Estimation of the detectability of optical orphan afterglows

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**ABSTRACT**

**Aims.** By neglecting sideways expansion of gamma-ray burst (GRB) jets and assuming their half-opening angle distribution, we estimate the detectability of orphan optical afterglows.

**Methods.** This estimation is carried out by calculating the durations of off-axis optical afterglows whose flux density exceeds a certain observational limit.

**Results.** We show that the former assumption leads to more detectable orphans, while the latter suppresses the detectability strongly compared with the model with half-opening angle \( \theta_j = 0 \). We also considered the effects of other parameters, and find that the effects of the ejecta energy \( E_j \) and post-jet-break temporal index \( -\alpha_2 \) are important but that the effects of the electron-energy distribution index \( p \), electron energy equipartition factor \( \epsilon_e \), and environment density \( n \) are insignificant. If \( E_j \) and \( \alpha_2 \) are determined by other methods, one can constrain the half-opening angle distribution of jets by observing orphan afterglows. Adopting a set of “standard” parameters, the detectable rate of orphan afterglows is about \( 1.3 \times 10^{-2} \text{deg}^{-2} \text{yr}^{-1} \), if the observed limiting magnitude is 20 in R-band.

**Key words.** gamma rays: bursts – ISM: jets and outflows – radiation mechanisms: non-thermal

1. Introduction

Orphan afterglows are defined as afterglows whose gamma-ray bursts (GRBs) are not detected, possibly because of the Doppler effect for an off-axis observer. If the GRB afterglows are modelled perfectly, the observed rate of orphans and GRBs can be used to constrain the beaming factor of GRBs, as first proposed by Rhoads (1997). However, as many parameters are not determined well for different afterglows, it will be difficult to constrain the beaming factor tightly from optical orphans. Because late radio afterglows behave isotropic emission, the survey of radio afterglows may be helpful for estimating the beaming factor (Levinson et al. 2002; Gal-Yam et al. 2006), although one should be careful to rule out radio transients from other sources.

Other than constraining the beaming factor (Rhoads 1997; Dalal, Griest & Pruet 2002; Totani & Panaitescu 2002), some authors have focused on investigations of the detectability of orphan optical afterglows both theoretically (Nakar, Piran & Granot 2002; Totani & Panaitescu 2002) and experimentally (Hudec 2004; Becker et al. 2004; Rykoff et al. 2005; Malacarino & Atteia 2006; Rau, Greiner & Schwarz 2006; Becker et al. 2004), give the results of a 5-year (1999-2004) survey of optical transients, but none was identified as an orphan. Rykoff et al. (2005) performed a 1.5-year survey (2003 September to 2005 March) of untriggered GRB afterglows. Although no orphan afterglow has been observed yet, they give the upper limit of the observed rate for a certain limiting magnitude. The surveys are still going (Malacarino & Atteia 2006; Malacarino et al. 2006). On the theoretical side, Nakar, Piran & Granot (2002) considered the following afterglow model: all jets propagating in a uniform medium (ISM) have a constant initial half-opening angle \( \theta_j \) and a constant jet energy \( E_j \). After a jet break takes place because the hydrodynamics of a sideways-expansion jet enters an exponential regime (Rhoads 1999; Sari, Piran & Halpern 1999), the temporal index of light curves becomes \(-p\) where \( p \) is the power-law index of shock-accelerated electrons. This decline is too steep for most of the observed late afterglows (Liang & Zhang 2005). On the other hand, many works (Moderski, Sikora & Bulik 2000; Huang et al. 2000; Wei & Li 2000; Salmonson 2003; Kumar & Granot 2003; Granot & Kumar 2003; Cannizzo, Gehrels & Vishniac 2004) show that the sideways expansion of jets is insignificant at the relativistic stage. Thus, we consider relativistic jets without...
sideways expansion, and their afterglow light curves for an on-axis observer. Dotted, dot-dashed and solid lines correspond to three jet opening angles 0.03, 0.1 and 0.3 respectively, with the same total kinetic energy $E_j = 1 \times 10^{51}$ ergs. The dashed line is the connection of jet breaks.

sideways expansion, and their afterglow light curves for an on-axis observer are shown in Fig. 1. The light curves are shown in the spherical case and the flux density $f_{\nu} \propto t^{-\alpha_1}$ when the Lorentz factor $\gamma > 1/\theta_j$. After the jet break time, the light curves steepen as $f_{\nu} \propto t^{-\alpha_2}$ ($\alpha_2 > \alpha_1$) because of the edge effect (Mészáros & Rees 1999), which is flatter than the sideways-expansion case. This will lead to more detectable orphan afterglows. A relationship between the jet break time and flux density ($f_{\nu,j} \propto t_j^{-p}$) was found by Wu, Dai & Liang (2004) analytically and statistically.

Fig. 1 is plotted based on the fact that the kinetic energies of all GRB jets have a similar value (Frail et al. 2001; Bloom, Frail & Kulkarni 2003). The statistical standard energy of jets has been discussed by several authors, e.g., Lipunov, Postnov & Prokhorov (2001), and Panaitescu & Kumar (2002), who conclude that the collimation-corrected gamma-ray energy has a relatively narrow distribution, around $5 \times 10^{50}$ ergs. Berger, Kulkarni & Frail (2003) also obtained a standard kinetic energy reservoir of afterglows from the statistics on X-ray luminosity.

Recently, the distribution of the half-opening angle or viewing angle was investigated based on several structured-jet models (Perna, Sari & Frail 2003; Liang, Wu & Dai 2004; Nakar, Granot & Guetta 2004; Guetta, Piran & Waxman 2005). Considering a uniform, sharp-edge jet (favored by Lamb, Donaghy & Graziani 2005), whose light curves are similar to those in the universal structured jet models (Rossi, Lazzati & Rees 2002); and using the observed distribution of half-opening angles of the jets given by Lamb, Donaghy & Graziani (2005), one can derive the intrinsic distribution of $\theta_j$, i.e., $P(\theta_j) \propto \theta_j^{-1}$ (see also Xu, Wu & Dai 2005). We use this distribution as a weight for different opening angles as suggested by Guetta, Piran & Waxman (2005).

By considering both the effects of the constant half-opening angle during jet propagation and the distribution of initial jet half-opening angles, we here estimate the detectability of orphan afterglows and find that our results are different from the ones in earlier works (e.g. Nakar, Piran & Granot 2002; Totani & Panaitescu 2002). We present the theoretical model in §2 and give the results of the detectability in §3. We summarize our findings and present a brief discussion in §4.

2. Theoretical analysis

We consider an adiabatic jet with a total kinetic energy $E_j$ and a half-opening angle $\theta_j$ and neglect sideways expansion. The hydrodynamics of the jet behaves as a spherical case (Sari, Piran & Narayan 1998). The Lorentz factor of the jet is given by

$$\gamma(t_{\odot}) = 8.9(1+z)^{3/8}E_j^{1/8}n_0^{-1/8}\theta_j^{-1/4}t_{\odot,d}^{-3/8},$$

where $z$ is the redshift of the GRB, $n$ the number density of the interstellar medium (ISM), and $t_{\odot,d}$ the observed time in units of days. We adopt the conventional notation $Q = Q_k \times 10^k$ in this paper except for special explanations.

For an on-axis observer, there is a break in the light curve because of the edge effect (Mészáros & Rees 1999) when the bulk Lorentz factor $\gamma$ equals $\theta_j^{-1}$. The jet-break time is given by

$$t_j = 0.82(1+z)E_j^{1/3}n_0^{-1/3}\theta_j^{-1} \text{ days.}$$

At the jet-break time, the flux density in the slow-cooling case ($\nu_m < \nu < \nu_c$) is (Wu, Dai & Liang 2004)

$$F_{\nu,j} = \frac{515t_j^{-p} \nu_{\text{day}}}{50.2}\frac{\nu}{\nu_{\text{day}}}^{p-2}E_j^{1/4}n_0^{-1/4}D_L^{-2}$$
$$\times (1+z)^{(p+3)/2}Jy,$$

where $\nu_{\text{day}} = 3 \times 10^{16}$ Hz is the R-band frequency taken as the observed frequency. On the other hand, in the fast cooling case ($\nu_c < \nu$), the flux density is (Wu, Dai & Liang 2004)

$$F_{\nu,j} = \frac{3508t_j^{-p} \nu_{\text{day}}}{50.2}\frac{\nu}{\nu_{\text{day}}}^{p-2}E_j^{1/4}n_0^{-1/4}D_L^{-2}$$
$$\times (1+z)^{(p+3)/2}(1+Y_f)^{-1}\frac{\nu}{\nu_R}^{-p/2}Jy,$$

where $Y_f = Y(t_i) = (-1+\sqrt{1+4\eta/\epsilon_R})/2$ is the Compton parameter (Panaitescu & Kumar 2001; Sari & Esin 2001), and $\eta$ is the radiation efficiency of electrons. Even though most GRB afterglows match the slow cooling case in the statistics by Wu, Dai & Liang (2004), we here consider both fast and slow cooling cases, which are different from Nakar, Piran & Granot.
index is about range of $\theta$ in the point source approximation, which is good enough when a parameter in the fast cooling case and density in the isotropic fireball case. As an orphan afterglow: $n$ (Porciani & Madau 2001), rate (SFR), but we use a different SFR model as follows $= t_0$ (Sari, Piran & Narayan 1998). As index at earlier times $(\theta_{\text{obs}} < \theta_j)$ one (Sari, Piran & Narayan 1998). As index properties are the same as those from an isotropic fireball. The beaming factor of GRBs and $\theta_{\text{lim}}$ (Granot et al. 2002). Following Nakar, Piran & Granot (2002), we assume that $\theta_{\text{obs}} = 0$ is not an orphan afterglow, which is plotted here as a reference. The horizontal dashed line represents a given limiting magnitude. The earliest and latest times ($t_{\text{min}}$ and $t_{\text{max}}$) at which an orphan afterglow are observed are represented by vertical dotted lines.

For an off-axis observer with observing angle $\theta_{\text{obs}}$, the time and frequency from on-axis ($t_0, v_0$) and off-axis ($t, \nu$) jets satisfy $t_0/t \sim \nu/v_0 = (1 - \beta)/(1 - \beta \cos \theta_{\text{obs}}) \equiv a$, where $\beta = \sqrt{1 - 1/\gamma^2}$ is the velocity in units of $c$; thus the flux density is

$$F_\nu(\theta_{\text{obs}}, t) = a^3 F_\nu(0, at), \quad (5)$$

in the point source approximation, which is good enough when $\theta_{\text{obs}} > \theta_j$ (Granat et al. 2002).

Given a limiting flux density $F_{\nu, \text{lim}}$ (corresponding to a limiting magnitude $m_{\text{lim}}$) for an instrument with a fixed exposure time, we can calculate the detectable duration of an orphan afterglow: $t_{\text{obs}}(z, \theta_{\text{obs}}, \theta_j, m_{\text{lim}}) = t_{\text{max}} - t_{\text{min}}$, where $t_{\text{min}}$ and $t_{\text{max}}$ represent the earlier and later times when $F_{\nu, \theta_{\text{obs}}} = F_{\nu, \text{lim}}$. If the maximum observed flux density $F_{\nu, \theta_{\text{obs}, \text{max}}} < F_{\nu, \text{lim}}$, we take $t_{\text{obs}} = 0$. Fig. 2 shows the light curves of afterglows for different observing angles.

Following Nakar, Piran & Granot (2002), we assume that the GRB rate $n(z)$ is proportional to the star formation rate (SFR), but we use a different SFR model as follows (Porciani & Madau 2001).

$$n(z) = B \times 3.4z^{\frac{1}{2}} \Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{1.5} \quad (6)$$

where $\Omega_m$ and $\Omega_\Lambda$ are the cosmological parameters, and $B$ the normalization factor. The parameter $B$ satisfies $R_{\nu, \text{GRB}} = \int_0^{\theta_{\text{obs}}(z, m_{\text{lim}})} (dz) n(z) (1 + z) dz$, where $\theta_{\text{obs}} = \int_0^{\theta_{\text{obs}, \text{max}}} (1 - \cos \theta_j)^{-1} P(\theta_j) d\theta_j / \int_0^{\theta_{\text{obs}, \text{max}}} P(\theta_j) d\theta_j$ is the mean beaming factor of GRBs and $R_{\nu, \text{GRB}} = 667 \gamma^{-1}$ is the observed GRB rate. Here we assume all the GRBs can be observed if the observer is located within the solid angles of the jets and the redshift range is $0 < z < 10$.

If the exposure time is not too long (shorter than $t_{\text{obs}}$), the number of detectable orphan afterglows in a single snapshot over the whole sky can be expressed as

$$N_{\text{orphan}} = \int_0^{\theta_{\text{max}}(z, m_{\text{lim}}) \arctan(z, \theta_{\text{obs}}, \theta_j, m_{\text{lim}} \theta_{\text{obs}}) d\theta_j \times \int_0^{\theta_{\text{max}}(z, m_{\text{lim}}) \arctan(z, \theta_{\text{obs}}, \theta_j, m_{\text{lim}} \theta_{\text{obs}}) d\theta_j \quad (7)$$

where $\theta_{\text{max}}(z, m_{\text{lim}})$ is the maximum observing angle, which satisfies $t_{\text{max}}(\theta_{\text{max}}) = t_{\text{min}}(\theta_{\text{max}})$, and $P(\theta_j)$ is the observational distribution function of half-opening angles of the jets.

Fig. 2. Sketch for observations of orphan R-band afterglows. The three solid lines indicate the light curves with different observing angles. The one with $\theta_{\text{obs}} = 0$ is not an orphan afterglow, which is plotted here as a reference. The horizontal dashed line represents a given limiting magnitude. The earliest and latest times ($t_{\text{min}}$ and $t_{\text{max}}$) at which an orphan afterglow are observed are represented by vertical dotted lines.

with the upper and lower limits $\theta_{\text{max}}$ and $\theta_{\text{min}}$, which satisfies (Lamb, Donaghy & Graziani 2005)

$$P(\theta_j) = \frac{\theta_j^{-1}}{\ln(\theta_{\text{max}}/\theta_{\text{min}})}. \quad (8)$$

3. Numerical results

If the model parameters are given, the detectability of orphan afterglows can be estimated by Eq. (6). The main difference in detectability comes from the limiting magnitudes of detectors. Fig. 3 shows the number of orphan afterglows that can be detected by one exposure on the whole sky. The solid line is the standard result, with parameters $E_j = 1 \times 10^{51}\text{erg}, n = 1\text{cm}^{-3}, \alpha = 3, \epsilon_e = 0.1, \epsilon_B = 0.01, \nu = 4.5 \times 10^{14}\text{Hz}, \theta_{\text{min}} = 0.01$, and $\theta_{\text{max}} = 1$, where $E_j, n, \nu, \epsilon_e, \epsilon_B, \nu$ are the same as in Nakar, Piran & Granot (2002). As the pre-break temporal index of the optical light curve is about $-1$ (Zhang & Mészáros 2004), we choose $\alpha_2 = \alpha_1 + 3/4 \approx 1.8$. The $\theta_{\text{min}} = 0.01$ is adopted from Lamb, Donaghy & Graziani (2005). We take $\theta_{\text{max}} = 1$, which does not influence the estimation significantly when we consider the distribution of half-opening angles of the jets. We also show the results of Nakar, Piran & Granot (2002) in this figure with their canonical ($\theta_j = 0.1$) and optimistic ($\theta_j = 0.05$) parameters. For comparison, we plot the dotted line for a fixed half-opening angle $\theta_j = 0.1$ and the SFR model in Nakar, Piran & Granot (2002). One difference between the dotted line and the thick dashed line is the temporal index after the break time. We can see that the difference in detectability is due to the sideways expansion. Approximately, the flux density after the break time $t_j$ is $F_\nu(t_j) \approx F_\nu(0) (t_j/t_0)^{-p}$.
Table 1. The ratio of the number of orphan afterglows to the total number of afterglows for different limiting magnitudes of detectors. The values without and with brackets correspond to models A and B in Nakar, Piran & Granot (2002) respectively to compare with their results.

| \(z_{\text{peak}}\) | \(\theta_j\) | \(m_{\text{lim}}=23\) | \(m_{\text{lim}}=25\) | \(m_{\text{lim}}=27\) |
|-----------------|---------|-----------------|-----------------|-----------------|
| 1               | 0.05    | 0.56(0.68)     | 0.73(0.78)     | 0.84(0.86)     |
| 1               | 0.10    | 0.33(0.39)     | 0.40(0.58)     | 0.63(0.71)     |
| 1               | 0.15    | 0.26(0.29)     | 0.34(0.40)     | 0.41(0.59)     |
| 2               | 0.10    | 0.22(0.36)     | 0.34(0.55)     | 0.60(0.70)     |

in the sideways expansion case and \(F_{\nu}(t_{\odot}) \approx F_{\nu,j}(t_{\odot}/t_j)^{-\alpha_2}\) in the non-sideways expansion case. Note that \(F_{\nu,j}\) and \(t_j\) have the same values in both cases, since the breaks both take place when \(\gamma \approx 1/\theta_j\), and before the jet break time, both cases show isotropic evolution behavior (Rhoads 1999, Mézsáros & Rees 1999). Neglecting \(t_{\text{min}}\) and \(\theta_j\) in Eq. (7) and the potential influence of different spectra, we obtain the ratio of the detectabilities in the two cases (i.e., no sideways expansion vs. sideways expansion): \(N_{\text{orph, NSE}}/N_{\text{orph, SE}} \approx (F_{\nu,j}/F_{\nu,\text{lim}})^{11/(8\alpha_2)-3/(2p)}\). In general, if \(\alpha_2 < p\), then \(11/(8\alpha_2) > 3/(2p)\) and thus \(N_{\text{orph, NSE}} > N_{\text{orph, SE}}\). For a larger limiting magnitude (i.e. smaller \(F_{\nu,\text{lim}}\)), the ratio becomes higher. This is why in Fig. 5 the dotted line is higher than the thick dashed line for greater \(m_{\text{lim}}\). To show the effect of different SFR models, the dot-dashed line uses the SFR model in Nakar, Piran & Granot (2002) with \(z_{\text{peak}} = 1\), and the dotted line considers the SFR model in Eq. (4). These two lines are close to each other, which shows that the effect of the SFR models is insignificant. We note that the distribution of half-opening angles of the jets leads to further suppression of the detectability, which results in the difference between the dot-dashed and the solid lines. Combining the effects of the sideways expansion and distribution of the jet’s half-opening angles, we obtain standard results (solid line in Fig. 3).

A more detailed comparison with Nakar, Piran & Granot (2002) was performed and the results are listed in Table 1, which includes the ratio of the numbers of observable orphan afterglows to total observable afterglows. We choose the same SFR model (see Eq. (13) in Nakar, Piran & Granot 2002), and the same model A and model B (i.e., the angle in Lorentz transformation \(\theta = \theta_{\text{obs}}\) for model A, and \(\theta = \max(0, \theta_{\text{obs}} - \theta_j)\) for model B), and neglect sideways expansion. We conclude that the ratios for model B are all higher than those for model A. Our ratios are somewhat lower than those in Nakar, Piran & Granot (2002). This is because, for a fixed half-opening angle, the on-axis afterglow is brighter than in the sideways expansion case and the flux density of orphan afterglows does not increase very much, being due to the Doppler effect (see Eq. (5)).

Recently, Rykoff et al. (2005) performed a search for orphan afterglows, but none has been detected. They gave an upper limit for the observed rate \(\eta_{\text{max}} < 1.9 \times 10^{-2}\text{deg}^{-2}\text{yr}^{-1}\) by using the method suggested by Becker et al. (2004): \(\eta = N/\langle (\epsilon) E \rangle \text{events deg}^{-2}\text{yr}^{-1}\), where \(N\) is the number of detected orphans, \(E\) the exposure, and \(\langle \epsilon \rangle\) the efficiency. Assuming a 30-minute exposure time as in Rykoff et al. (2005), we obtain the exposure \(E \approx 2.35 \times 10^{-2}\text{deg}^{2}\text{yr}^{-1}\) for one whole sky survey. If the theoretical efficiency \(\langle \epsilon \rangle\) is assumed to be unity, the observed rate is then \(\eta \approx 1.3 \times 10^{-2}\text{deg}^{-2}\text{yr}^{-1}\) and the detectability \(N\) extrapolated to the 20th magnitude \((N \sim 0.03)\) in the standard model. This is well below the upper limit \(1.9 \times 10^{-2}\text{deg}^{-2}\text{yr}^{-1}\) estimated by Rykoff et al. (2005) for the survey with limiting magnitude 20.

We also calculated the detectability for different parameters to show their effects. Fig. 4 shows the detectability with different total kinetic energy \(E_j\). The solid line is the standard one, the same as the solid line in Fig. 3. If the value of \(E_j\) increases by one order of magnitude, the detectability increases by a factor of about 12. It is reasonable that \(N\) is greater for a higher kinetic energy. Generally speaking, the detectability is sensitive to the \(E_j\).

Fig. 5 shows the detectability for different \(p\) and \(\epsilon_\nu\), with the solid line still the standard one. Remarkably, these parameters

\[ n(z) = B \begin{cases} \frac{10^{0.75}}{z \leq z_{\text{peak}}}, \\ \frac{10^{0.75}/z_{\text{peak}}}{z > z_{\text{peak}}}, \end{cases} \]
have minor effects on the results. Note that the $p$ and $\alpha_2$ are independent parameters here, unlike the sideways expansion case, where $\alpha_2 = p$ (Granot & Kumar 2003), so the variation in $p$ does not change the temporal index $\alpha_2$. The parameter $p$ influences the flux density at time $t_j$, which can be seen in Eqs. 3 and 4. The flux density is approximately proportional to $\epsilon_e$, and the detectability is somewhat sensitive to $\epsilon_e$. From those two equations, we can find that the other parameters $n$ and $\epsilon_B$ do not significantly influence the detectability of optical orphan afterglows.

4. Discussions

We have calculated the number of orphan optical (R-band) afterglows that can be detected in an ideal survey of the whole sky with different limiting magnitudes. We considered jets without sideways expansion during the afterglow phase. This leads to a flatter light curve after the jet-break time $t_j$, compared with the sideways-expansion case. Thus, orphan afterglows can persist for a longer time (above a certain flux density), and more expected orphans can be detected. The distribution of half-opening angles of jets was also considered, which suppresses the number of optical orphans compared with the case that all jets have one single half-opening angle $\theta_j = 0.1$. When combining these two effects, the detectability is less than the canonical results of Nakar, Piran & Granot (2002), who considered the case in which all jets have an initial half-opening angle $\theta_j = 0.1$ with sideways expansion.

From Figs. 3-5, we can conclude that the main factors for the detectability are the total kinetic energy $E_j$, half-opening angle of jet $\theta_j$, and temporal index $\alpha_2$. As $E_j$ is considered to be a standard energy (Frail et al. 2001), our results can be used to constrain the value of the $E_j$ by detecting orphans. If $E_j$ and $\alpha_2$ are determined accurately by other methods, the distribution function of the jet’s half-opening angles can be determined well by observations of orphan afterglows.

However, our estimation is simplified in several aspects. First, the parameters are undetermined and diverse in different bursts. For a variable parameter, we should know its distribution. But this is very difficult. For example, the circum-burst environment seems to be an ISM, a wind, or another density-profile media, but these media cannot be determined clearly in well-observed GRBs. For simplicity, we choose the ISM with number density $n = 1 \text{ cm}^{-3}$. Second, orphan afterglows may have properties similar to other phenomena: e.g., failed gamma-ray burst (Huang, Dai & Lu 2002; Rhoads 2003; Huang et al. 2005) and “on-axis orphan afterglow” (Nakar & Piran 2003). Third, we use the model with a power-law distribution of half-opening angles of uniform jets. However, there are some other structured jet models that cannot be ruled out (Dai & Guo 2001; Rossi, Lazzati & Rees 2002; Zhang & Méészáros 2002). These models also affect the detectability. Fourth, we assume that the GRB rate is proportional to the SFR, so our results are SFR-dependent. Fifth, when observing, one should distinguish orphan afterglows from other transients carefully (Levinson et al. 2002; Becker et al. 2004; Gal-Yam et al. 2006). Finally, the dust grains within the jet’s opening solid angle may be evaporated by the prompt UV/X-ray photons, and the dust is possibly opaque in optical/UV bands outside the jet cone, so an optical orphan afterglow may be generally suppressed.

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