THE BULK LORENTZ FACTOR OF OUTFLOW POWERING X-RAY FLARE IN GAMMA-RAY BURST AFTERGLOW

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ABSTRACT

We develop two methods to estimate the bulk Lorentz factor of X-ray flare outflow. In the first method, the outflow is assumed to be baryonic and is accelerated by the thermal pressure, for which the final bulk Lorentz factor is limited by the outflow luminosity as well as the initial radius of the outflow getting accelerated. Such a method may be applied to a considerable fraction of flares. The second method, based on the curvature effect interpretation of the quick decline of the flare, can give a tightly constrained estimate of the bulk Lorentz factor but can only be applied to a few giant flares. The results obtained in these two different ways are consistent with each other. The obtained bulk Lorentz factor (or just upper limit) of the X-ray flare outflows, ranging from ten to a few hundreds, is generally smaller than that of the gamma-ray burst outflows.

Key words: gamma-ray burst: general – radiation mechanisms: non-thermal – X-rays: general

Online-only material: color figures

1. INTRODUCTION

Cosmic gamma-ray bursts (GRBs) are the most luminous events ever known in the universe after the big bang. The luminosity, duration, and bulk Lorentz factor are crucial parameters of GRBs (Piran 1999). Based on the duration, GRBs can be divided into two main groups, short and long bursts. Once the redshift of a burst is measured, with a given cosmology model the luminosity distance is known, as are its luminosity and isotropic-equivalent γ-ray energy. Though the physical processes producing prompt emission and afterglow of GRBs are still unclear, it is widely accepted that the outflows move ultrarelativistically (i.e., their velocity is very close to the speed of light). The most reliable evidence is the measurement of superluminal movement of the radio afterglow image of GRB 030329 (Taylor et al. 2004). In the literature, several methods have been developed to constrain the initial bulk Lorentz factors of GRB outflows. (1) The detection of the high-energy photons implies that the emitting region is optically thin for pair annihilation. This argument leads to a lower limit on the Lorentz factor (Shemi & Piran 1990; Lithwick & Sari 2001). (2) In some cases, the peak in the early GRB afterglow light curves marks the deceleration of the external forward shock, at which the Lorentz factor is about half of the initial value. In such cases, the initial Lorentz factor, weakly depending on the isotropic-equivalent kinetic energy and the density of the medium, can be tightly constrained (Sari & Piran 1999; Molinari et al. 2007). (3) Detection of a thermal-emission component in the GRB afterglow spectrum provides a relatively direct way to estimate the Lorentz factor. Assuming a thermal radiation efficiency, with the measured temperature and flux of the thermal component, one can calculate the bulk Lorentz factor (Pe’er et al. 2007). (4) The non-detection of a hard X-ray to soft gamma-ray background emission in GRB prompt stage gives an upper limit on the initial Lorentz factor of GRB outflows (Zou & Piran 2010).

Many Swift GRBs were followed by energetic X-ray flares. Usually their fluences are only about 1%–10% of that of prompt emission. However, in quite a few events, the energy of the X-ray flare is comparable to that of the prompt emission. The temporal behavior and the hardness ratio evolution of X-ray flares are similar to those of prompt emission pulses (Chincarini et al. 2010), supporting the idea that they have the same physical origin as the prompt emission, i.e., they are also due to the activity of the central engine (e.g., Fan & Wei 2005; Zhang et al. 2006). In such a model, the central engine launches new outflow at late times. As in the prompt emission phase, the bulk Lorentz factor of the flare outflow is a crucial parameter. Unfortunately, most models constraining the bulk Lorentz factor of the GRB outflow are invalid for the X-ray flares. For example, the methods developed in Sari & Piran (1999) and Zou & Piran (2010) are irrelevant since there is a preceding and more energetic GRB outflow expanding into the medium. So far, there are three kinds of speculations on the bulk Lorentz factor of the flare outflows. (1) The typical bulk Lorentz factor of flares is just tens and is considerably smaller than that of the outflow powering prompt emission (Fan & Wei 2005). (2) The typical bulk Lorentz factor of flares is higher but not much higher than that of the outflow giving rise to prompt emission (Burrows et al. 2005; Zhang et al. 2006). Please note that in both case (1) and case (2), the flare photons are powered by the energy dissipation within the newly launched outflow. (3) In the X-ray flare model of up-scattered forward shock emission, late outflow with a bulk Lorentz factor ∼10^3 is required (Pantaleescu 2008). The divergency between these arguments are very large. In this work, we develop two different methods, as described in Section 2, to estimate the bulk Lorentz factor of the outflows. The case studies are presented in Section 3. We summarize our results with some discussion in Section 4.

2. THE METHODS

Method I. The physical composition of X-ray flare outflows is not well constrained yet. Fan et al. (2005) suggested that in the neutron star–neutron star (or black hole) merger model the outflow powering X-ray flares following short GRBs might be Poynting flux dominated since the fallback accretion onto the newly formed black hole is too low to launch an energetic ejecta via neutrino annihilation. But for long GRBs the argument is weak. Recently, Chincarini et al. (2010, and references therein) argued that the X-ray flare outflow was likely...
Poynting flux dominated if the prompt emission was powered by the magnetic energy dissipation. However, the physical origin of the prompt emission is still in debate. Therefore, here we assume that the flare outflow is baryonic. The central engine releases a large amount of energy into a compact region. Therefore, the outflow is very hot with a temperature ∼1 MeV, depending on the total luminosity of the flare outflow (L) as well as the initial radius of the outflow getting launched (R0).

As in the case of fireball powering prompt emission, the flare outflow will be accelerated by the thermal pressure until it becomes optically thin (i.e., the optical depth τ ∼ 1) or saturates at a radius Rf, depending on whether the outflow is baryon-rich or not. In the baryon-poor case, the outflow becomes transparent at R < ηRf, where η is the dimensionless entropy of the initial ejecta. The thermal energy has not been effectively converted into the kinetic energy of the outflow and will give rise to a quasi-thermal radiation component. The absence of such a soft component in the data may suggest that the flare outflow is baryon-rich, for which the final bulk Lorentz factor can be estimated as Γx ∼ η ∼ Rf/R0 (Piran 1999). On the other hand, the optical depth of the photon at the radius Rf can be estimated as (Paczyński 1990; Daigle & Mochkovitch 2002)

\[
\tau \sim \int_{R_f}^{\infty} (1 - \beta_x) \sigma_T dR \sim 1, \tag{1}
\]

where n ∼ L/4πR²Γₚmpc³ is the number density of electrons coupled with protons in the observer’s frame, σ_T is the Thomson cross section, and m_p is the rest mass of protons. Combining with the relations R_f ∼ Γx R₀ and β_x ∼ 1 − 1/2Γx, Equation (1) gives

\[
\frac{L \sigma_T}{8\pi \Gamma_x^2 m_p c^3 R_0} \sim 1. \tag{2}
\]

Therefore, the bulk Lorentz factor of X-ray flares is related to L and R₀ as (e.g., Mészáros & Rees 2000; Nakar et al. 2005; Fan 2010)

\[
\Gamma_x \leq \Gamma_{\text{max}} = 5 \times 10^2 L^{1/4}_{50} R_0^{-1/4}, \tag{3}
\]

throughout this work, the convention Q_x = Q/10⁶ has been taken into account except for some special notations. For η ≪ Γ_{max}, the photospheric radius of the flare outflow is estimated to be ∼6 × 10⁶ cm L_{50}η²/3 (Paczyński 1990; Fan 2010), much larger than R_f ∼ 10⁶ cm η²R₀. With a proper R₀ and the observed X-ray flare luminosity L_x (∼ε_x L), where ε_x is the X-ray flare efficiency and is taken to be comparable to that of GRBs, i.e., ~0.1 (e.g. Fan & Piran 2006)), we are then able to give an upper limit on Γ_x. The advantage of this method is that it may apply to a good fraction of X-ray flares (please see Section 3 for the case studies and Figures 1 and 2 for the numerical results). The limit of this approach is that it is only valid for the baryonic outflows.

**Method II.** The quick decline of the X-ray flares (Piro et al. 2005; Burrows et al. 2005) may have imposed a tight constraint on the emission radius R_i (Zhang et al. 2006; Lazzati & Begelman 2006; Dai et al. 2007), provided that the quickly decaying X-ray emission is the high latitude component of the flare pulses (Fenimore et al. 1996; Kumar & Panaitescu 2000; in some of the literature it is called the “curvature effect”). This interpretation, if correct, requires a very large variability timescale δT (Fan & Wei 2005, see also below). The corresponding bulk Lorentz factor thus can be estimated by

\[
\Gamma_x \approx \left[ R_i/(2c\delta T) \right]^{1/2}; \tag{4}
\]

please note that the timelapses involved here and below are all in the rest frame of the GRB source. If R_x as well as δT can be reliably estimated, Γ_x can be reasonably constrained.

For simplicity, we take the leading late internal shock model for illustration. Assuming that there are two shells, the slow one is ejected at T and moves with a bulk Lorentz factor Γ_x, the faster one is with Γ_f, and their ejection interval is δT (see also Kobayashi et al. 1997). The widths of both shells are ∼Δ (in the observer’s frame). The faster one would catch up with the slower at a radius

\[
R_{\text{coll}} \approx 2\Gamma_x^2 c \delta T. \tag{5}
\]

After the merger, the newly formed shell has a bulk Lorentz factor Γ_x ∼ √(Γ_f Γ_x), if the mass of these two shells are comparable (Piran 1999). The timescale of that merger is determined by the reverse shock (the fast shell is ∼Δ/c. The corresponding radius is

\[
R_x \sim (2\Gamma_x^2 c \delta T + 2\Gamma_f^2 \Delta), \tag{6}
\]

at which the emission peaks. In the internal shock phase, usually the electrons cool rapidly (Piran 1999). After the ceasing of the internal shock, the emission is from the high latitude θ > 1/Γ_x and takes a form (Fenimore et al. 1996; Kumar & Panaitescu 2000; Fan & Wei 2005)

\[
F \propto (T/\delta T)^{-(2+\beta)}, \tag{7}
\]

where δT ∼ R_x/(2Γ_x c) ∼ Δ/c for Γ_x > Γ_f and δT ∼ Δ/c, and the standard convention of the flux as a function of both time and frequency f_x ∝ T^{−α}ν^{−β} is adopted. In this work, we assume that the ejecta is uniform.

In reality, the flare consists of many (for example, k) pulses. After the ceasing of internal shocks at T_i, what we observe is the high latitude emission of the early pulses. The X-ray flux declines as

\[
F_x \approx \sum_{i=1}^{k} F_{x,i} \left[ (T - T_{0,i})/\delta T_i \right]^{-(2+\beta_i)}, \tag{8}
\]

where i represents the ith pulse, F_{x,i} is the peak emission of the ith pulse, T_{0,i} is the time when the ith pulse is ejected. Such a decline is much steeper than (T/T_i)^{-(2+\beta)} as long as T_i > max(δT_i) (see Figure 2 of Fan & Wei (2005) for illustration). This can be understood as follows. In the popular internal shock scenario, each prompt pulse is independent and is emitted at a radius ∼R_x. At late times, the emission contributed by early shells is from a very large angle, and is very weak due to the relativistic beaming effect. The observed flux is thus dominated by the curvature emission component of the last pulse (if all δT_i are comparable) or one early pulse having a very large duration ∼T_i. As a result, the net flux of these shells can be approximated by

\[
F_x \approx F_{x,i} \left[ (T - T_{0,i})/\delta T_i \right]^{-(2+\beta_i)}, \tag{9}
\]

which could be far sharper than (T/T_i)^{-(2+\beta)} since the internal shocks cease.

As shown in Liang et al. (2006) and Zhang et al. (2007), the sharp decline of some X-ray flares are well fitted by F_x ∝ (T - T_0)−(2+\beta), which is consistent with the curvature effect

1 Please bear in mind that the following discussion is valid as long as the prompt emission consists of many pulses. These pulses could be powered by either late internal shocks or late internal magnetic energy dissipation. So the validity of our method II, in contrast to method I, is independent of the physical composition of the outflow.
Combining Equation (10) with Equation (11), we have
\[ R_x \approx c T_{\text{tail}} \left( \frac{1 - \cos \delta \theta_j}{1 - \cos \delta \theta_j} \right)^{1/2}. \] (9)

So we have
\[ \Gamma_x \approx \left[ \frac{T_{\text{tail}}}{2(1 - \cos \delta \theta_j) \delta T} \right]^{1/2} \approx \left[ \frac{T_{\text{tail}}}{2(1 - \cos \delta \theta_j)(T_p - T_0)} \right]^{1/2}. \] (10)

In many cases, it is inconvenient to get \( T_p \) and \( T_0 \), respectively. Fortunately, a simpler way to estimate \( T_{\text{tail}}/\delta T \) is available. We introduce the factor \( \mathcal{R} \) to denote the ratio between the peak flux of the X-ray flare (\( F_{x,p} \)) and the flux when a cutoff emerges (\( F_{x,c} \)), i.e., \( \mathcal{R} \equiv F_{x,p}/F_{x,c} \) (see Figure 3). With Equation (8), we have
\[ \mathcal{R} \approx \left( \frac{T_{\text{tail}}}{\delta T} \right)^{2+\beta} \Rightarrow \frac{T_{\text{tail}}}{\delta T} \approx \mathcal{R}^{(2+\beta)}. \] (11)

Combining Equation (10) with Equation (11), we have
\[ \Gamma_x \approx \mathcal{R}^{1/2(2+\beta)^{1/2}}/\delta \theta_j. \] (12)

with a typical \( \beta \sim 1, \Gamma_x \propto \mathcal{R}^{1/6} \). So, our estimate of \( \Gamma_x \) cannot be significantly modified by the uncertainty of \( \mathcal{R} \). The choice of \( \delta \theta_j \), instead, is crucial for our purpose. For the X-ray flare outflow, there is no simple/reliable method to estimate its half-opening angle \( \theta_j \). However, it is reasonable to argue that \( \theta_j \) cannot be much smaller than \( \theta_j,\text{GRB} \). This is because X-ray flare(s) have been observed in about 40% of \textit{Swift} GRBs, so statistically speaking, \( \theta_j,\text{flare} \sim \sqrt{0.5} \theta_j,\text{GRB} \sim 0.7 \theta_j/\text{GRB} \) (X. Y. Dai 2006, private communication), where \( \theta_j,\text{GRB} \) is the half-opening angle of the GRB ejecta that can be inferred from the late afterglow break. Such a small correction can just increase our estimate of \( \Gamma_x \) (see Equation (12) for details) by a factor of 1.4 and thus does not change our basic conclusion. As a consequence, in the case studies (see below), we simply take \( \theta_j = \theta_j,\text{flare} = \theta_j,\text{GRB} \). The error of the resulting \( \Gamma_x \) can be estimated straightforwardly and can be approximated by \( \delta \Gamma_x \approx \sqrt{\frac{10}{4(2+\beta)}} \left( \frac{\mathcal{R}^{2+\beta}}{\delta \mathcal{R}^2 + \delta \theta_j^2} \right) \), where \( \delta \mathcal{R} \) and \( \delta \theta_j \) are the errors of \( \mathcal{R} \) and \( \theta_j \), respectively. For \( \beta \sim 1 \) and \( \delta \mathcal{R}/\mathcal{R} \ll 6 \delta \theta_j/\theta_j \), we have \( \delta \Gamma_x \sim \Gamma_x \delta \theta_j/\theta_j \). For a conservative estimate \( \delta \theta_j/\theta_j \sim 1/2 \), we have \( \delta \Gamma_x \sim 0.5 \Gamma_x \).

Different from method I, the current method can give a somewhat reliable estimate of \( \Gamma_x \) rather than an upper limit. However, a cutoff at the end of the quick decline is needed to achieve that goal. Unfortunately, an unambiguous cutoff in the quick decline phase has been identified in only a few giant flares, limiting the application of method II. We would like to point out that method II is also valid for estimating the bulk Lorentz factor of the late outflow of GRBs if the quick decline phase of prompt emission is also attributed to the so-called curvature effect.

3. CASE STUDIES

For method I, we take a sample consisting of 36 X-ray flares detected in 14 GRBs with measured redshift, as reported in Chincarini et al. (2007) and Falcone et al. (2007). The average bolometric luminosity, i.e., the bolometric energy divided by the duration, is derived for both the power law and the band function fits to the flares (Falcone et al. 2007). As already mentioned, the total luminosity of the flare is taken to be 10 times that of the X-ray emission. \( R_0 \) is taken as 10^7 cm, which is comparable to the radius of a neutron star or the last stable circle orbit for a rapidly rotating black hole (In the thermal radiation modeling of some GRBs, \( R_0 \) is estimated to be \( \sim 10^8 \) cm or even larger (e.g., Pe’er et al. 2007), so our estimate is likely conservative).
The results are presented in Figures 1 and 2. The resulting upper limits on $\Gamma_x$ are between tens to hundreds, which are generally smaller than the initial bulk Lorentz factor of GRB outflows $\sim10^2$–$10^3$ (e.g., Piran 1999; Lithwick & Sari 2001; Molinari et al. 2007; Zou & Piran 2010). For the baryonic outflow, we have $\Gamma_x \sim L/Mc^2$, where $M \sim 5 \times 10^{-6} L_{50} \Gamma_{x,1}^{-1} M_\odot$ s$^{-1}$ is the mass loading rate of the outflow. The inferred $\Gamma_x \gtrsim 10$ following the flares in GRB 050502B and GRB 050724 suggests that the flare outflows are still relativistic, strengthening the connection between the X-ray flares, and the prompt soft $\gamma$-ray emission. Since the typical total luminosity of the flare outflows is about two or more orders of magnitude lower than that of the GRB outflows, the mass loading rate of the flare outflow is expected to be lower than that of the GRB outflow otherwise relativistic ejecta cannot be launched. This is reasonable since the pole region of a dying massive star (or the remnant of the merger of two compact objects) is expected to be more and more clean as the time goes on.

Below, we focus on method II. The sharp decline has been well detected in a good fraction of X-ray flares. For our purpose, a cutoff of the tail emission, emerging when the emission at the edge of the ejecta is within the line of sight, is needed to constrain $R_{\text{flare}}$ reliably. Such a cutoff has been possibly identified in a few cases, for example, the giant flare in GRB 050502B (Falcone et al. 2006) and the giant flare in GRB 050724 (Campana et al. 2006). The reason for such rare detection is the following. In reality, the X-ray emission is not only contributed by the high latitude emission but also contributed by the forward shock emission. The latter would dominate over the former when the high latitude emission component has dropped by 2 or more orders (correspondingly, $T_{\text{tail}} \sim 58T$ for $\beta \sim 1$) unless the X-ray flare is strong enough, or the forward shock emission is very dim. On the other hand, when the flux has dropped to a level of $\sim10^{-11}$ erg s$^{-1}$ cm$^{-2}$, the signal to noise ratio is not high enough to get a good quality detection and thus renders the identification of the cutoff difficult. The data (together with corresponding references) are presented in Table 1.

Note that there is a possible independent argument favoring a $\Gamma_x \sim$ tens for giant flares following GRB 050502B and GRB 050724. As suggested in Fan & Wei (2005), in the leading late internal shock model, the X-ray flare outflow with a $\Gamma_x \sim$ tens will catch up with the initial GRB outflow when the latter has swept a large amount of material and then got decelerated. Such an energy injection process would give rise to a flattening (if there is also a wide range of the bulk Lorentz factors of the X-ray flare outflow) or rebrightening signature (if the range of the bulk Lorentz factors of the flare outflow is narrow). The rebrightening has been well detected in the late X-ray afterglow of GRB 050502B and GRB 050724. To attribute the very late X-ray flare in GRB 050502B to an energy injection caused by the giant X-ray flare outflow, a $\Gamma_x \sim 20$ is needed (Falcone et al. 2006), matching our result perfectly. As for GRB 050724, Panaitescu (2006) showed that the late multi-wavelength rebrightening could be well reproduced by an energy injection. Before the energy injection, the kinetic energy of the GRB ejecta $E_k \sim 10^{50}$ erg and the number density of the medium is $n \sim 0.1$ cm$^{-3}$. The decelerating GRB ejecta has a bulk Lorentz factor $\sim10(E_{50}/n^{-1})^{1/3}/(T/10^4 s)^{-3/8}$. If this energy injection is also caused by the flare outflow catching up with the GRB ejecta, a $\Gamma_x \sim 10$ is needed, which is consistent with our result.

Finally, we would like to point out that only the X-ray flares brighter than the forward shock X-ray emission can be identified. There could be some faint X-ray flares which have an even lower bulk Lorentz factor.

4. DISCUSSION AND SUMMARY

Bright X-ray flares have been well detected in the afterglow of a considerable fraction of GRBs. The radiation mechanism powering these events is still unclear. A widely accepted hypothesis is that a new outflow should be launched by the central engine and the flares should be powered by the energy dissipation within the new outflow. The lack of an optical flare associated with the X-ray flare is in general consistent with such a scenario (Fan & Wei 2005). The bulk Lorentz factor of the newly launched outflow is a crucial parameter for us to understand X-ray flares. For example, with the inferred bulk Lorentz factor we can see whether the outflow is relativistic or not. Then we can estimate the corresponding mass loading rate in the pole region of the central engine. If the inferred bulk Lorentz factor is so high that it surpasses the upper limit given in Equation (3), the baryonic outflow model will be ruled out.

In this work we have developed two methods to estimate the bulk Lorentz factor of X-ray flare outflow (see Section 2). In the first method, the outflow is assumed to be baryonic and is accelerated by the thermal pressure, for which the final bulk
Lorentz factor is limited by the outflow luminosity as well as the initial radius of the outflow getting accelerated. Such a method may be applied to a considerable fraction of flares. However, it can only give an upper limit and is invalid if the flare outflow is Poynting flux dominated. The second method, based on the curvature effect interpretation of the quick decline of flare, is independent of the physical composition of the outflow and can give a better constrained estimate of the bulk Lorentz factor of the flare outflow but can only be applied to a few events.\(^2\)

The obtained bulk Lorentz factors (or just upper limit) of the X-ray flare outflows in these two different ways are consistent with each other and are generally smaller than that of the GRB outflows (see Section 3). However, the flare outflows are still relativistic and the corresponding baryon loading rate is expected to be very low \((M \lesssim 10^{-5} M_\odot \text{ s}^{-1})\). This finding, together with other results from the analysis of the X-ray flare data such as the temporal behavior and the hardness ratio evolution, strongly favors the hypothesis that X-ray flares are the low energy analogy of the prompt soft \(\gamma\)-ray emission (Fan & Wei 2005; Zhang et al. 2006; Chincarini et al. 2010; Margutti et al. 2010; Shao et al. 2010). With method II, the Lorentz factors of the two giant flares are found to be \(\sim \text{a few} \times 10\), well below the upper limits given by method I (see also Table 1). Hence, the baryonic outflow model is not challenged. For the magnetic outflow with reasonable baryon loading, a moderate Lorentz factor is also possible. Furthermore, data like the high linear-polarization of the X-ray photons is needed to claim the magnetic nature of the flare outflow.

If the X-ray flare outflows do have a bulk Lorentz factor \(\sim 10^5\), as suggested in the flare model of up-scattered forward shock emission (Panaitescu 2008), the acceleration cannot be due to the thermal pressure. The only known such kind of extreme astrophysical object is the pulsar wind, which may move with a Lorentz factor as high as \(\sim 10^8\), and its acceleration is likely a result of the significant magnetic energy reconnection (Kennel & Coroniti 1984). It is less likely to be the case for the X-ray flares since the central engine of GRBs is not in a cavity as clean as that of a pulsar at an age of \(\gtrsim 10^5\) years. As for the flare model of up-scattered forward shock emission, one more challenge is that the similarities between the GRB prompt emission and the X-ray flare emission strongly suggest a similar physical origin of these two kinds of phenomena.

\(^2\) There is another method without the need for the nature of the outflow to constrain the bulk Lorentz factor. The idea is the following. In the synchrotron radiation model, the typical synchrotron radiation frequency and the cooling frequency, as well as the synchrotron self-absorption frequency, are functions of the radius of the flare emission and the bulk Lorentz factor. Therefore, with the measured redshift and the spectrum in a very wide energy range, in principle we can constrain the bulk Lorentz factor. A reliable infrared/optical to X-ray spectrum of the flare, however, is hard to obtain. For example, the infrared/optical emission of the flare is found to usually be outshone by simultaneous forward shock emission.

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