FAILED GAMMA-RAY BURSTS: THERMAL ULTRAVIOLET/SOFT X-RAY EMISSION ACCOMPANIED BY PECULIAR AFTERGLOWS

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1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most powerful explosion in the universe. The origin of prompt emission remains unresolved, owing to the fact that the prompt emission has a large explosion energy showing a nonthermal spectrum with rapid time variabilities.

It is widely accepted that the prompt emission is coming from a highly relativistic flow because it can reduce the optical depth of the flow, which makes the radiation spectrum nonthermal (Rees & Mészáros 1994). In fact, in the internal shock scenario, which is one of the most promising scenarios, the relativistic shells collide with each other after the system becomes optically thin (e.g., Piran 1999 for a review). However, it was pointed out by Mészáros & Rees (2000) that even such a relativistic flow should have a photosphere inevitably and thermal radiation should become from there. Since then, there have been many theoretical (Daigne & Mochkovitch 2002; Pe’er et al. 2006; Pe’er 2008; Pe’er & Ryde 2011) and observational (Ghirlanda et al. 2003; Ryde 2004, 2005; Ryde et al. 2010, 2011; Guiriec et al. 2011) studies on how the thermal component contributes to the prompt emission (or the precursor). In the present, the internal shock model with a photosphere is frequently discussed (e.g., Toma et al. 2011). In this picture, the radius of the photosphere, RPS, is usually smaller than the radius RIS where internal shocks are happening.

The above scenario is based on the assumption that the bulk Lorentz factor of the jet is as large as 100–1000. But what happens if the bulk Lorentz factor is not so high? Theoretically, it is natural to consider such a case because it is very hard to realize such a clean, highly relativistic flow. Especially, in the case of long GRBs, some bursts are at least coming from the death of massive stars where a lot of baryons should be coming from there. Since then, there have been many theoretical (Daigne & Mochkovitch 2002; Pe’er et al. 2006; Pe’er 2008; Pe’er & Ryde 2011) and observational (Ghirlanda et al. 2003; Ryde 2004, 2005; Ryde et al. 2010, 2011; Guiriec et al. 2011) studies on how the thermal component contributes to the prompt emission (or the precursor). In the present, the internal shock model with a photosphere is frequently discussed (e.g., Toma et al. 2011). In this picture, the radius of the photosphere, RPS, is usually smaller than the radius RIS where internal shocks are happening.

Qualitatively, RIS becomes smaller if the bulk Lorentz factor of the flow is smaller, while RPS increases with the decreasing of the bulk Lorentz factor. Thus, we can expect that the photosphere will fall outside of the internal shock region for some lower Lorentz factors (see Figure 1(a)). In such a case, gamma rays from the internal shocks cannot escape. Instead, softer thermal radiation from the photosphere followed by an afterglow will be seen.

We show that the photospheres of “failed” gamma-ray bursts (GRBs), whose bulk Lorentz factors are much lower than 100, can be outside of internal shocks. The resulting radiation from the photospheres is thermal and bright in the UV/soft X-ray band. The photospheric emission lasts for about 1000 s with a luminosity about several times 1046 erg s−1. These events can be observed by current and future satellites. It is also shown that the afterglows of failed GRBs are peculiar at the early stage, which makes it possible to distinguish failed GRBs from ordinary GRBs and beaming-induced orphan afterglows.

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

2 PHOTOSPHERIC EMISSION

In this study, we consider the axisymmetric jet and assume that the observer is on the axis OD in Figure 1(b). This is the extension of the one-dimensional formulation derived by Daigne & Mochkovitch (2002). For a baryon-rich ejecta in the stellar frame (i.e., burst source frame, and from now on all variables are defined in this frame), we assume that the ejecta has been accelerated at a distance racc from the central engine. The mass flux of the ejecta is written as \( M = E/\Gamma c^2 \), where \( \Gamma \) is the Lorentz factor of the ejecta and \( E \) is the energy injection rate. The energy injection begins at \( t_{\text{inj}} = 0 \) and stops at \( t_{\text{inj}} = t_{\text{e}} \), i.e., the central engine activity lasts for a period of time \( t_{\text{e}} \).

The ejecta can be subdivided into a series of concentric layers, where each layer has been injected at \( r_{\text{acc}} \) at a certain injection time \( t_J \). Each ejecta layer becomes transparent when
The escape radius can be estimated from the triangle defined by the direction of the stellar center and the observer located along the + internal shock radius is smaller than the photosphere radius. (b) Schematic diagram showing the path of a photospheric photon escaping from the ejecta inside the ejecta is shown in Figure 1(b). A photon emitted at point E will escape from the ejecta at a time \( t_{\text{esc}} \) to the end point of the solid curve in Figure 2(a).

A geometric sketch illustrating the escape path of photons into the ejecta is shown in Figure 1(b). A photon emitted at point E (at a distance \( r_{\text{inj}} \) and propagation angle \( \varphi \)) will escape from the ejecta at point G, such that the optical depth from E to G is

\[
\tau(t_j, \varphi) = \int_{r_{\text{inj}}=t_j}^{r_{\text{esc}}(t_{\text{esc}}(t_j \varphi))} d\tau(r),
\]

where \( d\tau(r) \) can be estimated as (Abramowicz et al. 1991; Daigne & Mochkovitch 2002; Pe’er 2008)

\[
d\tau(r) = \frac{k \dot{M}(1 - \beta \cos \varphi) \kappa}{4 \pi r^2} dr.
\]

We define the photospheric radius \( R_{\text{PS}}(t_j) = r(t_j, t) \) at which \( \tau \) is equal to unity. In light of Figure 1(b), we choose a cylindrical coordinate system (Pe’er 2008) with the central point \( O \) being the stellar center and the observer located along the \(+z\)-direction (defined by the direction of \( OD \)). Photons are emitted at a perpendicular distance \( r_{\min} = r(t_j, t) \) from the \( z \)-axis and a distance \( z_{\min} = r(t_j, t) \cos \varphi \) along the \( z \)-axis from point \( O \). The escape radius can be estimated from the triangle \( OEG \), i.e., \( r_{\text{esc}}(t_{\text{esc}}(t_j \varphi)) = r(t_j, t) + \beta c(t_j - 0) + \beta c(t_{\text{esc}} - t_j) = (r(t_j, t))^2 + c(t_{\text{esc}} - t_j)^2 - 2r(t_j, t)c(t_{\text{esc}} - t_j)\cos(\varphi - \varphi_j))^{1/2} \).

The integration for the optical depth can be conveniently rewritten in cylindrical coordinates as

\[
\tau(t_j, \varphi) = \int_{z_{\min}}^{z_{\max}} \frac{k \dot{M}(1 - \beta \cos \varphi) dr}{4 \pi r^2} dz,
\]

where \( r = \sqrt{z^2 + r_{\min}^2} \) and \( d\tau(r) = dz/\sqrt{z^2 + r_{\min}^2} \) and \( z_{\max} = \sqrt{r_{\text{esc}} - r_{\min}^2} \). The photospheric radius \( R_{\text{PS}} \), which depends on the propagation angle \( \varphi \), can be found readily by defining \( \tau = 1 \).

For a relativistic ejecta with Lorentz factor \( \Gamma \), the arrival time of photons emitted at the photosphere in the observer frame is delayed relative to that measured in the stellar frame,

\[
t_{\text{obs}} = t - R_{\text{PS}} \cos \varphi/c = t_j + (1 - \beta \cos \varphi) R_{\text{PS}}/\beta c,
\]

i.e., the observer time is a function of injection time and propagation angle. In this equation, we have neglected the effect of the acceleration radius \( r_{\text{acc}} \) because it is much smaller than the photosphere radius.

The evolution of photospheric radius with propagation angle is shown in Figure 2(b). The parameters are taken as \( \Gamma = 10, E = 10^{51} \text{ erg s}^{-1}, t_w = 2000 \text{ s} \). The solid curve shows its evolution at observer time \( t_{\text{obs}} = 100 \text{ s} \), and the dashed curve at \( t_{\text{obs}} = 2000 \text{ s} \). From this panel, we can see that in the observer frame, the photospheric radius decreases with propagation angle.

We also show the evolution of photospheric radius with observer time in Figure 2(a). The solid and dashed curves present the cases for \( \varphi = 0 \) and \( \varphi = 0.1 \text{ rad} \), respectively. As shown in this panel, the photospheric radius increases with time, and the duration of the photospheric emission is prolonged at larger propagation angle. The end points of the two curves indicate the observer time when the last layer of the ejecta becomes transparent.

According to the fireball model, the temperature of a layer at its photospheric radius is given by (Piran 1999)

\[
kT_{\text{PS}} = \frac{D \kappa T^{0}(R_{\text{PS}}/r_{\text{acc}})^{-2/3}},
\]

where \( D = [\Gamma(1 - \beta \cos \varphi)]^{-1} \) is the Doppler factor, \( r_{\text{acc}} \) is the saturation radius, and \( T^{0} \) is its blackbody temperature. In Figures 2(c) and (d), we show the evolution of \( T_{\text{PS}} \) with respect to the propagation angle and observer time, respectively. From the two panels, we find that the photospheric temperature decreases with the propagation angle and time in the observer frame.

The evolution of the injection time with respect to the observer time and the propagation angle is shown in Figures 3(a) and (b), respectively. For the “standard” parameter set \( \Gamma = 10, E = 10^{51} \text{ erg s}^{-1}, t_w = 2000 \text{ s} \), \( t_{\text{inj}}(t_{\text{obs}}) \) is mildly smaller than \( t_{\text{obs}} \) for different \( \varphi \), and \( t_{\text{inj}}(\varphi) \) is almost independent of \( \varphi \) for different \( t_{\text{obs}} \). In Figures 3(c) and (d), we also show the evolution of the escaping radius \( r_{\text{esc}} \) with respect to the observer time and the propagation angle, respectively. The relations of \( t_{\text{obs}} \) and \( \varphi \) with respect to \( r_{\text{esc}} \) are similar to that of the photospheric radius \( R_{\text{PS}} \).

As for a jet with half-opening angle \( \theta = 0.1 \text{ rad} \), constant Lorentz factor \( \Gamma = 10 \), and energy injection from \( t_{\text{inj}} = 0 \text{ to } t_{\text{inj}} = 2000 \text{ s} \) with energy injection rate per solid angle \( E/4\pi = 10^{51}/4\pi \text{ erg s}^{-1} \), we can estimate that \( r_{\text{acc}} \simeq 9 \times 10^{14} \text{ cm} \) and \( kT^{0} \simeq 0.41 \text{ MeV} \) for a fireball model (Piran 1999; Mészáros & Rees 2000; Daigne & Mochkovitch 2002). If the line of sight is along the jet central axis, we find that the photospheric radius is about \( 1.1 \times 10^{14} \text{ cm} \) when the last layer becomes transparent; the observer’s time can be calculated from Equation (4), which is found to be about 2020 s and corresponds to the end point of the solid curve in Figure 2(a).
Figure 2. Evolution of the photospheric radius and temperature with respect to the observer time and photon propagation angle. The parameters are taken as $\Gamma = 10$, $E = 10^{51}$ erg s$^{-1}$, and $t_{\text{ej}} = 2000$ s. (a) Photospheric radius vs. the observer time. The solid curve plots photons propagating along the expansion direction of the ejecta ($\varphi = 0$). The dashed curve corresponds to $\varphi = 0.1$ rad. (b) Photospheric radius vs. the photon propagation angle. The solid and dashed curves correspond to the observer times of 100 and 2000 s, respectively. (c) Photospheric temperature vs. observer time. The solid and dashed curves correspond to photon propagation angles of 0 and 0.1 rad, respectively. (d) Photospheric temperature vs. the photon propagation angle. The solid and dashed curves are for $t_{\text{obs}} = 100$ and 2000 s, respectively.

Figure 3. Evolution of the injection time and escaping radius with respect to the observer time and photon propagation angle. The parameters are the same as those in Figure 2. (a) Injection time vs. the observer time. The solid curve plots photons propagating along the expansion direction of the ejecta ($\varphi = 0$). The dashed curve is the evolution of the injection time for $\varphi = 0.1$ rad. (b) Injection time vs. the photon propagation angle. The solid and dashed curves are observed at 100 and 2000 s, respectively. (c) Escaping radius vs. the observer time. The solid and dashed curves correspond to propagation angles of 0 and 0.1 rad, respectively. (d) Escaping radius vs. the photon propagation angle. The solid and dashed curves are for $t_{\text{obs}} = 100$ and 2000 s, respectively.

The observed luminosity of photospheric emission can be determined by integrating over the surface of the photosphere,

$$L = \int_0^\vartheta \sigma T_{\text{PS}}^4 dS \cos \vartheta,$$

where $\vartheta$ is the angle between the tangential direction of the photosphere surface and the line of sight when the propagation angle is $\varphi$. Here $dS \cos \vartheta = 2\pi R_{\text{PS}}(t_{\text{obs}}, \varphi) \sin \varphi [R_{\text{PS}}(t_{\text{obs}}, \varphi + d\varphi) \sin(\varphi + d\varphi) - R_{\text{PS}}(t_{\text{obs}}, \varphi) \sin \varphi]$ is the photospheric surface area from propagation angle $\varphi$ to $\varphi + d\varphi$. The evolution of the photospheric luminosity with observer time is shown by the solid curve in Figure 4. There is a break in the light curve at about $t_{\text{obs}} \simeq 2020$ s, which is attributed to the culmination of energy injection by the central engine and when the last layer of the ejecta became transparent as the photons propagate along the line of sight. Afterward, only photospheric emission at high latitude (large propagation angles) contributes to the observed luminosity. The photospheric emission ceases when the last layer with propagation angle $\varphi = \theta = 0.1$ becomes transparent, which is about 2050 s in the observer frame.
dependence of the observer time. The identities of the curves are the same as in Figure 5. All the curves are derived when the last layer of ejecta along the line of sight became transparent, i.e., $\varphi = 0$ and $t_j = t_w$. The identities of the curves are the same as in Figure 5.

Figure 4. Evolution of the photospheric luminosity (solid curve) and effective temperature (dashed curve) with observer time for a jet with parameters $\theta = 0.1$ rad, $\Gamma = 10$, $E = 10^{51}$ erg s$^{-1}$, and $t_w = 2000$ s.

Figure 5. Parameter dependence of the photospheric emission. All curves are obtained when the last layer of the ejecta became transparent along the line of sight, i.e., $\varphi = 0$ and $t_j = t_w$. (a) Parameter dependence of the photospheric radius. The solid curve is derived using the standard parameters, i.e., $E = 10^{51}$ erg s$^{-1}$ and $t_w = 2000$ s; the dashed curve is for $E = 10^{50}$ erg s$^{-1}$ and $t_w = 2000$ s; and the dotted curve is for $E = 10^{51}$ erg s$^{-1}$ and $t_w = 200$ s. The evolution of the internal shock radii $R_{IS}$ for a variability timescale of $\delta t = 1$, 0.33, and 0.1 s is shown and marked correspondingly. (b) Parameter dependence of the observer time. The identities of the curves are the same as in (a).

We can also define an effective temperature for the photosphere:

$$T_{\text{eff}} = \frac{\int_0^\infty T dL}{\int_0^\infty dL}.$$  \hspace{1cm} (7)

This effective temperature is shown as a dashed curve in Figure 4. We can find that the photospheric emission of a failed GRB is presented as a short soft X-ray burst and then becomes a UV burst that lasts for about several thousand seconds.

We also investigated the parameter effect on the photospheric emission, which is shown in Figures 5 and 6. All the curves are derived when the last layer of ejecta along the line of sight became transparent, i.e., $\varphi = 0$ and $t_j = t_w$. As shown in Figure 5(a), the photospheric radii are decreasing with the increase of the Lorentz factor for different sets of parameters. The solid curve corresponds to the standard parameters ($E = 10^{51}$ erg s$^{-1}$, $t_w = 2000$ s), while the parameters for the dashed curve and the dotted curve are $E = 10^{69}$ erg s$^{-1}$, $t_w = 2000$ s and $E = 10^{51}$ erg s$^{-1}$, $t_w = 200$ s, respectively. A lower energy injection rate and shorter injection time will decrease the duration of the photospheric emission. From Figure 6, we can find that the duration of photospheric emission decreases with an increase of the Lorentz factor. A lower energy injection rate and shorter injection time will decrease the duration of the photospheric emission.

In Figure 6, we show the parameter effect on the photospheric luminosity and effective temperature. The parameters of each curve are the same as in Figure 5. From Figure 6(a), we can find that the luminosity of the photospheric emission is low in both high and low Lorentz factors. A lower energy injection rate results in lower luminosity. As shown in Figure 6(b), the effective temperatures are increasing with the increase of the Lorentz factor. A lower energy injection rate and shorter injection time will decrease the radii of the photosphere and hence result in a higher effective temperature.

As for a jet with half-opening angle of about 0.1 rad, Lorentz factor $\Gamma = 2–20$, energy injection rate $E = 10^{49–51}$ erg s$^{-1}$, and injection time $t_w = 200–2000$ s, from Figures 5 and 6 we can conclude that the prompt emission for a failed GRB is thermal soft X-ray or UV photospheric emission; there will be no significant nonthermal gamma-ray emission. The photospheric luminosity is about $10^{46}$ erg s$^{-1}$ and lasts for about 1000 s. Note that the photospheric luminosity is far lower than the energy injection power; most of the energy is reconverted into the ejecta’s kinetic energy. From Figure 5(a), we find that the radius of the photosphere is about $10^{14}$ cm, which is larger than the prediction for the internal shock’s radius, i.e., $R_{IS} \approx \Gamma^2 c \delta t \approx 10^{13}$ cm (Mészáros 2006), where $\delta t \sim 0.33$ s is the variability timescale of the prompt emission. The evolution of $R_{IS}$ with respect to $\Gamma$ for $\delta t = 1, 0.33,$ and 0.1 s is shown and marked in Figure 5(a) correspondingly. This radius is consistent with Figure 1(a).

This thermal radiation will be in the UV or the soft X-ray band. The lower band of Swift/XRT (0.2–10 keV) may cover this energy range, and it is sensitive enough to detect
such a photospheric emission component (Gehrels et al. 2004). MAXI/SSC monitors all of the sky in the energy range 0.5–10 keV and also has a chance of detecting such events (Matsuoka et al. 1997). Future UV satellites may also have the capability to detect these events, such as TAUVEX (wavelength range 120–350 nm; Safonova et al. 2008).

3. AFTERGLOW EMISSION

As the outflow expands outward, it will collide with the surrounding medium and afterglow will be produced. The dynamical evolution of a relativistic jet in the interstellar medium has been studied by Huang et al. (1999). Their codes can be used in both ultrarelativistic and nonrelativistic phases.

In our model, we consider a jet with the bulk Lorentz factor $\Gamma = 10$, the half-opening angle $\theta = 0.1$, and the isotropic energy $E = 10^{50}$ erg. The jet expands laterally at the comoving sound speed and collides with a medium whose number density is $n_{\text{ISM}} = 1 \text{ cm}^{-3}$. We also assume typical values for some other parameters of the jet, i.e., the electron energy fraction $\epsilon_e = 0.1$, the magnetic energy fraction $\epsilon_B = 0.01$, and the power-law index of the energy distribution function of electrons $p = 2.5$. Multiband afterglow emission is expected from synchrotron radiation of relativistic electrons. Using this exquisite model, we numerically calculated the afterglow light curves and spectra with line of sight parallel to the jet axis. As shown in Figure 7, the spectra of the failed GRB and the ordinary GRB are similar at the late stage (thick solid and thin dashed curves) because their energies and Lorentz factors are both similar at this moment. But at the early stage, they are very different (thick solid and thick dashed curves) owing to their very different initial Lorentz factors and the corresponding minimum Lorentz factors of electrons (Sari et al. 1998). The peak frequency of the GRB afterglow is much larger than that of the failed GRB afterglow.

In Figure 7, we also show the spectra of a beaming-induced orphan afterglow (afterglow from an ordinary highly collimated GRB outflow, but with the observing angle larger than the jet half-opening angle so that no prompt gamma rays can be observed in the main burst phase; Rhoads 1997; Huang et al. 2002). Here we assume the same parameters as the ordinary GRB except $\theta_{\text{obs}} = 0.125$. The early and late spectra of this orphan afterglow are shown in Figure 7 with thick dotted and thin dotted curves, respectively. From this figure, we find that the spectra of a beaming-induced orphan afterglow are similar to those of the ordinary GRB. Although it is hard to distinguish a beaming-induced orphan afterglow from a failed GRB afterglow through their afterglow light curves (Huang et al. 2002), they can be potentially distinguished from their spectra at the early stages. Their spectra of early afterglows are very different: the peak frequency of a failed GRB afterglow is far lower than that of a beaming-induced orphan afterglow. Another way to distinguish them is through their early light curves. Early afterglow of a beaming-induced orphan afterglow will show a rebrightening, while failed GRBs will not (Huang et al. 1999, 2002; Xu & Huang 2010).

4. CONCLUSION AND DISCUSSIONS

The analysis in this paper shows that the emission of ejecta with low Lorentz factors is very different from that expected from ejecta with high Lorentz factors. Prompt emission of a GRB is nonthermal and bright in the gamma-ray band. For a failed GRB, however, the emission originates from the photosphere with a thermal spectrum and is bright in the UV or the soft X-ray band instead of gamma rays. This photospheric emission lasts for about 1000 s with a luminosity about several times $10^{46}$ erg s$^{-1}$.

Since the photospheric emission manifests as a UV or a soft X-ray transient, it can be detected by some current and future satellites, such as Swift/XRT, MAXI/SSC, and TAUVEX. On 2008 January 9, Swift/XRT discovered a peculiar X-ray transient 08109 in NGC 2770 (Berger & Soderberg 2008; Page et al. 2008). No gamma-ray emission was detected. This X-ray transient reached its peak at about 60 s and lasted for about 600 s. Its spectrum can be fitted with an absorbed double blackbody model with temperatures of about 0.36 and 1.24 keV, respectively (Li 2008). This transient may be a candidate of photospheric emission from a failed GRB. Meanwhile, some unidentified X-ray transients have been detected by MAXI during its one-year of monitoring (Nakajima et al. 2009; Suzuki et al. 2010). These transients generally showed an absorbed blackbody spectrum and lasted for tens of seconds. It is possible that some of them are photospheric emission from failed GRBs.

If we extend the injection time to about $10^5$ s and the jet half-opening to about 0.4 rad in our model, we find that the photospheric radius is about $10^{15}$ cm and the effective temperature is decreased to lower than 1 eV, i.e., there will be an

![Figure 7. Evolution of the afterglow spectra for the three types of GRBs. The solid, dashed, and dotted curves are spectra of a failed GRB afterglow, an ordinary GRB afterglow, and a beaming-induced orphan afterglow, respectively.](image-url)
This kind of optical burst will last for about several thousand seconds with a luminosity of about $10^{42}$ erg s$^{-1}$, which may be detected by the Hyper-Suprime Camera of the Subaru telescope in the future.

In this work, we have assumed that the prompt emission is thermal radiation coming from the photosphere where the optical depth is unity. Owing to the low density of GRB jets, however, it has been pointed out that the last-scattering positions of the observed photons may not simply coincide with the photosphere, but instead possess a finite distribution around it (e.g., Pe’er et al. 2006; Pe’er 2008; Beloborodov 2010; Pe’er & Ryde 2011). This stochastic effect can lead to differentiation of the observed spectrum from a thermal one of purely photospheric origin. Such a mechanism can work even in failed GRBs, and it is our future work to study how the spectrum will be reshaped using Monte Carlo calculations. We are planning to investigate this effect in the context of failed GRBs as a next step of our study.

From the comparison of afterglow emissions from failed and ordinary GRBs, while it is not expected for ordinary or beaming-induced orphan GRBs. We can thus define a hardness ratio, for instance, as the flux contrast between $10^{12}$ and $10^{14}$ Hz at an observed time of 1000 s, i.e., $f_{1ks} = F_{10^{12}Hz}/F_{10^{14}Hz}$. If $f_{1ks} > 1$, then it is quite likely that the emission is coming from a failed GRB. If $f_{1ks} < 1$, then it would be more likely to come from an ordinary GRB afterglow or a beaming-induced orphan afterglow. In addition, at the early afterglow stage, a rebrightening phase will be present in the case of a beaming-induced orphan GRB, while it is not expected for ordinary or failed GRBs. Therefore, the afterglows of failed GRBs can be distinguished from both ordinary GRB afterglows and beaming-induced orphan afterglows through observations at the early stages.

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