Rebrightening of XRF 030723: Further Evidence for a Two-Component Jet in Gamma-Ray Burst

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ABSTRACT

Optical afterglows from two-component jets under various configurations are investigated numerically. Generally, the light curve is characterized by a rapid rebrightening when the observer is off-axis with respect to the narrow component, with the amplitude and peak time depending on detailed parameters. We further show that the optical afterglow of XRF 030723, especially its notable and rapid rebrightening, can be well explained by a typical two-component jet. This X-ray flash, together with GRB 030329, strongly hints the two-component jet model as a unified picture for X-ray flashes and gamma-ray bursts. With a narrow but ultra-relativistic inner outflow and a wide but less energetic outer ejecta, a two-component jet will be observed as a typical gamma-ray burst if our line of sight is within the angular scope of the narrow outflow. Otherwise, if the line of sight is within or slightly beyond the cone of the wide component, an X-ray flash will be detected.

Subject headings: gamma rays: bursts — ISM: jets and outflows — X-rays: bursts

1. Introduction

Jets play an important role in gamma-ray bursts (GRBs) (Rhoads 1997). Theoretically, collimation is essential to resolve the energy crisis derived from a few GRBs, such as GRB 971214, 990123, and 990510 (Bloom et al. 1998; Kulkarni et al. 1998, 1999; Andersen et al. 1999;...
The existence of jets also sheds light on the enigmatic nature of GRBs, indicating that the births of accreting, rapidly rotating black holes might be involved. Till now, jets in GRBs have been investigated in great detail, and many important effects are revealed, such as the break in afterglow light curves (e.g., Rhoads 1999; Sari, Piran, & Halpern 1999; Panaitescu & Kumar 2001; Huang & Cheng 2003), orphan afterglows (e.g., Rhoads 1997; Granot et al. 2002; Huang, Dai, & Lu 2002), and polarization (e.g., Gruzinov 1999; Hjorth et al. 1999; Mitra 2000; Rol et al. 2003; Coburn & Boggs 2003; Waxman 2003). Recently it is further realized that collimated jets, when off-beamed, can also give birth to a special kind of GRBs, X-ray flashes (XRFs).

XRFs have been identified as a sub-class of GRBs only recently. They are characterized by relatively softer spectra, but with durations and temporal structures typical of most long GRBs (Frontera et al. 2000; Heise et al. 2003; Kippen et al. 2003; Barraud et al. 2003). However, in addition to the off-beam GRB mechanism (Woods & Loeb 1999; Nakamura 1999; Yamazaki, Ioka, & Nakamura 2002, 2003; Jin & Wei 2003), XRFs can also be produced by dirty fireballs (Dermer, Chiang, & Bottcher 1999; Zhang & Meszaros 2002b; Heise et al. 2003), or namely failed GRBs (Huang, Dai, & Lu 2002). As the newly identified sub-class, XRFs still seem to be quite enigmatic, but can hopefully give useful hints on the nature of typical GRBs.

In the field of X-ray rich GRBs, optical afterglows were first observed (Soderberg et al. 2002) from XRF 020903 (Sakamoto et al. 2003), with the redshift being measured as \( z = 0.251 \) (Soderberg et al. 2003b). XRF 030723 (Prigozhin et al. 2003) is another important event, whose optical afterglow light curve has even been satisfactorily determined. It is quite striking that its afterglow decays in a way very similar to that of typical GRBs, i.e., following a simple power-law function of time. This strongly indicates that XRFs and other long GRBs may have similar origins. However, a prominent characteristics of the optical counterpart of XRF 030723 is that it rebrightened by about one magnitude from \( t \sim 11 \) d to \( t \sim 14 \) d (Fynbo et al. 2003b). Such a rapid rebrightening is somewhat unexpected to us.

In this paper, we show that the behaviour of the optical afterglow of XRF 030723 can be well explained by the two-component jet model advocated by Berger et al. (2003b). Our results suggest that both the baryon loading mechanism and the off-beam mechanism are taking effect in XRF 030723. The structure of our paper is organized as follows. The model is described briefly in §2. We then numerically investigate the afterglow behaviour of two-component jets in §3, presenting optical light curves under various configurations. Our fit to the optical afterglow of XRF 030723 is illustrated in §4. §5 is the conclusion and discussion.
2. Model

2.1. Two-component jet

The simplest jet model involves a homogeneous conical outflow. But in reality a jet can be complicatedly structured (Zhang, Woosley, & Heger 2003a; Zhang, Woosley, & MacFadyen 2003b). In this case, it is usually assumed that the energy per unit solid angle depends as a power-law or a Gaussian function on the angular distance from the axis (Mészáros, Rees, & Wijers 1998; Dai & Gou 2001; Rossi, Lazzati, & Rees 2002; Zhang & Mészáros 2002a; Kumar & Granot 2003; Salmonson 2003; Granot & Kumar 2003; Zhang, Dai, Lloyd-Ronning, & Mészáros 2003). Recently, our attention was drawn to another special kind of structured jets, i.e., two-component jets (Berger et al. 2003b; Sheth et al. 2003).

A two-component jet has two components: a narrow ultra-relativistic outflow and a wide but mildly relativistic ejecta (Berger et al. 2003b; Sheth et al. 2003; also see: Frail et al. 2000; Ramirez-Ruiz, Celotti, & Rees 2002). At first glance, the two-component jet model still seems to be too coarse, but it strikingly gives a perfect explanation to the multi-band observations of GRB 030329. As suggested by Berger et al. (2003b), the $\gamma$-ray and early afterglow emission of GRB 030329 come from the narrow component, while the radio and optical afterglow beyond 1.5 days should be produced by the wide component. They even derived the half opening angles of the two components as $\sim 5^\circ$ and $\sim 17^\circ$ respectively. The total intrinsic kinetic energy of these two components is perfectly consistent with the standard energy reservoir hypothesis (Frail et al. 2001; Panaitescu & Kumar 2001; Bloom, Frail, & Kulkarni 2003; Berger, Kulkarni, & Frail 2003a).

In this paper, we designate the initial half opening angle of the narrow and the wide component as $\theta_{0,N}$ and $\theta_{0,W}$, respectively, where the subscript “N” means “narrow” and “W” means “wide”. We further assume that their isotropic equivalent kinetic energies are $E_{N,\text{iso}}$ and $E_{W,\text{iso}}$, and initial Lorentz factors are $\gamma_{0,N}$ and $\gamma_{0,W}$, respectively. We will model the dynamical evolution and radiation process of the two components in §2.2, and calculate their optical afterglows numerically in §3.

2.2. Dynamics and radiation process

We assume that the two components are coaxial. To simplify the problem, the interaction and overlapping of the two components are generally neglected. We then can essentially calculate the dynamical evolution of the two components independently, and add their emission together to get the total afterglow light curve of the entire jet.
We use the model developed by Huang et al. (Huang, Dai, & Lu 2000a; Huang et al. 2000b) to describe the evolution and radiation of each component. In this model, evolution of the bulk Lorentz factor is given by (Huang, Dai, & Lu 1999a, b),

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon m + 2(1 - \epsilon)\gamma m},$$

(1)

where $m$ is the mass of swept-up interstellar medium (ISM), $M_{ej}$ is the initial mass of the ejecta, and $\epsilon$ is the radiative efficiency. Equation (1) has the virtue of being applicable in both the ultra-relativistic and the non-relativistic phases (Huang et al. 1999a, b). The lateral expansion of the outflow is described realistically by (Huang et al. 2000a, b),

$$\frac{d\theta}{dt} = c_s(\gamma + \sqrt{\gamma^2 - 1})R,$$

(2)

with

$$c_s^2 = \frac{\hat{\gamma}(\hat{\gamma} - 1)(\gamma - 1)}{1 + \hat{\gamma}(\gamma - 1)}c^2,$$

(3)

where $\theta$ is the half opening angle, $c_s$ is the co-moving sound speed, $R$ is the radius, and $\hat{\gamma} \approx (4\gamma + 1)/(3\gamma)$ is the adiabatic index. For simplicity, we assume that the ejecta is adiabatic, which means the radiative efficiency in equation (1) is $\epsilon \equiv 0$.

Optical afterglows can be calculated by considering synchrotron radiation from shock-accelerated electrons in the outflow. In our model, we use a realistic electron distribution function that takes into account the cooling effect (Sari, Piran, & Narayan 1998) and the non-relativistic effect (i.e., the minimum Lorentz factor of electrons, $\gamma_{e,\text{min}}$, will be less than a few when the outflow enters the “deep Newtonian phase” (Huang & Cheng 2003)). Additionally, the equal arrival time surface effect (Waxman 1997; Sari 1998; Panaitescu & Mészáros 1998) is also included in our consideration.

3. Numerical Results

We now present our numerical results for afterglows of two-component jets. For convenience, let us first define a set of “standard” parameters as following: $\theta_{0,W} = 0.3$, $E_{W,\text{iso}} = 10^{52}$ ergs, $\gamma_{0,W} = 30$, $\theta_{0,N} = 0.1$, $E_{N,\text{iso}} = 5 \times 10^{53}$ ergs, $\gamma_{0,N} = 300$, ISM number density $n = 1 \text{ cm}^{-3}$, electron energy ratio $\epsilon_e = 0.1$, magnetic energy ratio $\epsilon_B = 0.01$, luminosity distance $D_L = 2 \text{ Gpc}$, electron distribution index $p = 2.5$, and viewing angle $\theta_{\text{obs}} = 0.35$. These parameter values are typical in GRB afterglows. Most of them are also roughly consistent with those derived for GRB 030329 by Berger et al. (2003b). A two-component jet with this standard configuration has an intrinsic kinetic energy of $\sim 1.5 \times 10^{51}$ ergs, also
approximately meets the requirement of the standard energy reservoir hypothesis (Frail et al. 2001; Panaitescu & Kumar 2001; Bloom et al. 2003; Berger et al. 2003a).

Figure 1 illustrates R-band afterglows from a two-component jet under the “standard” configuration. It also shows clearly how emission from the two components is compounded together to give out the total light curve. In the current configuration, since the line of sight is notably outside the initial angular range of the narrow component, we see that the afterglow is dominated by emission from the wide component before $\sim 10^6$ s. But as the narrow component decelerates and expands laterally, its emission increases rapidly until the flux density finally comes to a peak at about $\sim 1.6 \times 10^6$ s. The total light curve is dominated by this component thereafter.

At the peak time mentioned above, the Lorentz factor of the narrow component is $\gamma_N \approx 2.4$, and its angular width is $\theta_N \approx 0.24$. Note that $\theta_N$ is still notably less than $\theta_{\text{obs}}$, but the inverse of the Lorentz factor ($1/\gamma_N \approx 0.4$) is very close to $\theta_{\text{obs}}$. We conjecture that the peak time is roughly determined by the condition of $\gamma_N \sim 1/\theta_{\text{obs}}$. This conjecture is confirmed by our further calculations under other configurations.

Another important characteristics that deserves mentioning in Figure 1 is the rapidness of the increase of the narrow component emission before the peak point. This behaviour hints that a two-component jet can potentially explain the quick rebrightening of optical afterglows of XRF 030723.

The shape of the total optical light curve will surely be affected by the energy ratio of the two components. To illustrate the effect, we fix the isotropic equivalent energy of the wide component, but vary that of the narrow component, and calculate the afterglow emission. The results are presented in Figure 2. Generally speaking, a more powerful narrow component can reasonably result in a more prominent peak, but with the peak time slightly postponed. From Figure 2, we can also imagine that in some special cases, when $E_{N,\text{iso}}$ is not much larger than $E_{W,\text{iso}}$, the peak will become anonymous so that we can observe nothing but a short plateau in the total light curve.

Another factor that affects the energy ratio of the two components is their relative angular width. In Figure 3, we illustrate the impact of $\theta_{0,N}$ on the total light curve. Again, we see that a larger $\theta_{0,N}$, which leads to a more powerful narrow component, makes the peak more prominent. However, unlike the effect of $E_{N,\text{iso}}$ (see Figure 2), a larger $\theta_{0,N}$ tends to make the light curve peak slightly earlier. This in fact is not difficult to understand.

Figure 4 illustrates the effect of viewing angle ($\theta_{\text{obs}}$) on the light curve. When $\theta_{\text{obs}} \leq \theta_{0,N}$, the entire light curve is dominated by the narrow component emission. When $\theta_{\text{obs}} > \theta_{0,N}$, the light curve is dominated by the wide component emission initially, but is dominated by
emission from the narrow component at late stages. It is clear that the viewing angle affects
the peak time notably. It should also be noted that the light curve of $\theta_{\text{obs}} = 0.1$ differs from
that of $\theta_{\text{obs}} = 0$ only slightly. Similar behaviour can also be observed in the light curves
of $\theta_{\text{obs}} = 0.2$ and $\theta_{\text{obs}} = 0.3$ at early stages. It means the light curves will almost be the
same as long as the line of sight is within the initial angular range of the outflow, consistent
with previous studies (Huang et al. 2000a). However, the light curve difference between
$\theta_{\text{obs}} = 0.2$ and $\theta_{\text{obs}} = 0.3$ at early phase is noticeably larger than that between the $\theta_{\text{obs}} = 0$
and $\theta_{\text{obs}} = 0.1$ curves. This is because the wide component is expanding with a much smaller
Lorentz factor ($\gamma_{0,W} = 30$).

In Berger et al.’s study of GRB 030329, the observer is assumed to be on the axis of
the two-component jet (Berger et al. 2003b). The overall R-band optical afterglow can then
be divided into three different stages. The early optical afterglow ($t \leq 1$ d), which shows a
notable light curve break (evolving from $\sim t^{-1}$ to $\sim t^{-2.3}$) at about $t \sim 0.6$ d, is believed
to originate from the narrow component; The mid-term afterglow ($1.5$ d $\leq t < 20$ d) comes
from the wide component; Optical emission at late stages ($t > 20$ d) is attributed to a hidden
supernova. Of special interest is the fact that in their calculation, the emission is dominated
by the narrow component in the first stage (i.e. $t \leq 1$ d), and then dominated by the wide
component thereafter (i.e. $1.5$ d $\leq t < 20$ d). This seems to be completely opposite to the
cases illustrated in our Figures 1 — 4, where the emission is generally dominated by the
wide component initially, and then by the narrow component at late times. Note that in
most of our calculations, $\theta_{\text{obs}}$ has been taken as 0.2 or even larger, so that the observer is
initially well outside the opening angle of the narrow jet. The reversal of the roles played by
the wide and narrow components is thus in fact due to the difference of the viewing angle,
and to the difference in the relative intrinsic kinetic energies of the two components as well,
as explained further below.

In Figure 4 we have also evaluated $\theta_{\text{obs}}$ as zero in one case, i.e. the thick dashed
line. In this case, the light curve is really dominated by the narrow component initially,
but a bump or a plateau indicating the contribution from the wide component can barely
be seen even at late stages. In other words, the light curve is virtually dominated by the
narrow component all the time. One thus may doubt the ability of the two-component jet
model to reproduce the optical light curve of GRB 030329 as suggested by Berger et al. In
fact, there are slight differences in the parameter values taken by Berger et al. and by us.
Berger et al. (2003b) evaluated their parameters as $\theta_{0,W} \sim 0.3$, $E_{W,\text{iso}} \sim 5.6 \times 10^{51}$ ergs,
$\theta_{0,N} \sim 0.09$, and $E_{N,\text{iso}} \sim 1.2 \times 10^{52}$ ergs. The intrinsic kinetic energies of their wide and
narrow components are then $\sim 1.2 \times 10^{50}$ ergs and $\sim 2.4 \times 10^{49}$ ergs respectively. Note
that their $E_{N,\text{iso}}$ is only twice their $E_{W,\text{iso}}$, so that the intrinsic kinetic energy of the wide
component is essentially larger than that of the narrow component by a factor of $\sim 5$. It
is then easy to understand that the late time emission should be dominated by the wide component. But in our “standard” configuration, $E_{N,\text{iso}}$ is higher than $E_{W,\text{iso}}$ by a factor of $\sim 50$, and the intrinsic kinetic energies of the wide and narrow components are $\sim 2.2 \times 10^{50}$ ergs and $\sim 1.2 \times 10^{51}$ ergs respectively. We see that the intrinsic kinetic energy of our narrow component is virtually $\sim 6$ times as large as that of our wide component. This explains why the thick dashed line in our Figure 4 is overall dominated by the narrow component.

Anyway, it should be of some interest to examine numerically whether the two-component jet model is really capable of reproducing the optical afterglow of GRB 030329 or not. We have repeated our calculation by taking a set of parameters that are very close to those recommended by Berger et al. (2003b), i.e. $\theta_{0,W} = 0.3$, $E_{W,\text{iso}} = 5 \times 10^{51}$ ergs, $\theta_{0,N} = 0.08$, $E_{N,\text{iso}} = 10^{52}$ ergs, and $n = 2 \text{ cm}^{-3}$. The results are presented in Figure 5. In Figure 5a we see that the wide component emission (dashed line) is really stronger than the narrow component emission (dash-dotted line) after $\sim 4 \times 10^4$ s. The slope of the dashed line is also obviously flatter than that of the dash-dotted line. A two-component jet thus does have the potential of reproducing the behavior of GRB 030329. However, Figure 5a also clearly shows that the total light curve differs from that of GRB 030329 markedly. The major problem is that although the wide component emission is weaker than the narrow component emission before $\sim 4 \times 10^4$ s, it is weaker only slightly. As a result, we cannot observe the expected flatening after $\sim 4 \times 10^4$ s, nor can we observe the jet break caused by the narrow component before $\sim 4 \times 10^4$ s.

Figure 5a indicates that while the two-component jet model basically has the potential of explaining the afterglow behavior of GRB 030329, the problem might in fact be much more complicate than what we have expected. Maybe we need to consider many other details that may take effect in the process. In Berger et al.’s (2003b) modeling of GRB 030329, the wide component emission is assumed to be very weak before $\sim 2$ d, with the reason unexplained explicitly. We should bear in mind that our consideration of the two-component jet model here is in fact still very preliminary. Many details, some of which we believe do have the effect of reducing the early emission from the wide component, have been omitted for simplicity. For example, we do not consider the overlap of the two components. In fact, since there is a central narrow component resided on the axis, the wide component should be empty at the center in reality. In other words, the wide component should be a hollow one. It should be invisible to the observer at early times as long as the line of sight is within the central hole, i.e. $\theta_{\text{obs}} < \theta_{0,N}$. In Figure 5b, we have re-drawn the light curves by cutting the emission from the central cone of the wide component occupied by the narrow one. We see that the wide component emission is really reduced markedly before $\sim 10^5$ s, and the total light curve now seems much better. Of course, this total light curve still cannot be entitled “completely satisfactory” as compared with the observed optical afterglow light curve of GRB 030329,
but we believe a satisfactory fit should be possible when more details, including more realistic interaction between the two components, are considered. We will not attempt to present an overall fit to the multi-band observations of afterglows of GRB 030329 here. It is beyond the scope of this study.

4. Fit to XRF 030723

XRF 030723 occurred at 06:28:17.45 UT on July 23, 2003, and was detected by the High Energy Transient Explorer-II (HETE-2) (Prigozhin et al. 2003). The burst duration ($T_{90}$) in the 7 — 30 keV band was $\sim 25$ s, with a total fluence of $\sim 2 \times 10^{-7}$ ergs cm$^{-2}$. In contrast, its fluence in 30 — 400 keV band was less than $7 \times 10^{-8}$ ergs cm$^{-2}$, which is less than 0.4 times the fluence in the 7 — 30 keV band. An XRF nature thus is strongly favored by these HETE-2 observations (Prigozhin et al. 2003).

A preliminary localization with an error radius of $\sim 30'$ was distributed through the internet as early as 42 s later, triggering an extensive campaign searching for its afterglows in various bands. The optical counterpart was first reported by Fox et al. (2003), and then followed by many other groups. The transient has also been detected in X-rays (Butler et al. 2003a, b), but no radio counterpart was observed with a $3\sigma$ upper limit of 180 $\mu$Jy at 8.46 GHz on July 26.42 UT (Soderberg et al. 2003a).

XRF 030723 is an important event in the studies of XRFs. For the first time the optical afterglow light curve is determined satisfactorily for an XRF. Strikingly but not unexpectedly, the optical transient decays in a way very similar to that of typical GRBs, i.e., roughly following a power-law of time, strongly indicating that XRFs and other long GRBs may have similar origins.

However, a special feature of XRF 030723 is that the optical transient rebrightened by about one magnitude from $t \sim 11$ d to $t \sim 14$ d (Fynbo et al. 2003b). Such a rapid increase in the afterglow light curve (see Figure 6) needs an appropriate explanation. In a recent study, Dado et al. (Dado, Dar, & De Rújula 2003) have interpreted the afterglow of XRF 030723 in the frame-work of their cannonball model. They attributed the rebrightening to a hidden supernova (also see Fynbo et al. 2003b). However, we notice that a typical type Ib/c supernova usually cannot enhance the emission so steeply.

From Figures 1 — 4 we have seen that the rapid rebrightening is a general feature for two-component jets if the observer is off-center. Motivated by this phenomenon, we have tried to use a two-component jet to model the R-band light curve of XRF 030723. In Figure 6, we illustrate our best fit, where the parameters are taken as: $\theta_{0,W} = 0.3$, $E_{W,\text{iso}} = 10^{52}$
ergs, $\gamma_{0,W} = 30$, $\theta_{0,N} = 0.09$, $E_{N,iso} = 3 \times 10^{53}$ ergs, $\gamma_{0,N} = 300$, $n = 1 \text{ cm}^{-3}$, $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, $p = 3.2$, and $\theta_{\text{obs}} = 0.37$. Under this configuration, the total intrinsic kinetic energy is $\sim 8.3 \times 10^{50}$ ergs, consistent with the standard energy reservoir hypothesis. Since the redshift is still unknown, we arbitrarily take the luminosity distance as $D_L = 2.5 \text{ Gpc}$. In our calculation, we omit the overlapping of the two components since the observer is outside the scope of the narrow component. Note that the error bars of the two observational data points near $10^6$ s are not plotted, because they are not available in the literature. But we can imagine that they might be comparable to those of the points which are just preceding or behind them. Figure 6 shows clearly that the two-component jet model can reproduce the light curve satisfactorily.

In our fit, we have taken $\theta_{\text{obs}}$ as 0.37. If we change $\theta_{\text{obs}}$ to 0.35 or an even smaller value, then the theoretical light curve will be notably above those upper limits and flux densities (totally 6 points) obtained by ROTSE-III between $t \sim 50$ s and $t \sim 2600$ s (Smith et al. 2003). This is a good example showing how the early afterglows can provide valuable clues to our understanding of the nature of GRBs.

Our results strongly suggest that XRF 030723 might be produced by a two-component jet. The central narrow component has an initial Lorentz factor typical of most GRB fireballs (i.e., $\sim 100 \sim 1000$). It can generate a GRB successfully if viewed on or near the axis. But since the observer is highly off-center, the event is finally completely undetectable. The wide component has an initial Lorentz factor of $1 \ll \gamma_{0,W} \ll 100$. It fails to produce a typical GRB, but can give birth to an XRF (Huang et al. 2002). This XRF is detectable even though our line of sight is slightly outside the angular range of the wide component.

It should be noted that in our model, the main burst of XRF 030723 is essentially attributed to the dirty fireball effect (Dermer et al. 1999; Huang et al. 2002), not to the off-beam effect. The off-beam mechanism is included here mainly to meet the requirement of the early afterglow observations.

5. Conclusion and Discussion

Optical afterglows from two-component jets under various configurations have been investigated numerically. The light curve is generally characterized by a rapid rebrightening when the observer is off-beamed with respect to the narrow component. Depending on parameters such as $\theta_{0,W}, \theta_{0,N}, E_{W,iso}, E_{N,iso}$ and $\theta_{\text{obs}}$, the amplitude and peak time of the rebrightening vary accordingly. In some special cases, when the central component is not much more powerful than the outer, wide component, the rebrightening will become so
shallow that it simply manifests as a short plateau in the light curve. In fact, when taking
the parameters recommended by Berger et al. (2003b) for GRB 030329, we can imagine that
no rebrightening or plateau would be seen in the total optical light curve even a non-zero
viewing angle was assumed (cf. Figure 5). In this case, since the intrinsic kinetic energy of
the narrow component is much less than that of the wide one, we virtually would only see a
simple light curve which barely differs from that produced by the wide component alone.

XRF 030723 may play an important role in the studies of XRFs as well as GRBs. We
have shown that its afterglow, especially the rapid rebrightening at \( t \sim 14 \) d, can be well
presented by the two-component jet model. XRF 030723, together with GRB 030329 (Berger
et al. 2003b), strongly hints the two-component jet model as a unified picture for XRFs and
GRBs. In this framework, the central, narrow component has a Lorentz factor of \( \sim 100 -
1000 \), and the outer, wide component has a Lorentz factor of \( 1 \ll \gamma_0, W \ll 100 \) due to baryon
loading. If the observer is within the angular range of the central component, a typical GRB
will be observed. Otherwise, if the observer is within or slightly beyond the scale of the wide
component, an XRF or an X-ray rich GRB will be detected. Additionally, since the wide
component is a highly decelerated outflow and has been affected seriously by circum-engine
baryons, we can imagine that it will lose its memory of the central engine so that the XRF
emission should be produced mainly by external shocks (Zhang et al. 2003b). Of course,
strong variability is still possible in the XRF light curve, since the condition of the wide
component as well as its environment may be very complicated in reality.

Recently it has been realized that the homogeneous jet assumption is only a coarse
approach to the outflows in GRBs. Structured jets, which find support in numerical simulations
of massive star collapse (Zhang et al. 2003a, b), are receiving more and more attention. In a
recent study, Zhang et al. (2003a) found that when an ultra-relativistic jet breaks out from
a massive Wolf-Rayet star, it is usually surrounded by a cocoon of less energetic, but still
highly relativistic ejecta (see Ramirez-Ruiz, Celotti, & Rees (2002) for a theoretical under-
standing of the formation of the cocoon). Thus although the two-component jet model still
seems to be too coarse, it in fact is supported by numerical simulations. It is very interesting
that Zhang et al. (2003a) also noted that these cocoons may give birth to XRFs.

The rapid rebrightening of XRF 030723 should not be due to a hidden supernova. We
have interpreted the rebrightening as evidence for the existence of a narrow component in
a wider ejecta. But it deserves mentioning that a density-jump, i.e., an abrupt increase in
the ISM density, can also give birth to a rapid rebrightening (Dai & Lu 2002; Lazzati et
al. 2002; Dai & Wu 2003). In this case, we expect that a simultaneous decrease in radio
brightness could be seen since self-absorption will be enhanced in a denser environment.
Lacking an ideal coverage and multi-band observations between \( t \sim 11 \) d and \( t \sim 14 \) d, the
density-jump interpretation for XRF 030723 cannot be completely excluded currently. Still another possible interpretation may involve refreshed shocks, i.e. shells produced by the central engine at late times. This mechanism has been adopted to explain the variability in the optical afterglows of GRB 021004 and 030329 (Nakar, Piran, & Granot 2003; Granot, Nakar, & Piran 2003). Refreshed shocks can potentially give birth to many rebrightenings in a single afterglow light curve. In the future, when afterglows are observed from more and more XRFs, these interpretations can then be tested in more details.

Finally, since two-component jets are most likely produced in massive star collapses, it is possible that XRF 030723 may be accompanied by a supernova. Wu et al. (2003) pointed out that the supernova component usually peaks at about $\sim (1 + z) \times 15$ d in the optical light curve of typical GRBs, where 15 d is approximately the peak time of a type Ic supernova in its comoving frame. Since the redshift of XRF 030723 is not large ($z < 2.1$, Fynbo et al. 2003a), we expect that the supernova component should appear $\sim 20 \text{—} 40$ days after the trigger. A search for such a supernova component should deserve trying, because XRF 030723 may not be unacceptably far away. It is interesting that XRF 030723 has been observed at $t \sim 11$ d, 12 d, 64 d, and 71 d respectively. These observations show that the optical transient is still decaying rapidly about 70 days later, further monitoring of the optical transient is thus interesting and valuable. However, lacking observational data between $\sim 12$ d and 60 d, the existence of a supernova is unfortunately uncertain.

We thank an anonymous referee for valuable comments and suggestions that lead to an overall improvement of this study. This research was supported by the Special Funds for Major State Basic Research Projects, the National Natural Science Foundation of China (Grants 10003001, 10233010, and 10221001), the Foundation for the Author of National Excellent Doctoral Dissertation of P. R. China (Project No: 200125), and the National 973 Project (NKBRSF G19990754).
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Fig. 1.— Optical (R-band) afterglow of a two-component jet with “standard” parameters, which are defined in section 3 of the main text. The dashed line corresponds to emission from the wide component and the dash-dotted line is for the narrow component. The solid line illustrates the total light curve.

Fig. 2.— Effects of isotropic equivalent energy of the narrow component on the afterglow from a two-component jet. The solid line is plot with “standard” parameters defined in section 3. Other lines are drawn with only $E_{N,\text{iso}}$ altered.
Fig. 3.— Effects of initial opening angle of the narrow component on the afterglow from a two-component jet. The solid line is plot with “standard” parameters defined in section 3. Other lines are drawn with only $\theta_{0,N}$ altered.

Fig. 4.— Effects of viewing angle on the afterglow from a two-component jet. The solid line is plot with “standard” parameters defined in section 3. Other lines are drawn with only $\theta_{\text{obs}}$ altered.
Fig. 5.— (a) Afterglow from a two component jet when $E_{\text{N,iso}}$ is only twice $E_{\text{W,iso}}$ and when the observer is on-axis. Note that the parameters are evaluated as $\theta_{0,W} = 0.3$, $E_{\text{W,iso}} = 5 \times 10^{51}$ ergs, $\theta_{0,N} = 0.08$, $E_{\text{N,iso}} = 10^{52}$ ergs, $n = 2 \text{ cm}^{-3}$, $\theta_{\text{obs}} = 0$, with other parameters the same as in Figure 1. Under this configuration, the wide component has an intrinsic kinetic energy of $1.1 \times 10^{50}$ ergs, and the narrow component’s energy is $1.6 \times 10^{49}$ ergs. The dashed line corresponds to emission from the wide component, the dash-dotted line corresponds to emission from the narrow component, and the solid line is the total light curve. (b) Same as (a), except that the wide component is now assumed to be a hollow cone since its central portion is occupied by the narrow component.
Fig. 6.— Fit to the optical afterglow of XRF 030723 by using the two-component jet model. Parameter values adopted in this plot are given in section 4 of the main text. The dashed line corresponds to emission from the wide component and the dotted line is for the narrow component. The solid line illustrates the total light curve. Observed data points have been taken from the GCN (Prigozhin et al. 2003; Fox et al. 2003; Dullighan et al. 2003a, b; Bond 2003; Smith et al. 2003; Fynbo et al. 2003b, c; Kawai et al. 2003). Note that the error bars of the two points near $10^6$ s are not plotted, since they are not available in the literature.