Intrinsic parameters of GRB 990123 from its prompt optical flash and afterglow

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ABSTRACT
We have constrained the intrinsic parameters, such as the magnetic energy density fraction ($\epsilon_B$), the electron energy density fraction ($\epsilon_e$), the initial Lorentz factor ($\Gamma_i$), and the Lorentz factor of the reverse external shock ($\Gamma_{ri}$), of GRB 990123, in terms of the afterglow information (forward shock model) and the optical flash information (reverse shock model). Our result shows: (1) the inferred values of $\epsilon_e$ and $\epsilon_B$ are consistent with the suggestion that they may be universal parameters, comparing to those inferred for GRB 970508; (2) the reverse external shock may have become relativistic before it passed through the ejecta shell. Other intrinsic parameters of GRB 990123, such as the energy contained in the forward shock $E$ and the ambient density $n$, are also determined and discussed in this paper.

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

1 INTRODUCTION
The current standard model for gamma-ray bursts (GRBs) and their afterglows is the fireball-plus-shock model (see Piran 1999 for a review). It involves a large amount of energy, $E_0 \sim 10^{51} - 54$ erg, being released within a few seconds in a small volume with negligible baryonic load, $Mc^2 < E_0$. This leads to a fireball that expands ultrarelativistically with a Lorentz factor $\Gamma_i = E_0/Mc^2 > 100$, which is required to avoid the attenuation of hard $\gamma$-rays owing to pair production (e.g. Fenimore, Epstein & Ho 1993; Woods & Loeb 1995). A substantial fraction of the kinetic energy of the baryons is transferred to a non-thermal population of relativistic electrons through Fermi acceleration in the shock (Mészáros & Rees 1993). The accelerated electrons cool via synchrotron emission and inverse Compton scattering in the post-shock magnetic fields and produce the radiation observed in GRBs and their afterglows (e.g. Katz 1994; Sari, Narayan & Piran 1996; Vietri 1997; Waxman 1997a; Wijers, Rees & Mészáros 1997). The shock could be either internal, arising from collisions between fireball shells caused by outflow variability (Paczynski & Xu 1994), or external, arising from the interaction of the fireball with the surrounding interstellar medium (ISM; Mészáros & Rees 1993). The radiation from internal shocks can explain the spectra (Pilla & Loeb 1998) and the fast irregular variability of GRBs (Sari & Piran 1997), while the synchrotron emission from the external shocks provides a successful model for the broken power-law spectra and the power-law decay of afterglow light curves (e.g. Vietri 1997; Waxman 1997a,b; Wijers et al. 1997; Dai & Lu 1998a,b,c; Huang, Dai & Lu 1998a; 1999a,b; Huang et al. 1998b; Dai, Huang & Lu 1999; Wang et al. 2000a; Wang, Dai & Lu 2000b).

The properties of the synchrotron emission from GRB shocks are determined by the magnetic field strength, $B$, and the electron energy distribution behind the shock. Both of them are difficult to estimate from first principles, and so the following dimensionless parameters are often used to incorporate modelling uncertainties (Sari et al. 1996), $\epsilon_B = U_B/UI$, $\epsilon_e = U_e/UI$. Here $U_B$ and $U_e$ are the magnetic and electron energy densities and $UI = nm_p^2c^2(\gamma_p - 1)$ is the total thermal energy density behind the shocks, where $m_p$ is the proton mass, $n$ is the proton number density and $\gamma_p$ is the mean thermal Lorentz factor of the protons. In spite of these uncertainties, an important assumption that $\epsilon_B$ and $\epsilon_e$ do not change with time, has been made in the standard external shock model. Through the computation, Wijers & Galama (1999; hereafter WG99) even suggested that they may be universal parameters, i.e. the same for different bursts.

The BeppoSAX satellite ushered in 1999 with the discovery of GRB 990123 (Heise et al. 1999), the brightest GRB seen by BeppoSAX to date. This is a very strong burst. An assumption of isotropic emission and the detection of the source’s redshift $z = 1.6004$, lead to a huge energy release about $1.6 \times 10^{54}$ erg (Briggs et al. 1999; Kulkarni et al. 1999a) in $\gamma$-rays alone. GRB 990123 would have been amongst the most exciting GRBs even just on the basis of these facts. Furthermore, ROTSE discovered a prompt optical flash of ninth magnitude (Akerlof et al. 1999). It is the first time that a prompt emission in another wavelength apart from $\gamma$-rays has been detected from GRB. Such a strong optical flash was predicted to arise from a reverse external shock propagating into the relativistic ejecta (Mészáros & Rees 1997;
Sari & Piran 1999a,b; hereafter SP99a,b). This is the so-called ‘early afterglow’. The five last exposures of ROTSE show a power-law decay with a slope of \( \sim 2.0 \), which can also be explained by the reverse shock model (SP99b; Mészáros & Rees 1999). The usual afterglows in X-ray, optical, infrared (IR) and radio bands were also detected after the burst. They have two distinguishing features: (1) the radio emission is unique both because of its very early appearance and its rapid decline; (2) the temporal decaying behaviour of the \( r \)-band light curve after 2 d steepens from about \( t^{-1.1} \) to \( t^{-1.8} \) (Castro-Tirado et al. 1999; Fruchter et al. 1999; Kulkarni et al. 1999a), and this steepening might be caused by a jet which has transited from a spherical-like phase to a sideways expansion phase (Rhoads 1999; Sari, Piran & Halpern 1999; Wei & Lu 2000) or a dense medium which has slowed down the relativistic expansion of a shock quickly to a non-relativistic one (Dai & Lu 1999a,b).

Galama et al. (1999) assumed that the radio emission is produced by the forward shock as usual and then reconstructed the radio-to-X-ray afterglow spectrum on January 24.65 UT. However, later work shows that the simplest interpretation of this ‘radio flare’ is that it arises in the reverse shock and that such radio emission is an inevitable consequence of the prompt bright optical flash seen by ROTSE (Kulkarni et al. 1999b; Sari & Piran 1999b). Kulkarni et al. (1999b) also constrained two key parameters of the forward shock, the peak flux \( F_{\nu} \) and the peak frequency \( \nu_{\text{m}} \), to within a factor of 2. For previous bursts, we have no other information apart from the afterglow to infer the intrinsic parameters of the external shocks. However, now the optical flash of GRB 990123 has been fortunately detected, which enables us to determine another two key parameters, the initial Lorentz factor \( \Gamma_0 \) and the Lorentz factor of the reverse shock \( \Gamma_{\nu} \). WG99 computed the intrinsic parameters of GRB 970508 and GRB 971214 in terms of their afterglow data, and found that \( \epsilon_e \) is nearly the same for these two bursts, suggesting it may be a universal parameter. Granot, Piran & Sari (1999a,b; hereafter GPS99a,b) modified the set of equations derived by WG99, and inferred the electron energy density fraction and the magnetic energy density fraction of GRB 970508 to be \( \epsilon_e = 0.57 \) and \( \epsilon_B = 8.2 \times 10^{-3} \). Here we apply the set of equations of GPS99a to GRB 990123 and try to determine some intrinsic parameters based on the information of the two aspects of GRB 990123 – the optical flash and the afterglow.

The initial Lorentz factor \( \Gamma_0 \) is also an important physical parameter of GRBs. It is a crucial ingredient for constraining models of the source itself, since it specifies how ‘clean’ the fireball is as the baryonic load is \( M = E_0/\Gamma_0 c^2 \). Unfortunately, the spectrum of GRBs can provide only a lower limit to this Lorentz factor (\( \Gamma_0 > 100 \)). Moreover, the current afterglow observations, which detect radiation from several hours after the burst, do not provide a verification of the initial extreme relativistic motion. A possible method of estimating \( \Gamma_0 \) of GRBs has been suggested in SP99a, based on identifying the ‘early afterglow’ peak time. In this paper, the initial Lorentz factor has been inferred more precisely from the full set of equations describing the reverse shock region.

In Sections 2 and 3, we compute the intrinsic parameters of GRB 990123 from its afterglow and optical flash information. In the final section, we give our conclusions.

## 2 Parameters from the Afterglow

Intrinsic parameters such as the magnetic energy density fraction \( \epsilon_B \), the electron energy density fraction \( \epsilon_e \), the energy in the forward external shock \( E = E_{52} \times 10^{52} \text{erg} \) and the ambient density \( n \) can be determined from the afterglow spectrum (GPS99a,b; WG99), i.e. if we know all three break frequencies (not necessary at the same time) and the peak flux of the afterglow, we can infer all of these parameters.

From the observations of the afterglow of GRB 990123, Kulkarni et al. (1999b) have estimated two key parameters of the forward shock: \( \nu_{\text{m}} \sim 1.1 \times 10^{18} \text{Hz} \) and \( F_{\nu_{\text{m}}} \sim 170 \mu \text{Jy} \) at the time \( t = 1.25 \) d after the burst. The cooling frequency \( \nu_c \) cannot be seen from the radio-to-X-ray spectrum obtained by Galama et al. (1999). This indicates that \( \nu_c \) is at or above the X-ray frequencies. We need to determine it more precisely. The X-ray afterglow, observed 6 h after the burst, decayed with \( \alpha_X = 1.44 \pm 0.07 \) (Heise et al. 1999), while the optical afterglow with \( \alpha_\nu = 1.10 \pm 0.03 \) (Kulkarni et al. 1999a,b). An X-ray afterglow decay slope steeper by \( \frac{1}{2} \) than an optical decay, which seems to be the case in this burst, is predicted by Sari, Piran & Narayan (1998), if the cooling frequency is between the X-rays and the optical. So at the time 6 h after the burst, \( 4 \times 10^{14} \leq \nu_c \leq 5 \times 10^{14} \) Hz. Extrapolating it to the time \( t = t^* \), we obtain \( 1.8 \times 10^{14} \leq \nu_c(t^*) \leq (2-20) \times 10^{17} \) Hz. Another speculative constraint on \( \nu_c \) is obtained from the GRB spectrum itself by Sari & Piran (1999b), who constrained \( \nu_c \approx 2 \times 10^{19} \) Hz at the time \( t \approx 50 \) s. Extrapolating it to \( t \), we obtain \( \nu_c(t^*) \approx 0.4 \times 10^{18} \). Now \( \nu_c \) is almost determined, and we take the approximate value \( \nu_c = 0.5 \times 10^{18} \) Hz, which is in agreement with the estimate of Galama et al. (1999). In addition, Kulkarni et al. (1999a) have inferred the electron index \( p \) (defined as \( N(\gamma_e) \propto \gamma_e^{-p} \)) to be \( p = 2.44 \). Now, apart from the self-absorption frequency \( \nu_s \), we have all other three quantities of the afterglow spectrum required to calculate the intrinsic parameters:

\[
\nu_{\text{m}} \sim 1.1 \times 10^{18} \text{Hz}, \quad \nu_c \sim 0.5 \times 10^{18} \text{Hz},
\]

\[
F_{\nu_{\text{m}}} \sim 170 \mu \text{Jy}, \quad p = 2.44.
\]

Following GPS99b, we adopt the formulae of \( \nu_{\text{m}} \) and \( F_{\nu_{\text{m}}} \) from GPS99a and \( \nu_c \) from Sari et al. (1998):

\[
\nu_{\text{m}} = 2.9 \times 10^{5}(1 + z)^{1/2}\left(\frac{p - 2}{p - 1}\right)^{1/2} \epsilon_e^{1/2} \epsilon_B^{3/2} E_{52}^{1/2} \text{Hz}.
\]

\[
F_{\nu_{\text{m}}} = 1.7 \times 10^4 (1 + z) \epsilon_B E_{52} n_1^{1/2} \left(\frac{d_L}{10^{25} \text{cm}}\right)^{-2} \mu \text{Jy};
\]

\[
\nu_c = 2.7 \times 10^{12} \epsilon_B^{-3/2} E_{52}^{-1/2} n^{-1/2} (1 + z)^{-1/2} \text{Hz}.
\]

where \( z \) is the redshift of the burst and \( d_L = 2cz(1 + z - \sqrt{1 + z})/H_0 \) is the luminosity distance.

Now we have three equations, (2)–(4), with four unknowns: \( \epsilon_e, \epsilon_B, E_{52} \) and \( n \). To solve these equations, we assume here that the electron density fraction \( \epsilon_e \) is the same for different bursts, just an argument of WG99, though in which a different set of equations are used. Since here we use the formulae of GPS99a, we adopt the value of \( \epsilon_e \) from that of GRB 970508 inferred according to the above formulae, i.e. \( \epsilon_e \sim 0.57 \) (GPS99b).

By combining equations (1) and (2)–(4), we obtain the values of four intrinsic parameters of the forward shock region:

\[
\epsilon_e \sim 0.57 \quad \epsilon_B \sim 3.1 \times 10^{-3} \quad n \sim 0.01 \quad E_{52} \sim 5.
\]

Astonishingly, we find that the value \( \epsilon_e \) inferred is very close to that of GRB 970508 (\( \epsilon_B = 8.2 \times 10^{-3} \); GPS99b), considering the uncertainties in the \( \nu_{\text{m}} \) and \( F_{\nu_{\text{m}}} \) of a factor of 2. This result

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supports our above adoption of the value of $\varepsilon_e$ and implies that $\varepsilon_e$ and $\varepsilon_p$ may be universal parameters (i.e. constants for every GRB), favouring the argument of WG99.

The ambient density $n$ inferred for GRB 990123 is $n \sim 0.01$. This density is on the low side of normal for a galactic disc, but definitely higher than expected for a halo, lending further support to the notion that bursts occur in a gas-rich environment. The inferred isotropic energy left in the adiabatic forward shock is $E \sim 5 \times 10^{53}$ erg, about 30 times less than the isotropic energy in $\gamma$-rays. This case is very similar to GRB 971214 (WG99).

We think, for GRB 990123, there are two processes causing $E_{52} < E_{52,\gamma}$. One is that there is a radiative evolution phase before the adiabatic phase, causing it to emit more of the initial explosion energy and leaving less for the adiabatic phase. According to Sari et al. (1998), we can estimate the reduced energy of the forward shock in the self-similar deceleration stage, i.e.

$$E_{52} \sim 0.02 \varepsilon_B^{-3/5} \varepsilon_e^{-3/5} E_{52,\gamma}^{4/5} (\Gamma_\Lambda/100)^{-4/5} n^{-2/5},$$

where $E_{52,\gamma}$ denotes the initial isotropic energy of the forward shock during the self-similar stage and $E_{52}$ denotes the final energy after the radiative phase. The value of $E_{52,\gamma}$ is difficult to determine precisely and it may be less than $E_{52,\gamma}$ for GRB 990123, according to Friedman & Waxman (2000). If we use $E_{52} \sim E_{52,\gamma}$, $\varepsilon_e \sim 0.57$, $\varepsilon_B \sim 8.2 \times 10^{-3}$ (instead of $\varepsilon_B \sim 3.1 \times 10^{-3}$, since the latter is less reliable than the former, considering the uncertainties in the $v_m$ and $F_{\nu_m}$ of a factor of 2 for GRB 990123), $\Gamma_\Lambda \sim 300$ (see the next section) and $n \sim 0.01$, we then obtain $E_{52} \sim 56$. The other process is the sideways expansion of the fireball jet (Kulkarni et al. 1999a,b), which can also reduce the energy per solid angle, hence the isotropic energy $E_{52,\gamma}$. Since the opening angle of the jet is $\theta_0 + c t_p \rho / c t \sim \theta_0 + \gamma^{-1} \Gamma_\Lambda$ (Rhoads 1999; Sari et al. 1999), at the time $t = 1.25 \text{d}$ (very near the break time of the jet evolution $t_b \sim 2.1 \text{d}$), $\gamma \sim 1/\theta_0$ (note that $\gamma \propto t^{-3/8}$), then $\theta \sim 2\theta_0$. Therefore, the real isotropic energy $E_{52,\gamma}$ left in the late adiabatic forward shock should be $56(2\theta_0/\theta_0)^{-2} \sim 14$, in rough agreement with the above value inferred from the afterglow spectrum. An additional possible loss of energy may be the reverse shock itself if it is radiative.

### 3 PARAMETERS FROM THE OPTICAL FLASH

An optical flash is considered to be produced by the reverse external shock, which heats up the matter of the shell and accelerates its electrons (SP99b; Mészáros & Rees 1999). The observations of BATSE triggered \textit{ROTSE} via the BACODINE system (Akerlof et al. 1999) An 11.82 mag optical flash was detected on the first 5 s exposure, 22.18 s after the onset of the burst. Then the optical emission peaked in the following 5 s exposure, 25.5 s later, which revealed an 8.95 mag signal (~1 Jy). The optical signal decayed to 10.08 mag 25 s later and continued to decay down to 14.53 mag in the subsequent three 75 s exposures that took place up to 10 min after the burst. The five last exposures depict a power-law decay with a slope ~2.0 (Akerlof et al. 1999; SP99b). Sari & Piran (1999); Mészáros & Rees (1999) assumed that the ejecta shell follows the Blandford–McKee (1976) self-similar solution after the reverse shock has passed through it and explained the decay of $t^{-2.0}$.

So we assume that at the optical emission peak time ($t = 50$ s) the reverse shock had just passed through the ejecta shell. At this time, the Lorentz factor of the reverse shock $\Gamma_{rs}$ is given approximately by

$$\Gamma_{rs} = \frac{\Gamma_0}{\Gamma_\Lambda},$$

where $\Gamma_0$ is the initial Lorentz factor of the ejecta and $\Gamma_\Lambda$ is the Lorentz factor of the ejecta at the optical flash peak time. Then the random minimum Lorentz factor $\gamma_{min}$ of the electrons in the reverse shock region is

$$\gamma_{min} = \frac{m_e p - 2}{m_e p - 1} \frac{\Gamma_0}{\Gamma_\Lambda}.$$  

The formulae of $v_m$ at the reverse shock were given in SP99b. Here we add the correction for redshift,

$$v_m = 1.2 \times 10^{13} \left(\frac{\varepsilon_e}{0.1}\right)^2 \left(\frac{\varepsilon_B}{10^{-3}}\right)^{1/2} \left(\frac{\Gamma_0}{300}\right)^2 \times n^{1/2}(1+z)^{-1} \text{Hz} \lesssim 5 \times 10^{14} \text{Hz}.$$  

The observed flux at $v_m$ can be obtained by assuming that all the electrons in the reverse shock region contribute the same average power per unit frequency $P'_{\nu_m}$ at $v_m$, which is given by $P'_{\nu_m} = \sqrt{3 \varepsilon_B B^* \rho_c c^2}$, where $B^* = \Gamma_\Lambda c / \sqrt{32 \pi m_e c \varepsilon_B}$. Adding one factor of $\Gamma_\Lambda$ to transform to the observer frame and accounting for the redshift, we have

$$F_{\nu_m} = \frac{N_e \Gamma_\Lambda P'_{\nu_m} (1+z)}{4\pi d_L^2},$$

where $N_e$ is the total number of radiating electrons in the ejecta shell, and $d_L = 2cz(1+z) / \sqrt{1+z} / H_0$ is the luminosity distance. Please note that $N_e$ here is different from the $N_e$ adopted in the forward shock region, which is the total number of swept-up electrons by the forward external shock. We consider $N_e$ here to be the total number of electrons contained in the baryonic load:

$$N_e = \frac{M}{m_p} \frac{E_\gamma}{\Gamma_0 m_p c^2} = 1.08 \times 10^{54} \left(\frac{E_\gamma}{1.6 \times 10^{52}}\right) \left(\frac{\Gamma_0}{1000}\right)^{-1},$$

where $E_\gamma$ is the total energy in $\gamma$-rays. Substituting the expression of $P'_{\nu_m}$ and $z = 1.6$ into equation (10), we obtain

$$F_{\nu_m} = 0.74 \left(\frac{E_\gamma}{1.6 \times 10^{52}}\right) \left(\frac{\Gamma_0}{1000}\right)^{-1} \left(\frac{\Gamma_\Lambda}{100}\right)^{1/2} \times n^{1/2} \left(\frac{\varepsilon_B}{10^{-3}}\right)^{1/2} \text{Jy}.$$

Please note that this formula always holds whether the ejecta are jet-like or spherical, because the beaming factor in equations (10) and (11) will cancel out each other in the jet-like case. According to the jump condition of the shock, the Lorentz factor of the shocked shell should be approximately equal to that of the shocked ISM (Piran 1999). The Lorentz factor of the forward shocked ISM can be obtained from the standard afterglow model (e.g. Sari et al. 1998):

$$\Gamma_{\Lambda,6}(t) = 6 \left(\frac{E_{52}}{n}\right)^{1/8} \left(\frac{t_d}{1+z}\right)^{-3/8}.$$  

For $E_{52} \sim 5$ and $n \sim 0.01$, we obtain

$$\Gamma_{\Lambda,6}(50\text{ s}) = \Gamma_{\Lambda,6}(50\text{ s}) = 300.$$  

Taking the above inferred value $\varepsilon_B \sim 3.1 \times 10^{-3}$, from the equations (9), (12) and (14) with the conditions: $v_m \lesssim 5 \times 10^{14} \text{Hz}$ and $F_{\nu_m} \lesssim 1 \text{Jy}$, we finally obtain

$$\Gamma_\Lambda = 300, \quad \Gamma_0 = 1200, \quad \varepsilon_e \lesssim 0.6.$$  

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Please note that here the value $\epsilon_e$ $\approx$ 0.6 inferred from the optical flash data is consistent with that inferred independently from the afterglow information. On the other hand, if we substitute the value $\epsilon_e$ $=$ 0.57 into equation (9), we find that the peak frequency of the reverse shock $\nu_{rs}$ is almost located at the optical band. In addition, our inferred initial Lorentz factor $\Gamma_0$ is 6 times larger than that obtained in SP99b, who have used the ambient density $n$ of GRB 970508. Consequently, at the time the reverse shock has just passed through the ejecta shell, its Lorentz factor was $\Gamma_{rs} = \Gamma_0/\Gamma_\Lambda \approx 4$. This indicates that the reverse shock had become relativistic before it crossed the entire shell. This result is also different from that obtained in SP99b, which found the Lorentz factor of the reverse shock of GRB 990123 was only near one. However, we argue that our result is reasonable according to the criterion presented by Sari & Piran (1995) (also see Kobayashi et al. 1999). They defined a dimensionless parameter $\xi$ constructed from $l$, $\Delta$ and $\Gamma_0$:

$$\xi = (l/\Delta)^{1/2}/\Gamma_0^{-4/3},$$

where $l = (E/nm_ec^2)^{1/3}$ is the Sedov length, $\Delta = c \delta T$ is the width of the shell ($\delta T$ is the duration of GRB) and $\Gamma_0$ is the initial Lorentz factor of the ejecta. If $\xi \leq 1$, the reverse shock becomes relativistic before it crosses the shell; otherwise ($\xi > 1$), the reverse shock remains Newtonian or at best mildly relativistic during the whole energy extraction process. For GRB 990123, we find $\xi \sim 0.3 < 1$. So the reverse shock of GRB 990123 had become relativistic before it crossed the shell, consistent with our calculated result.

4 CONCLUSIONS AND DISCUSSIONS

We have constrained some intrinsic parameters, such as the magnetic energy density fraction ($\epsilon_B$), the electron energy density fraction ($\epsilon_e$), the isotropic energy in the adiabatic forward shock $E_{\text{fs}}$ and the ambient density $n$. As a result of the lack of the value of the self-absorption frequency $\nu_a$, we made an assumption that $\epsilon_e$ of GRB 990123 is the same as that of GRB 970508, then astonishingly find that the inferred value of $\epsilon_B$ is also nearly equal to that of GRB 970508. This result favours the argument proposed by WG99 that the magnetic energy fraction and the electron density fraction may be universal parameters.

Another two important intrinsic parameters of GRB 990123 are also inferred from the optical flash information: the initial Lorentz factor $\Gamma_0$ and the Lorentz factor $\Gamma_\Lambda$ at the prompt optical emission peak time of the ejecta. They are $\Gamma_0 = 1200$ and $\Gamma_\Lambda = 300$. Our inferred value of the $\Gamma_0$ is 6 times larger than that obtained in SP99b, which used the ambient density $n$ inferred for GRB 970508. A larger initial Lorentz factor is reasonable in consideration of the huge energy of this burst. The Lorentz factor of the reverse shock at the optical flash peak time is $\Gamma_{rs} \sim \Gamma_0/\Gamma_\Lambda \sim 4$, which shows that the reverse shock had become relativistic rather than mildly relativistic before it crossed the entire ejecta shell. This result is in agreement with the criterion presented by Sari & Piran (1995) to judge the RRS case or NRS case.

Prompt optical flash has added another dimension to GRB astronomy. Prompt observations in the optical band during and immediately after GRB may provide more and more events of optical flash in the near future, and they will enable us to make more detailed analyses, make more precise determination of intrinsic parameters and test the reverse–forward external shock model.

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