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Optical Flash of GRB 990123: Constraints on the Physical Parameters of the Reverse Shock

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Abstract The optical flash accompanying GRB 990123 is believed to be powered by the reverse shock of a thin shell. With the best-fit physical parameters for GRB 990123 and the assumption that the parameters in the optical flash are the same as in the afterglow, we show that: 1) the shell is thick rather than thin, and we have provided the light curve for the thick shell case which coincides with the observation; 2) the theoretical peak flux of the optical flash accounts for only 3×10^{-4} of the observed. In order to remove this discrepancy, the physical parameters, the electron energy and magnetic ratios, $\epsilon_{\rm e}$ and $\epsilon_{\rm B}$, should be 0.61 and 0.39, which are very different from their values for the late afterglow.

Key words: gamma rays: bursts — gamma rays: theory

1 INTRODUCTION

BeppoSAX ushered in 1999 with the discovery of a super-bright γ-ray burst, GRB 990123. This GRB was intensively studied by many groups world wide. At that time this burst was notable for the richness of new results: the discovery of prompt optical emission by ROTSE (Akerlof et al. 1999), the discovery of the brightest optical afterglow and its redshift $z = 1.6004$ leading to a huge energy release of 1.6×10^{54} erg in $\gamma-$rays alone (Briggs et al. 1999; Kulkarni et al. 1999a), and a break in the optical afterglow light curve (Fruchter et al. 1999; Castro-Tirado et al. 1999), and the radio flare (Kulkarni et al. 1999b). In the past three years, all of these phenomena have been discussed in great detail. For instance, the steepening of the r-band light curve from about $t^{-1.1}$ to $t^{-1.8}$ after two days might be due to a jet which has passed from a spherical-like phase to a sideways expansion phase (Rhoads 1999; Sari, Piran & Halphern 1999; Huang et al. 2000a, b, c, d; Wei & Lu 2000). The steeping might also be due to a dense medium which has slowed down the shock quickly to a non-relativistic one (Dai & Lu 1999).

The most natural explanation for the strong optical emission accompanying GRB 990123 is the synchrotron emission from a reverse shock propagating into the fireball ejecta after it interacts with the surrounding gas (Sari & Piran 1999; Mészáros & Rees 1999). Under this framework, the light curve of GRB optical flash in a homogenous medium or in a stellar

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* E-mail: daizigao@public1.ptt.js.cn wind and its corresponding synchrotron self-Compton emission have been discussed in detail (Kobayashi 2001; Wang, Dai & Lu 2001a, b; Wu et al. 2002; Fan et al. 2002). Several authors attempted to constrain such intrinsic parameters as the Lorentz factor of the shocked fireball ejecta relative to the unshocked fireball ejecta ($\Gamma_{\rm rs}$) (Wang, Dai & Lu 2000; Sari & Piran 1999). It should be noted, however, that these estimates were made before accurate burst parameters for GRB 990123 were known, and consequently they include approximations and parameters from other GRB afterglows. Recently, by fitting the multi-frequency afterglow light curves, physical parameters for eight GRBs, including GRB 990123 have been reported (Panaitescu & Kumar 2001, hereafter PK01). This fitting has provided us the possibility to study this unique event more quantitatively. With these parameters Soderberg & Ramirez-Ruiz (2002, hereafter SR02) have estimated the expected prompt reverse shock emission for these eight bursts.

After a careful calculation with the parameters for GRB 990123 (we assume these parameters in the optical flash are the same as those in the late afterglow), in Section 2 we find the shell is thick and we provide the adjusted light curve for the thick shell case that matches the observation. In Section 3, we find the theoretical peak flux of the optical flash accounts for only 3×10^{-4} of the observed, if it is the reverse shock which accounts for the optical flash. To remove this large discrepancy, the physical parameters of the electron energy ratio and magnetic field energy ratio, $\epsilon_{\rm e}$ and $\epsilon_{\rm B}$, should be much different in the optical flash phase and the late afterglow phase. In the final section we present a discussion and give our conclusions.

2 LIGHT CURVES OF THE REVERSE SHOCK EMISSION FOR THE THICK SHELL CASE

By fitting multi-frequency afterglow light curves, physical parameters for eight GRBs have been reported in PK01. The best-fit parameters for GRB 990123 are: initial jet energy in afterglow phase $E_{j,50} = 1.5^{+3.3}_{-0.4}\,$erg, initial opening angle $\theta_0 = 2.1^{+0.1}_{-0.9}$deg, environment number density $n_{0,-3} = 1.9^{+0.5}_{-1.5}\,{\rm cm}^{-3}$, $\epsilon_{{\rm e},-2} = 13^{+1}_{-4}$, $\epsilon_{{\rm B},-4} = 7.4^{+23}_{-5.9}$, and electron distribution power-law index $p = 2.28^{+0.05}_{-0.03}$.

The thin shell deceleration time, t_γ, can be estimated by $t_\gamma \simeq 3E_{52}^{1/3} n_{0,5}^{-1/3} \eta_{300}^{-8/3}$ (Kobayashi 2000), where the scaled parameters are $E_{52} = E/10^{52}\,$erg, $n_{0,5} = n_0/5\,{\rm cm}^{-3}$, $\eta_{300} = \eta/300$, η is the initial Lorentz factor of the fireball at the end of the Gamma-ray burst: here we take its best estimated value $\eta = 900$ (SR02), E is the isotropic energy of the fireball in the afterglow. With these parameter values we have $t_\gamma \simeq 8\,{\rm s} < \Delta/c \simeq 20\,{\rm s}$, where Δ is the shell width. Therefore the shell is thick, rather than thin. In fact if the shell is thin, the reverse shock will be sub-relativistic. However, it is generally suggested that $\eta \simeq 900$ to 1200 (Wang, Dai & Lu 2000; SR02), and at the reverse shock crossing time Γ, the Lorentz factor of the fireball $\simeq 300$ (PK01), i.e., $\Gamma_{\rm rs} \simeq 5/3$ to 2 which is mid-relativistic, so the shell should be thick. This conclusion coincides with the result of Wang, Dai & Lu (2000). Some authors argued that if the shell was thick, the theoretical light curve would be much different from what was observed (Sari & Piran 1999; Kobayashi 2000; SR02). Below we give an analysis of this issue.

In the thick shell case, the reverse shock crosses the shell at $T \simeq \Delta/c$. At the reverse shock crossing time T the break frequency ν_m and the peak flux are

$$\nu_m = 10^{13}\Big(\frac{p-2}{p-1}\Big)^2\Big(\frac{\epsilon_{\rm e}}{0.1}\Big)^2\Big(\frac{\epsilon_{\rm B}}{10^{-3}}\Big)^{1/2}\Big(\frac{n}{10^{-2}}\Big)^{1/2}\Big(\frac{\Gamma_{\rm A}}{300}\Big)^2\Big(\Gamma_{\rm rs}-1\Big)^2\frac{1}{(1+z)}\,{\rm Hz}, \tag{1}$$

$$F_{\nu m} = 1.2\times10^{-2}\Big(\frac{D}{10^{28}}\Big)^{-2}\frac{N_{\rm e}}{10^{52}}\Big(\frac{\Gamma_{\rm A}}{300}\Big)^2\Big(\frac{n}{10^{-2}}\Big)^{1/2}\Big(\frac{\epsilon_{\rm B}}{10^{-3}}\Big)^{1/2}(1+z)\,{\rm Jy}, \tag{2}$$

where the relations $\gamma_m = (p-2)/(p-1)(m_\mathrm{p}/m_\mathrm{e})\epsilon_\mathrm{e}(\Gamma_\mathrm{rs}-1)$ for $p > 2$, $F_{\nu m} = \frac{N_\mathrm{e}\Gamma_\mathrm{A}P_{\nu m}(1+z)}{4\pi D^2}$, $P_{\nu m} = \phi_\mathrm{p}\frac{\sqrt{3}e^3 B}{m_\mathrm{e}c^2}$ and $B = 3.9\times10^{-2}n_1^{1/2}(\epsilon_\mathrm{B}/10^{-2})^{1/2}\Gamma_\mathrm{A}$ have been used, Γ_A is the Lorentz factor of the shocked shell, Γ_rs is approximated by $(\Gamma_\mathrm{A}/\eta+\eta/\Gamma_\mathrm{A})/2$ for Γ_A, $\eta\gg1$, N_e is the total number of electrons in the shell, D is the luminosity distance (we assume $H_0 = 65\,\mathrm{km\ s^{-1}}$ Mpc^{-1}, $\Omega_\mathrm{M} = 0.3$, $\Omega_\wedge = 0.7$), z is the redshift of the burst, ϕ_p is a function of p, whose value is ~ 0.6 for $p\sim 2.28$ (Wijers & Galama 1999).

The scalings before and after T in the homogenous medium case have been discussed by Kobayashi (2000). A difference between Kobayashi's and our scalings is: at early times the reverse shock is Newtonian (Kobayashi assumed it was relativistic), so $\Gamma_\mathrm{rs}-1\propto\Gamma_\mathrm{A}^2 f^{-1}$, $\Gamma_\mathrm{A}\simeq\eta$ (Sari & Piran 1995). In the thick shell case: spreading is not important, then $f\equiv\frac{n_4}{n_1}\propto R^{-2}$. Noting $R\sim 2\Gamma_\mathrm{A}^2 tc$, we have $f\propto t^{-2}$, i.e., $\Gamma_\mathrm{rs}-1\propto t^2$. Substituting this relation into Equation (1) we obtain $\nu_m\propto t^4$. Noting $N_e(t)\propto t$ (Kobayashi 2000) and substituting this relation into Equation (2), we have $F_{\nu m}\propto t$. For $\nu_m<\nu<\nu_c$ we have $F_\nu\propto t^{2(p-1)}F_{\nu m}\propto t^{2p-1}$.

For $\Gamma_\mathrm{rs}\gg1$, $(\Gamma_\mathrm{rs}-1)^2\Gamma_\mathrm{A}^2\sim\eta^2/4$, Equation (1) reduces to $\nu_m\sim$ constant, as the case suggested by Kobayashi (2000). Combining Kobayashi's results and ours we obtain the flux at a given frequency ν, for $\nu_m<\nu<\nu_c$,

$$F_\nu(t<T) \;\propto\; \begin{cases} t^{2p-1}, & \text{for } \Gamma_\mathrm{rs}-1\ll1, \\ t^{1/2}, & \text{for } \Gamma_\mathrm{rs}-1\gg1, \end{cases} \tag{3}$$

$$F_\nu(t>T) \;\propto\; t^{-(73p+21)/96}. \tag{4}$$

The observed optical light curve of GRB 990123 at early times shows a fast rise and a slower decay, with power-law indices 3.3 and –2.0 respectively. On the other hand, for $p = 2.28$ we have $2p-1 = 3.56$ and $-(73p+21)/96 = -1.95$, then we expect that the light curve rises faster at early times (for a power-law index 3.56), then more slowly (for a power-law index 0.5) before it reaches its peak. Unfortunately, the lack of data for the optical flash prevents us to check it more quantitatively. By now we have successfully explained the fast rise of $t^{3.3}$ and slow decay of $t^{-2.0}$ in the thick shell case.

3 THE EXPECTED PEAK FLUX OF THE OPTICAL FLASH

With the best fit parameters of GRB 990123 afterglow for a homogeneous medium at 90% confidence level, we have (see PK01): $M_\mathrm{jet}\simeq0.28\times10^{-6}M_\odot$, $\Gamma_0\simeq300$. Correspondingly, N_e and Γ_A in Equation (2) are $N_\mathrm{e}\simeq5\times10^{53}$ and $\Gamma_\mathrm{A}\simeq300$. The synchrotron spectrum for $\nu_m<\nu_\mathrm{obs}<\nu_c$ is given by

$$F_\mathrm{obs} = F_{\nu m}(\nu_\mathrm{obs}/\nu_m)^{\frac{-(p-1)}{2}}. \tag{5}$$

Substituting Equations (1) and (2) into Equation (5) we have

$$\begin{aligned} F_\mathrm{obs,\,peak} \;=\; & 0.012\times\left[0.14\left(\tfrac{p-2}{p-1}\right)\left(\tfrac{\epsilon_\mathrm{e}}{0.1}\right)(\Gamma_\mathrm{rs}-1)\right]^{p-1}\left[\left(\tfrac{\epsilon_\mathrm{B}}{10^{-3}}\right)\left(\tfrac{n}{10^{-2}}\right)\right]^{\frac{p+1}{4}} \\ & \left(\tfrac{D}{10^{28}}\right)^{-2}\tfrac{N_\mathrm{e}}{10^{52}}(1+z)^{\frac{3-p}{2}}\left(\tfrac{\Gamma_\mathrm{A}}{300}\right)^{p+1}\ \mathrm{Jy}. \end{aligned} \tag{6}$$

When $\nu_\mathrm{obs} = 5\times10^{14}\,\mathrm{Hz}$, $\Gamma_\mathrm{rs}-1\simeq1$ and other best fitted parameters of GRB 990123 have been taken in the calculation, we have $F_\mathrm{obs,\,peak} = 3\times10^{-4}\,\mathrm{Jy}$, which is much less than what was observed, $F_\mathrm{peak}\simeq1\,\mathrm{Jy}$ (Akerlof et al. 1999).

One may argue that if the optical flash was born in a dense envelope, for instance, $n\simeq 40\,\mathrm{cm}^{-3}$, the discrepancy will disappear. However, there is no more evidence for that. Another way is to assume that the physical parameters in the optical flash are different from those in the late afterglow, for example, $\epsilon_{\rm e} \simeq 0.61$, $\epsilon_{\rm B} \simeq 0.39$ (n is kept the same as in the afterglow phase) can remove this discrepancy safely, but this would mean that in the different phases (the GRB, very early afterglow and the late afterglow) the physical parameters are much different. In fact, as early as in 2000, it was proposed that the high energy spectral power-law indices (β) for GRBs 970508, 990123, 990510, 991216 are –1.88, –2.30, –2.49, –2.00 respectively (Fenimore & Ramirez-Ruiz 2000), i.e., the corresponding p in the GRB phase are 1.76, 2.60, 2.98, 2.00, respectively. However, the best fitted p in the afterglow phase are 2.18, 2.28, 1.83, 1.36, respectively for these four GRBs (PK01). Obviously they are quite different.

Dai & Lu (1999) have proposed the dense medium model to explain the afterglow decay of GRB 990123. The parameters derived from that model are $\epsilon_{\rm e} \sim 0.1$, $\epsilon_{\rm B,-6} \sim 0.02$, $n \sim 3 \times 10^6$. In this case, if we set $\Gamma_{\rm A} \simeq 300$, $N_{\rm e} = E_{{\rm iso},\gamma}/\Gamma_0 m_p c^2$, $p = 2.3$, we have $F_{\rm obs,\,peak} \simeq 1{\rm Jy}$. However, according to the jump conditions of the shock, the Lorentz factor of the shocked shell should approximately be equal to that of the shocked ISM. The Lorentz factor of the forward shocked ISM could be obtained from the standard afterglow model (e.g. Sari, Piran & Narayan 1998): $\Gamma_{\rm A,fs}(t) \simeq 6(\frac{E_{52}}{n})^{1/8}(\frac{t_d}{(1+z)})^{-3/8}$. For $E_{52} \sim 22\,{\rm erg}$ and $n \sim 3 \times 10^6\,{\rm cm}^{-3}$, we have $\Gamma_{\rm A,\,rs}(50\,{\rm s}) = \Gamma_{\rm A,\,fs}(50\,{\rm s}) \simeq 32$, which is much below 300. From Equation (6), such small $\Gamma_{\rm A,\,rs}$ will lead to a much smaller $F_{\rm obs,\,peak}$ than the observed. This negative result favors our opinion that these parameters for later forward and early reverse shocks are different, at least in the case of GRB 990123.

4 SUMMARY AND DISCUSSION

With the parameters for GRB 990123 provided in PK01, we have shown that the shell is thick rather than thin. The adjusted light curve for the thick shell case can account for the observed light curve of the optical flash of GRB 990123. However, the expected peak emission flux is much less than the observed. The parameters derived from the dense medium model by Dai & Lu (1999) have been considered, too, but the expected peak emission is still much less than the observation. If the optical flash was really produced by the reverse shock, the parameters $\epsilon_{\rm B}$, $\epsilon_{\rm e}$, even p in the optical flash should be much different from that in the late afterglow. Unfortunately there is not enough data for us to study it more quantitatively. New observations are needed to provide us a chance to understand optical flashes in more detail.

With the parameters of eight GRBs', SR02 have estimated the reverse shock peak emission for seven bursts—for reasonable assumptions about the velocity of the source expansion, a strong optical flash $m_V \sim 9$ was expected from the reverse shock, then the best observational prospects for detecting these prompt flashes were high-lightened. It is easy to see that Equation (6) in this note provides similar results. For instance: for GRB 000926, we have $F_{\rm obs,\,peak} \sim 0.2(\Gamma_{\rm rs} - 1)^{p-1}{\rm Jy}$. Surprisingly, although many researchers have tried their best, no more optical flashes have been observed (Akerlof et al. 2001; Kehoe et al. 2001). SR02 suggested that dust obscuration seems to be the most likely reason for non-detection. However, considering the discrepancy between the observed peak flux and the theoretically expected value, the reverse shock emission might be insignificant, and a more reliable model to explain that "unique" observation is needed.

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