The Variable Light Curve of GRB 030329: The Case for Refreshed Shocks

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ABSTRACT

GRB 030329 is unique in many aspects. It has a very low redshift for a GRB, $z = 0.1685$, and is therefore very bright and easy to monitor, making it the most well studied afterglow to date. It shows a supernova bump in the light curve, with a spectrum very similar to SN 1998bw, thus establishing with much better confidence the connection between GRBs and core collapse SNe. There are also two important physical characteristics that make this burst especially interesting, aside from its remarkably low redshift. First, unlike most GRB afterglows, the light curve of GRB 030329 shows a very large variability a few days after the burst. These fluctuations show a roughly constact amplitude, and a constant duration Δt, while $\Delta t/t$ decreases with time t. Second, its γ-ray energy output and X-ray luminosity at 10 hr are a factor of ~ 20 and ~ 30, respectively, below the average value around which most GRBs are narrowly clustered. We consider several interpretations for the variability in the light curve, in the context of different physical mechanisms, and find that the most likely cause is refreshed shocks, i.e. slow shells that are ejected from the source and catch up with the afterglow shock at late times. In GRB 030329 this happens after the jet break, which implies an approximately constant duration Δt of the bumps, in agreement with the observations. This interpretation also explains the anomalously low initial energy of this burst, as the total energy of the afterglow shock is increased by a factor of ~ 10 due to the refreshed shocks, thus bringing the total energy output close to the average value for all GRBs.

1. Introduction

The afterglow light curve of most GRBs shows a smooth power law decay with the time after the burst. This is consistent with the prediction of the simplest model of a spherical blast wave propagating into a uniform medium, where the spectrum consists of several power law segments in which $F_\nu \propto \nu^{-\beta} t^{-\alpha}$ (Sari, Piran & Narayan 1998), and remains valid for an external density that drops as r^{-2} as expected for the stellar wind of a massive star progenitor (Chevalier & Li 2000) and for a jetted outflow (Rhoads 1999; Sari, Piran & Halpern 1999).

However, a few GRBs do show deviations from a smooth power law light curve. GRB 970508 showed a brightening at $t \sim 2$ days, which was observed in optical (Galama et al. 1998) and possibly also in X-rays (Piro et al. 1998). An achromatic bump was observed in the afterglow of GRB 000301C at $t \sim 4$ days (Berger et al. 2000; Sagar et al. 2000) and was attributed, among other interpretations, to gravitational microlensing (Garnavich, Loeb & Stanek 2000). In these two cases a single epoch of re-brightening was observed. In contrast to this, GRB 021004 displayed a highly variable light curve, with several wiggles and deviations from a simple power law behavior. This variable light curve was interpreted as arising either due to a variable external density (Lazzati et al. 2002; Nakar, Piran & Granot 2003; Heyl & Perna 2003) or due to a variable energy in the observed portion of the afterglow shock. The latter can arise due to an irregular initial distrubotion of the energy per unit solid angle in the outflow (the patchy shell model, e.g. Kumar & Piran 2000b). The early slow decay of GRB 021004 was interpreted by Fox et al. (2003) as arising from delayed shocks and continuous energy ejection from the source (Rees & Mészáros 1998; Kumar & Piran 2000a; Sari & Mészáros 2000).

GRB 030329 was detected by HETE-II on March 29, 2003 (11:37:14.67 UT), and its location was distributed (Vanderspek et al., 2003) $t = 1.4$ hr later. Optical observations from ground based telescopes soon followed, and a bright optical afterglow with R=12.6 was detected at $t = 1.5$ hr (Peterson & Price 2003, Torii 2003). Observations at many different wavelengths followed, and a very bright afterglow emission was detected in the radio, sub-millimeter, millimeter and X-ray (Marshall & Swank 2003, Berger, Soderberg & Frail 2003, Hoge et al. 2003, Kuno, Sato & Nakanishi 2003). Its redshift, $z = 0.1685$ (Greiner et al. 2003), places it as the closest GRB whose redshift was firmly established[1]. It is therefore not surprising that the afterglow of GRB 030329 is by far the brightest afterglow detected so far[2], and is also the most well studied GRB afterglow to date.

A spectral signature very similar to SN 1998bw began to emerge in the spectrum of GRB 030329 after ~ 7 days (Stanek et al. 2003), and became more prominent in the following days. This provides the best evidence so far for the association of GRBs with core collapse supernovae of the type of SN 1998bw, which are also called hypernovae. The optical light curve showed a jet break at $t = 0.45$ days, and several re-brightenings between ~ 1.5 and ~ 6 days, each with a duration of $\sim 0.3 - 0.8$ days. We explore different possible explanations for the variability in the light curve using different physical mechanisms and show that the most likely explanation for the observed variability is refreshed shocks.

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[1]GRB 980425, if indeed associated with SN 1998bw, was at a still lower redshift, of $z = 0.0085$.

[2]Here we exclude the prompt optical emission which was observed for GRB 990123 (Akerlof et al. 1999) and peaked at tens of seconds after at 9th magnitude, which is attributed to the reverse shock (Sari & Piran 1999; Mészáros & Rees 1999).

2. Interpretation of the Variable Light Curve

The optical light curve of GRB 030329 steepened from $\alpha_1 = 0.93 \pm 0.04$ to $\alpha_2 = 1.90 \pm 0.03$ at $t_j \approx 0.45$ days (http://space.mit.edu/HETE/Bursts/GRB030329/). The most likely explanation for this smooth change in the temporal decay index α is a jet break, and in the following we shall assume that this is indeed the case. Since the jet break is quite sharp, a roughly constant (underlying) external density is required. A stellar wind profile would not produce a sufficiently sharp jet break (Kumar & Panaitescu 2000).

The fluence GRB 030329 in the $15 - 5000$ keV range was measured by Konus-Wins to be 1.6×10^{-4} erg cm^{-2} (Golenetskii et al. 2003), which for its redshift of $z = 0.1685$ and using the WMAP cosmological parameters, implies an isotropic equivalent γ-ray energy output of $E_{\gamma,\rm iso} \sim 1 \times 10^{52}$ erg. The X-ray flux in the $2 - 10$ keV range was measured by RXTE at $t = 5$ hr to be $F_X = 1.4 \times 10^{-10}$ erg sec^{-1} cm^{-2}, which implies an isotropic equivalent X-ray luminosity at $t = 10$ hr of $L_{X,\rm iso} \sim 5 \times 10^{45}$ erg sec^{-1} (Marshall & Swank 2003). Using the same formula and the fiducial parameter values of Frail et al. (2001) we find $\theta_{j,0} = 0.07$ which corresponds to a beaming factor of $f_b \approx \theta_{j,o}^2/2 \approx 1/400$. This implies a true γ-ray output of $E_\gamma \sim 3 \times 10^{49}$ erg, and a true X-ray luminosity at $t = 10$ hr of $L_X \sim 1 \times 10^{43}$ erg sec^{-1}. Both values are at the very low end of the standard distribution for GRBs: Frail et al. (2001) find $\log_{10}(E_\gamma[\rm erg]) = 50.7 \pm 0.5$, while Berger, Kulkarni & Frail find $\log_{10}(L_X) = 44.5 \pm 0.5$.

The optical light curve shows a well monitored re-brightening between $t \sim 1.3$ and ~ 1.7 days. This re-brightening begins to effect the light curve after about one day, which is only a factor of ~ 2 in time after t_j. Therefore, we expect that the asymptotic decay slope α_2 has not yet been reached, and the value of 1.9 inferred from observations may be regarded as a lower limit. At least 3 additional and similar features appear in the light curve at $t \sim 2.4 - 2.8$ days, $t \sim 3.1 - 3.5$ days and t$\sim$ $4.9 - 5.7$ days, though the latter are not as densely monitored (see Figure 1). Another possible flattening of the light curve is observed at $t \sim 9 - 10$ days, however this may be at least in part due to the contribution of an the underlying SN 2003dh, and is therefore not included in our analysis. If the amplitude of each bump is measured as the offset between the decay epochs before and after the rise in the flux (which is roughly constant, as the temporal decay indices α after the different bumps are rather similar), we find that the amplitude of the first bump is a factor of ~ 2, while the amplitude of the following bumps is $\sim 1.3 - 1.4$. The exact determination of the amplitude depends on the assumption for the underlying "average" flux, and may vary somewhat.

2.1. Variable External Density

Variations in the external density was the first mechanism proposed to account for variability in the light curve of GRB afterglows. The variability due to small amplitude density fluctuations caused by interstellar turbulence was considered by Wang & Loeb (2000). A density bump in the external medium was suggested as a possible explanation for the bump in the light curve of

GRB 000301C (Berger et al. 2000), and a highly variable external medium was suggested as an explanation for the large variability in the afterglow of GRB 021004 (Lazzati et al. 2002; Nakar, Piran & Granot 2003; Heyl & Perna 2003). A variable external density produces a much larger variability below the cooling break frequency ν_c (typically optical or IR), compared to above ν_c (typically X-ray). For a spherically symmetric external density distribution, it cannot produce sharp variations in the flux on time scales $\Delta t < t$ (Nakar & Piran 2003), due to angular spreading (i.e. the spreading in the arrival time of photons to the observer due to the curvature of the shock).

Turning to GRB 030329, we find that the rise in the normalization of the decaying part of the light curve after each bump implies that the external density would have to increase with radius, and to do so in discrete steps, rather than in a smooth manner. However, such a density profile seems very unlikely. If such a density profile would still somehow occur, then the observed optical light curve could be reproduced, if the jet would hardly expand sideways at $t > t_j$. In this case, we expect much smaller fluctuations in the X-ray light curve. As of yet, there is no good X-ray light curve available that would enable us to compare the variability in the light curve below and above ν_c.

2.2. Patchy Shell

The patchy shell model (Kumar & Piran 2000b) suggests a variability in the energy per unit solid angle of the GRB outflow, on some typical angular scale. According to this model, the amplitude of the fluctuations in the afterglow light curve is expected to decrease with time $\propto \gamma$ (Nakar, Piran & Granot 2003). However, in GRB 030329 the bumps occur after the jet break, when all the jet is visible, so that fluctuations in the energy per unit solid angle across the jet should no longer induce significant fluctuations in the light curve. Therefore, assuming that the smooth steepening in the light curve at $t = 0.45$ days is indeed a jet break, the patchy shell model can be ruled out as the source of the variability at $t > 1$ day.

2.3. Refreshed Shocks

According to the refreshed shocks scenario, slow moving shells that were ejected from the source with a modest Lorentz factor catch up with the afterglow shock at late times well after the internal shocks that are responsible for the prompt γ-ray emission have ceased (Rees & Mészáros 1998; Kumar & Piran 2000a; Sari & Mészáros 2000). Each such shell injects energy into the afterglow shock as it collides with it from behind, and causes a re-brightening in the afterglow light curve. After the re-brightening the same power law decay as before the bump should be resumed, as long as the observed frequency remains within the same power law segment of the spectrum (i.e. if no break frequency passes through the observed band). Similarly, under these conditions the color indices should not change. The normalization of the decaying light curve after the bump is higher than before the bump by a factor f, due to the increase in the energy of the afterglow shock. The energy increases by a factor $f^{4/(3+p)}$ for $\nu_m < \nu < \nu_c$ and $f^{4/(2+p)}$ for $\nu_m, \nu_c < \nu$. For GRB 030329 $p \approx 2$ and $\nu_c(t_j)$ is around the optical, so that the increase in the energy is approximately linear in f. We find that across all the bumps in the first several days, this normalization increased by a factor of $f_{\rm total} \sim 10$, and deduce that this implies a similar increase in the energy of the afterglow shocks due to energy injection from the shells that caught up with it. The conservative estimate of $f_{\rm total}$ using the value of α_2 from just after t_j is ~ 5, while if we take α_2 from the decay after the second or third bumps we obtain $f_{\rm total} \sim 20$ (see Figure 1). Therefore $f_{\rm total} \sim 10$ with an uncertainty of a factor ~ 2 seems like a reasonable estimate.

In the original refreshed shocks scenario it was expected that these shocks occur before the jet spreading, and therefore $\Delta t \sim t$ (Kumar & Piran 2000b). However, in GRB 030329 the jet break is at 0.45 days, and the refreshed shocks took place at a later time, after the whole jet becomes visible as its Lorentz factor is smaller than the inverse of its opening angle. We expect that all the shells ejected from the central source will have roughly the same opening angle, $\theta_{j,0}$ (see illustration in Figure 2). The most forward shell sweeps up the ambient medium and produces the afterglow emission. Since it is very hot, with an internal energy much higher than its rest energy, it could potentially expand sideways at close to the speed of light c (or $c/\sqrt{3}$) in its local rest frame, though the lateral expansion could still be much smaller than this. However, the slower shells that follow in the wake of the forward shell encounter very little material before they catch up with the forward shell, and therefore are expected to be cold, and should not expand sideways significantly before colliding with the afterglow shock. In this case the duration of the bump in the light curve is given by the angular time $\Delta t \sim R\theta_{j,0}^2/2 = t_j(R/R_j) = t_j(t/t_j)^a$, where $a = 1/4$ if the lateral spreading of the jet is negligible, while $a \approx 0$ if the lateral spreading is at the local sound speed. This allows $\Delta t < t$. Numerical simulations suggest that the lateral spreading is quite modest (Granot et al. 2001), implying $a \approx 1/4$. This is consistent with the almost constant duration of the first 3 bumps, and the slightly larger duration of the fourth bump, that are seen in GRB 030329.

The temporal decay slope after the first bump is very close to α_2, while after the second and third bumps α is slightly larger than α_2. Unfortunately, it is hard to accurately determine the value of α after the forth bump due to the contribution from the underlying SN, though it seems similar to the values for the preceding bumps. The steeper temporal decay slopes, $\alpha > \alpha_2$, may be due to the fact that the asymptotic power law decay after the jet break was not reached, and is underestimated by α_2. The small differences between the slopes may be attributed to a slight inhomogeneous distribution of the Lorentz factor across the slow shell that catches up (i.e. its Lorentz factor decreases smoothly from its front edge to its back edge, so that the energy injection is not step-like but more gradual). We conclude that the refreshed shocks model provides the best explanation for the variability in the light curve of GRB 030329. The timing of the bumps suggest that the Lorentz factors of the slower shells ranged from ≥ 6 to ≥ 3.5. The lower limit is obtained for the extreme case of when after the jet break the jet expands sideways at the the local speed of sound and its radius is almost constant (Rhoads 1997). The higher values are obtained if the jet does not spread sideways significantly, as suggested by the results of Granot et al. (2001). In this case the radius of the front shell increases with time and the inner shells need a larger Lorentz factor to catch up with the forward one.

3. Discussion

We have compared the variable light curve of GRB 030329 to the predictions of the different models for variability in GRB afterglows and find that the only satisfactory explanation for the observed variability in GRB 030329 is refreshed shocks that take place after the jet break. This interpretation is supported by the almost constant durations of the different bumps, $\Delta t \sim 0.4 - 0.8$ days, which is also of the order of the jet break time, $t_j = 0.45$ days, and by the step-wise shape of the light curve. According to the refreshed shocks interpretation, we find that the energy injected into the afterglow shock by all the slow shells that catch up with it, increases its initial energy by a factor of ~ 10. This implies that the total energy in this GRB outflow is an order of magnitude larger than the energy inferred from the prompt γ-ray emission, or from the early afterglow emission before ~ 1 day, and thus explains the anomolously low values inferred for E_γ and L_X. A direct prediction of this interpretation is that we should expect very significant radio flares corresponding to the observed optical bumps. These should arise from emission by the reverse shocks that form in the refreshed shocks.

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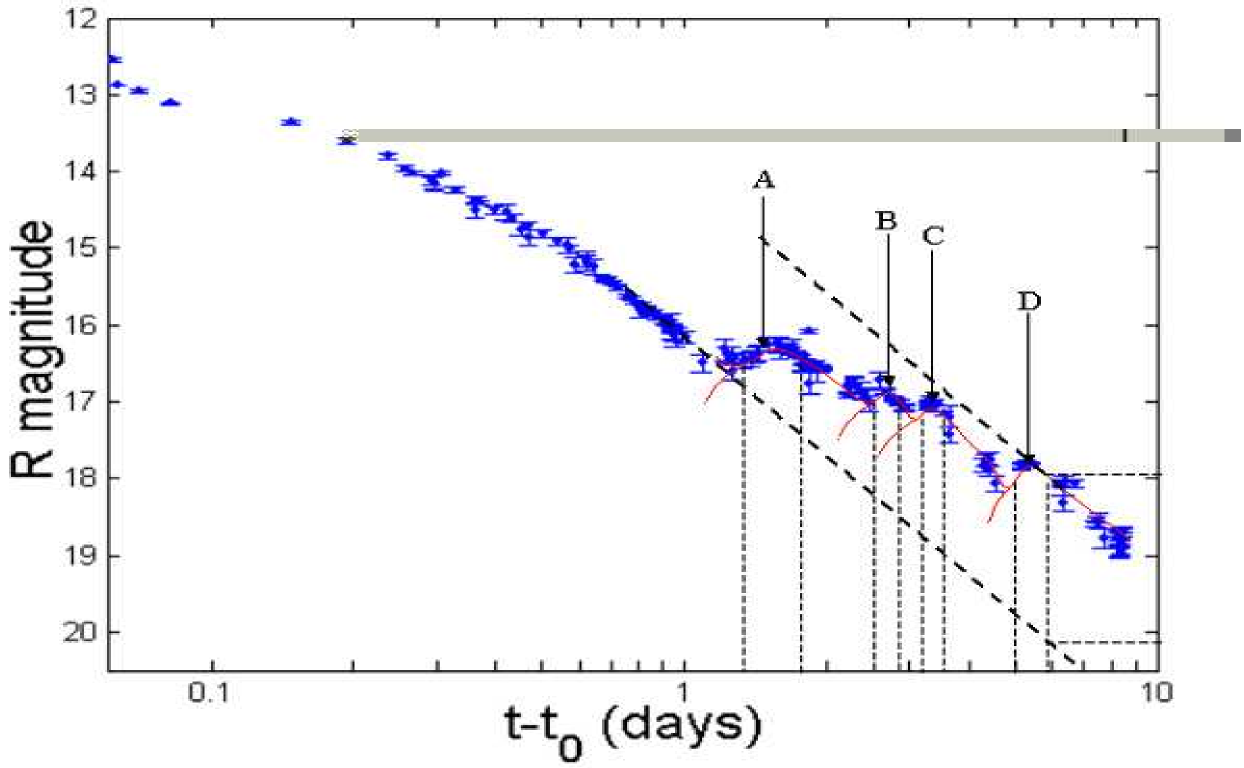

Fig. 1.— The GCN light curve of GRB 030329 during the first 9 days. The vertical dashed lines mark the position of the four bumps (A at $t \sim 1.3- \sim 1.7$ days, B at $t \sim 2.4 - 2.8$ days, C at $t \sim 3.1 - 3.5$ days, and D at $t \sim 4.9 - 5.7$ days). The thick slanted lines mark the asymptotic decay slopes before and after the bumps. The horizontal dashed lines mark the difference in magnitude between these two curves. The thin lines depicts the schematic shapes of an individual refreshed shock light curve. The data points are taken from the following GCNs: Rykoff et al. 2003; Burenin et al. 2003a,b,c,d,e; Pavlenko et al. 2003a,b,c; Bartolini et al. 2003; Price, A. et al. 2003a,b,c; Weidong et al. 2003; Martini et al. 2003; Zharikov et al. 2003a,b; Brodney et al. 2003a,b; Halpern et al. 2003; Lipkin et al. 2003a,b,c; Rumyantsev et al. 2003; Klose et al. 2003; Stanek et al. 2003 ; Zeh et al. 2003; Ibrahimov et al. 2003a,b,c; Cantiello et al. 2003; Sato et al. 2003; Khamitov et al. 2003a,b,c. An arbitrary errorbar of 0.1mag is taken for any data point with no error included in the GCN. The collection of data from the GCN at the the first 80 hours is taken from http://astron.berkeley.edu/ bait/grb/gcn030329.r.dat.

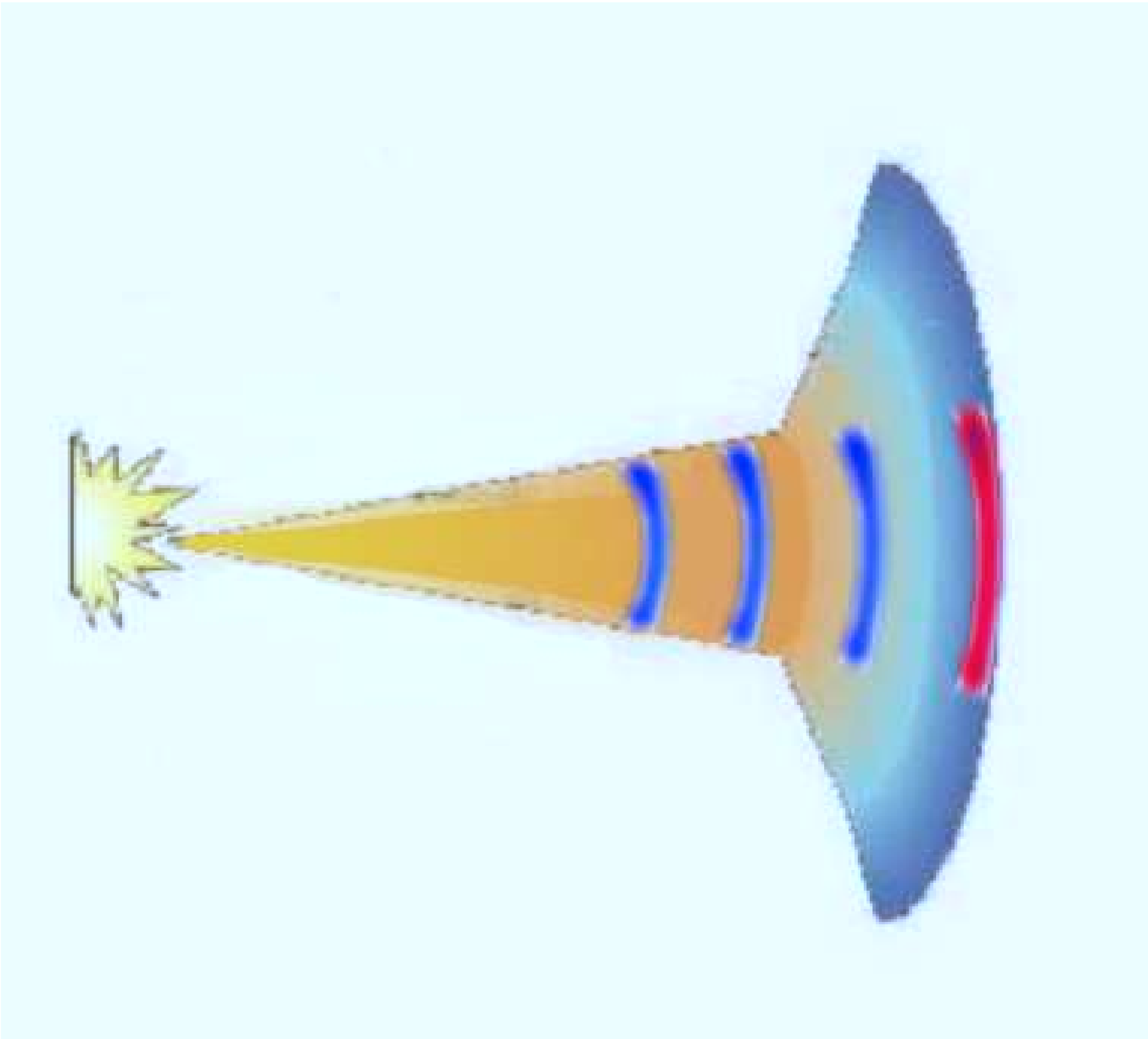

Fig. 2.— A schematic diagram that describes the refreshed shocks scenario after a jet break. The original flow is collimated to an opening angle $\theta_{j,o}$. At $t \sim R\theta_{j,o}^2/2c$ the Lorentz factor reaches $\gamma \sim \theta_{j,o}^{-1}$ and begins spreading sideways. The following shells, which propagate in the wake of the forward shell, remain cold and do not spread sideways until they collide with the forward shell and a refreshed shock forms. The duration of the brightening (which is dominated by the angular spreading time) is determined by the angular size of the slow shells, $\sim R\theta_{j,o}^2/2c$, which is comparable to the jet break time.