int [(1 + z)(1 - \beta dr)/c = [(1 + x^2)^{3/2} - 1] dx$, so when $x < 1$ ($\gamma \gg 1$), $r \propto t^{1/4}$, while when $x > 1$ ($\gamma \sim 1$), $r \propto t^{3/5}$.

The light curve of the afterglow is also dependent on the intrinsic photon spectrum. We assume that the comoving intensity is $I_{e'} \propto e$ for $e < \epsilon_m$ and $I_{e'} \propto e^\alpha$ for $e > \epsilon_m$. From equation (8), we can see, in the relativistic case, $\gamma \propto t^{-3/8}$, $B \propto \gamma$, $\epsilon_m \propto \gamma^2 B \propto t^{-3/8}$, and $t_m \propto n_1 B_d \propto t^{-3/8}$, so the observed peak flux $F_{\text{syn}} \propto t^{-3/8} \epsilon_{\text{syn}} \propto t^{0}$ constant (Meszáros & Rees 1997). Before $\epsilon_m$ crosses the optical (radio) band, the flux $F_{\epsilon} \propto F_{\text{syn}}(e/\epsilon_m)^{\alpha}$ and when $\epsilon_m$ crosses the optical (radio) band, we have $F_{\epsilon} \propto F_{\text{syn}}(e/\epsilon_m)^{\alpha} \propto t^{3/8}$. In the nonrelativistic case, $\gamma \propto t^{-3/8}$, $B \propto t^{-3/8}$, $\epsilon_m \propto t^{-3}$, $I_m \propto t^{-3}$, $t_m \propto t^{-3/5}$ and $F_{\text{syn}} \propto t^{-3}$. So the observed optical (radio) flux for $e < \epsilon_m$ is $F_{\epsilon} \propto F_{\epsilon_m}(e/\epsilon_m)^{\alpha} \propto t^{3/8}$ and for $e > \epsilon_m$ is $F_{\epsilon} \propto F_{\epsilon_m}(e/\epsilon_m)^{\alpha} \propto t^{3/8}$. These features have also been discussed from Wijers et al. (1997). Figure 1 gives an example of the variation of observed flux with time. We have taken $\alpha = 0$, $\beta = -1$, and $E = 5 \times 10^{51}$ ergs. The solid, dashed, and dot-dashed lines correspond to optical, X-ray, and radio flux, respectively. It can be seen from Figure 1 that the slope ($e > \epsilon_m$) changes from $-1.5$ (relativistic case) to $-2.4$ (nonrelativistic case) gradually.

### 3.2. Nonadiabatic Case

It can be seen from equation (5) that for the nonadiabatic case ($\gamma > 1$), we cannot obtain the explicit expression for the evolution of the bulk Lorentz factor, $\gamma$; only when $\gamma \gg 1$ can it be written as the form of equation (6). In order to compare with the adiabatic case, we write $\alpha = 3/8 + \alpha'$, where $\alpha'$ should be less than 3/8. Then we can write the evolution of the Lorentz factor as $\gamma = \gamma_0 (t/t_0)^{-3}$; $t_0 \approx 1$ (100 s) is the typical duration of $\gamma$-ray flash. We then see that after 1 day, $\gamma/\gamma_0 \sim 0.75$ for $t_0 \approx 10$ s, $\alpha' = 3/8$; the exact value will depend on the parameter $\epsilon_0$. In the meanwhile, from equation (11), the time delay between the GRB event and the onset of the optical flash will be shorter by a factor $(t/t_0)^{-8/3\alpha'} \sim 0.43$, i.e., it could range from a few hours to more than 1 day.

![Fig. 1.—Evolution of observed flux with time, $t$. We have taken $\alpha = 0$, $\beta = -1$, and $E = 5 \times 10^{51}$ ergs. The solid, dashed, and dot-dashed lines correspond to optical, X-ray, and radio flux, respectively.](image-url)

This will also affect the light curve of the afterglow. Just as discussed above, for the relativistic case, $\gamma \propto t^{-3/8} x^{1/2}$, $B \propto \gamma$, and $\epsilon_m \propto t^{-3/8} x^{1/2}$, it should be noted that, in the nonadiabatic case, the electron cooling time is shorter than the expansion time, and the effective width of the emission region is narrower than the width of swept-up matter, so $t_m \propto n_1 B t_{\text{syn}} \propto t^{3/8} x^{1/2}$ (Meszáros, Rees & Wijers 1997), and the observed peak flux, $F_{\text{syn}} \propto t^{1/2} x^{-4/5}$, is not constant; it increases with time. Then the flux $F_{\epsilon} \propto (t^{1/2} x^{-4/5} a + 4 \alpha / (1 - 4 \alpha))$ for $\epsilon < \epsilon_m$ and $F_{\epsilon} \propto (t^{1/2} x^{-4/5} a + 4 \alpha / (1 - 4 \alpha))$ for $\epsilon > \epsilon_m$. Therefore, we see that for $\epsilon < \epsilon_m$ the flux $F_{\epsilon}$ may either increase or decrease with time, depending on the values of $\alpha$ and $\epsilon'$. For the nonrelativistic case, the variation of $\gamma$ with $t$ is more complicated. However, it should be pointed out that radiative energy loss may be important only in early time. The ratio of synchrotron cooling time to the expansion time in the comoving frame is

$$\frac{t_{\text{syn}}}{t_{\text{ex}}} = 7 \times 10^6 \frac{\gamma_0^{-4} \epsilon_0^{-1} \epsilon_b^{-1} n_1^{1/2} t_0^{-1}}{(\gamma/100)^{4/7}}. \quad (12)$$

Taking $\alpha = 9/22$, for $t_{\text{syn}}/t_{\text{ex}} = 1$, we obtain $t_e \approx 0.4 \pi^{11/7} x^{1/7} B_c^{2/3} P_m^{1/3} (\gamma/100)^{4/7}$ day. Therefore, we expect the synchrotron cooling time to be longer than the dynamical time for long-delay afterglow (usually $t_e < 1$ day). When $t_{\text{syn}} > t_{\text{ex}}$, the synchrotron radiation efficiency, $e_{\text{syn}}$, decreases rapidly, and so $e_{\epsilon} \ll 1$. At that time, the adiabatic expansion is a very good approximation.

### 3.3. Synchrotron Self-Absorption

We have shown that the typical photon energy, $\epsilon_m$, might not be able to enter the radio region when $\gamma \gg 1$, so the detected radio flash within a few days after a GRB (Frail et al. 1997) may be possible due to the source becoming optically thin. As Waxman (1997b) and Vietri (1997b) have
pointed out, the synchrotron self-absorption optical depth for photon energy, \(\epsilon < \epsilon_m\), may scale as \(\tau = \tau_m(\epsilon/\epsilon_m)^{-2}\) due to the presence of a low-energy electron population. The optical depth, \(\tau_m\), can be estimated as \(\tau_m \approx 1.2 \times 10^{-13} n_{e}^{1/2} \epsilon^{-5/2} \epsilon_{AB}^{-1/2}\) where \(\epsilon_{AB}\) is the synchrotron self-absorption optical depth. When the expansion is nonrelativistic, the absorption frequency for \(\gamma \gg 1\) is \(v_{ab} \approx 2n_{e}^{1/2} \epsilon^{-5/2} \epsilon_{AB}^{-1/2} E_{51}^{1/4} E_{m}^{-1/4} t_{day}^{-1/4}\) GHz, while for \(\gamma \sim 1, v_{ab} \approx 0.2n_{e}^{1/2} \epsilon^{-5/2} \epsilon_{AB}^{-1/2} E_{51}^{1/4} t_{day}^{-1/4}\) GHz. So the absorption frequency first decreases with time as \(v_{ab} \propto t^{-1/4}\), while when the expansion is nonrelativistic, \(v_{ab} \propto t^{1/2}\). When photon energy \(\epsilon > \epsilon_m\), \(\tau \propto \epsilon^{-(p+4)/2}\), where \(p\) is the index of electron distribution, then \(v_{ab} = \tau_{AB}^{2(p+4)} / \epsilon_{AB}\). Taking \(p = 3\), then \(v_{ab} = 317n_{e}^{1/2} \epsilon_{AB}^{1/2} E_{51}^{1/4} t_{day}^{-1/4}\) GHz for \(\gamma \gg 1\), and \(v_{ab} = 1556n_{e}^{1/2} \epsilon_{AB}^{1/2} E_{51}^{1/4} t_{day}^{-1}\) GHz for \(\gamma \sim 1\). The observed flux may consist of several components. If \(v_{ab} < \epsilon_m\), then \(F_{v} = F_{v_{ab}}(v_{ab}/\epsilon)^{p+2}\) for \(v < v_{ab}\), \(F_{v} = F_{v_{ab}}(v/\epsilon)^{p}\) for \(v_{ab} < v < \epsilon_{AB}\), and \(F_{v} = F_{v_{ab}}(v/\epsilon_{AB})^{p}\) for \(v > \epsilon_{AB}\). If \(v_{ab} > \epsilon_{AB}\), then \(F_{v} = F_{v_{ab}}(v_{ab}/\epsilon_{AB})^{p}\) for \(v < v_{ab}\), and \(F_{v} = F_{v_{ab}}(v/\epsilon_{AB})^{p}\) for \(v > \epsilon_{AB}\). These components can be seen in our calculated radio flux in Figure 1.

4. DISCUSSION AND CONCLUSION

The detection of \(\gamma\)-ray bursts in the optical and radio bands has greatly furthered our understanding of the objects. Some people have discussed the afterglow emission using the adiabatic expansion or highly radiative expansion. Here we have investigated the evolution of the fireball Lorentz factor, \(\gamma\), when it interacts with the ISM. We find that even though we included the radiative energy loss, the difference of the evolution of the \(\gamma\) between our results and that in the adiabatic case is small. Thus, adiabatic expansion can be treated as a good approximation.

From equation (6), we can also obtain the evolution of the total system energy (when \(\gamma \gg 1\)), \(E/E_{0} = (t/t_{0})^{-n_{e}/(p+3)}\), which is different from the results of Sari (1997), who obtained \(E \propto t^{-7}\). This is because Sari had used the self-similar solution to obtain his results, while our results are obtained by solving the energy loss equation without any assumptions. Our results show that the decrease of total energy is slower than that predicted by Sari (1997).

We have shown that the energy loss due to radiation may be important only in the early time of afterglow (usually \(t < 1\) day), since the synchrotron cooling time may be much longer than the expansion time for long-delay emission. We argue that the detection of afterglow within a short time after the GRB event is very important, since it may provide more information about the GRB sources, the radiation processes, the surrounding matter features, etc.

The afterglow has been detected for more than 1 month. The interesting question is, How long can the afterglow be sustained? From Figure 1, we see that the optical flux decays with time as a power law, \(F \propto t^{-n}\), with the index \(n\) increasing gradually from \(3/2\) to \([3/5 + 3\beta]\). Therefore, we argue that the optical flux should be detected for a longer time without a sudden cutoff. In addition, it is also possible to observe radio emission for a very long time.

The detection of very long afterglows strongly suggests that the sources of GRBs are at cosmological distances, which means that the total energy of GRB event should be about \(10^{51} - 10^{52}\) ergs. Now the most fundamental problem, the ultimate energy source and the physical processes leading to the fireball formation, has not yet been solved. Recently, the popular model—coalescing of two neutron stars—seems to have difficulty accounting for the GRBs (Ruffert et al. 1997), and now a new way [a very strong magnetic field \((B \sim 10^{15}\) G) combined with rotation] has been suggested to power the fireball (Paczynski 1997). We expect that the detection of GRB afterglow can provide information about the origin of GRBs.

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