LATE-TIME RADIO REBRIGHTENING OF GAMMA-RAY BURST AFTERGLOWS: EVIDENCE FOR DOUBLE-SIDED JETS

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ABSTRACT

The central engine of gamma-ray bursts (GRBs) is believed to eject double-sided ultrarelativistic jets. For an observed GRB, one of the twin jets points toward us and is responsible for the prompt gamma-ray and subsequent afterglow emission. We consider in this Letter the other receding jet, which is expected to give rise to late-time radio rebrightening (RRB) when it becomes nonrelativistic (NR) and radiatively isotropic. The RRB peaks at a time $t_{\text{GRB}} = 2(E_j/n)^{1/3}$ yr after the GRB (where $t_{\text{GRB}}$ is the observed NR timescale for the preceding jet, $E_j$ is the jet energy, and $n$ is the ambient medium density). The peak flux is comparable to the preceding jet emission at $t_{\text{GRB}}$. We expect the RRB of GRB 030329 1.7 yr after the burst, with a flux of ~0.6 mJy at 15 GHz. The cases of GRBs 970508 and 980703 have also been discussed. The detection of RRB, which requires a dense monitoring campaign as much as a few years after a GRB, will be the direct evidence for the existence of double-sided jets in GRBs and prove the black hole–disk system formation in the cores of progenitors.

Subject headings: gamma rays: bursts — ISM: jets and outflows — radio continuum: general

1 INTRODUCTION

A standard shock model of gamma-ray burst (GRB) afterglows has now been well established, in which the GRB outflow (jet) drives a relativistic expanding blast wave that sweeps up and heats the GRB ambient medium to produce the long-term X-ray, optical, and radio afterglow by synchrotron/inverse-Compton (IC) emission (see Zhang & Mészáros 2004 or Piran 2004 for recent reviews).

The remarkable supernova signature in GRB 030329 afterglow (Hjorth et al. 2003) has confirmed that GRBs, at least the long-duration ones, originate from explosions of massive stars. Their progenitors are believed to form black hole–disk systems in their cores and produce double-sided jets, which are responsible for the GRB emission, along the spinning axis of the black hole (Mészáros 2002). For the observed hard GRB photons to escape freely, avoiding electron/positron pair formation, the outflows must be ultrarelativistic, with a Lorentz factor $\Gamma \gtrsim 100$. Because of the relativistic beaming effect, the GRB emission is confined within a narrow cone and can only be observed when the light of sight is within the cone. Interestingly, it was this beaming effect that caused many authors to expect the present of “orphan afterglows” (Rhoads 1997; Dalal et al. 2002; Granot et al. 2002; Granot & Loeb 2003), which correspond to off-axis GRBs without gamma rays associated, but with afterglows detected when the shocks decelerate.

With the exception of Granot & Loeb (2003), the previous works only discussed the emission from the preceding jet (PJ), which is pointing toward us, and neglected the emission from the other receding jet (RJ), since it always points away from us. However, in this Letter we specifically address the emission from the RJ, which will emerge when the RJ becomes nonrelativistic (NR) and the radiation becomes isotropic. Because of the light-travel time delay, the RJ contribution will overlay the late-time, already decayed PJ emission. In the NR phase, the afterglow peak emission has moved to radio frequencies, so the rebrightening from the RJ is only expected in late-time radio afterglows. We predict the late-time radio rebrightening (RRB) of GRB 030329 and discuss the long-term radio observations for GRBs 970508 and 980703. The observation of RRBs will be particularly important, because of their straightforward implication of the existence of double-sided jets in GRBs.

2 EMISSION FROM THE RECEIVING JET

Consider two collimated jets that are ejected in opposite directions from the central engine of a GRB. For an observed GRB, the observer should be almost on the jet axis. We assume the two jets have the same characteristics, such as the half-opening angle $\theta_j$, the initial Lorentz factor $\Gamma_j$, and the kinetic energy $E_j/2$ (or with equivalent isotropic energy $E_{iso} = 2E_j/\theta_j^2$). Since most afterglow fits seem to favor a uniform medium (Panaitescu & Kumar 2002), we assume a constant particle density $n$ for both jets.

In the above assumptions, we have taken the standard view of a homogeneous jet with a sharp edge (Rhoads 1999). Recently, a structured jet model (Meszéros et al. 1998; Dai & Gou 2001; Rossi et al. 2002; Zhang & Mészáros 2002) was proposed, but detailed fits to afterglow data are still needed to determine whether it is consistent with current observations (Granot & Kumar 2003). Since the standard jet model has been successful in data fits (e.g., Panaitescu & Kumar 2002), we only discuss homogeneous jets here.

2.1 Jet Dynamics

We first discuss the PJ, the evolution of which can be divided into four phases:

1. Initially, $\Gamma \gg 1/\theta_j$; that is, the transverse size of the jet is larger than that of the causally connected region, therefore the jet evolves as if it were a conical section of a spherical relativistic blast wave. The PJ first undergoes a coasting phase, with $\Gamma = \Gamma_j$.

2. After the jet-induced shock sweeps up enough medium, the jet’s kinetic energy is mostly transferred into the shocked medium, and the jet begins to decelerate significantly. This occurs at the deceleration radius $r_d = [3E_{iso}/(4\pi n\Gamma_j^2 m_e c^2)]^{1/3}$ at an observer time $t_d = t_j/(2\Gamma_j c)$, where the relation $dr \approx 2\Gamma^2 c dt$ has been taken to be due to superluminal motion. At
the deceleration phase, the dynamics can be well described by
the Blandford & McKee (1976) self-similar solution, in which
\[ \Gamma \propto r^{3/2} \propto t^{-1/2} \]

As the jet continues to decelerate, the Lorentz factor drops to \( \Gamma \) at a time \( t_r = t_p (\Gamma_0 \theta)^{3/2} \), corresponding to a radius \( r_j = r_0 (\Gamma_0 \theta)^{2/3} \). From that time on, the transverse size of causally connected regions exceeds that of the jet, therefore the sphere approximation breaks down and the jet starts expanding sideways. The dynamical evolution in this stage depends on the degree of lateral expansion. If the lateral velocity in the comoving frame equals the local sound speed, the jet will spread quickly, with the opening angle increasing and \( \Gamma \) dropping exponentially (Rhoads 1999). At this stage, the radius hardly increases and can be regarded as a constant \( r \approx r_j \), and \( \Gamma \propto t^{-1/2} \).

Finally, the jet goes into NR phase, with \( \Gamma \approx 1 \) at \( t_{NR} = t_j / \theta_j \), where the evolution can be well described by the Sedov-Taylor solution \( \beta \propto r^{-3/2} \propto t^{-3/5} \), with \( \beta = (1 - 1/\Gamma^2)^{1/2} \).

In summary, the evolution is

- **coasting**: \[ t < t_d, \quad \Gamma = \Gamma_0, \quad r \propto t \]
- **sphere**: \[ t_d < t < t_j, \quad \Gamma \propto t^{3/5}, \quad r \propto t^{1/4} \]
- **spreading**: \[ t_j < t < t_{NR}, \quad \Gamma \propto t^{-1/2}, \quad r \approx r_j \]
- **NR**: \[ t > t_{NR}, \quad \beta \propto t^{-3/5} (\Gamma \approx 1), \quad r \propto t^{3/5} \]

Using the above simplified dynamical relations, the NR time and radius, defined as the point at which \( \Gamma = 1 \), can be calculated as

\[ t_{NR} = \frac{1}{2 \Gamma^3} \left( \frac{3E_p}{2 \pi m_e c^4 n} \right)^{1/3}, \quad r_{NR} \approx r_j = \left( \frac{3E_p}{2 \pi m_e c^4 n} \right)^{1/3} \cdot (2) \]

These are independent of \( \Gamma_0 \) and \( \theta_j \). With typical values \( E_p = 10^{45} E_{51} \text{ ergs} \) and \( n = 1 \text{ cm}^{-3} \) (e.g., Frail et al. 2001; Panaitescu & Kumar 2001), we have

\[ t_{NR} = 130 \left( \frac{E_{51}}{n} \right)^{1/3} \text{ days}. \cdot (3) \]

Note that this \( t_{NR} \) refers to the PJ.

As for the RJ, it also transits into NR phase at a radius \( r_{NR} \). However, due to the light-travel time, the observer time epoch is delayed by a time \( 2r_{NR}/c \), so the observed NR time for the RJ is

\[ t_{NR}^{RJ} = t_{NR} + \frac{2r_{NR}}{c} = 5t_{NR}. \cdot (4) \]

which is 5 times that of the PJ.²

There are uncertainties about the lateral spreading of jets, and it might be that little spreading occurs, as shown in some numerical simulations (e.g., Cannizzo et al. 2004). If we assume the extreme case, that the lateral velocity is zero, then the jet remains geometrically conical and continues to evolve as if it were a conical section of a spherical relativistic blast wave after \( \Gamma < 1/\theta_j \). In this case, the NR time for the PJ is \( t_{NR} = (1/2)(3E_p/(2\pi m_e c^4 \theta_j ^3))^{1/3} = 610(E_{51}/n\theta_j ^3)^{1/3} \) days, with \( \theta_j = \theta_j /10^{-1} \), and the corresponding radius is \( r_{NR} = 2c t_{NR} \). Therefore, for the RJ, the NR time is \( t_{NR}^{RJ} = t_{NR} + 2r_{NR}/c = 5t_{NR} \).

² It can be shown that the factor of 5 is also valid for the wind case, in which the external density decreases as the square of the distance from the source (Dai & Lu 1998; Chevalier & Li 2000).
might be gradual, and the jet edge might not be sharp; therefore, both of these can smooth the RRB feature on the plot.

3. Observations

3.1. GRB 970508 and GRB 980703

As discussed above, if a GRB were to be monitored in radio bands over a long period of time (e.g., a few years), the RRB might be detectable. So far, there are two GRBs that have been reported in the literature and involve radio monitoring longer than 1 yr: GRB 970508 and GRB 980703 (Frail et al. 2000, 2003; Berger et al. 2001).

Frail et al. (2000) report an extensive monitoring of the radio afterglow of GRB 970508, lasting 450 days after the burst. In the data analysis, they found that the spectral and temporal radio behavior indicate a transition to NR expansion at $t_{nR} \approx 100$ days; therefore, we should expect the RRB to be around day 500. However, this would unfortunately have occurred after the last observation of this burst, so we might have missed this phenomenon.

GRB 980703 was monitored for an even longer period of time, up to $\sim 10^3$ days, as shown in Fig. 1 of Frail et al. (2003). Two obvious flattenings appear in the radio light curves: while the late-time transition to a constant flux is thought to be the host galaxy contribution, the earlier flattening at $\sim 40$ days is attributed to the transition into NR expansion (Berger et al. 2001). Modeling the $G$ evolution has also inferred a similar value of $t_{nR} = 30 \pm 50$ days (Frail et al. 2003). Therefore, the expected RRB should arise at $\sim 200$ days, and then after another time interval of 200 days (around 400 days from the burst), the radio flux should decline to a value similar to just before the RRB. At first glance, the radio light curves of Figure 1 of Frail et al. (2003), which are somewhat more extensive at 8.5 and 4.8 GHz, seem to show only decays, without any rebrightening. However, we notice that there are no observational data collected between 210 and $\sim 400$ days; therefore, the RRB may have been missed once again, because of a lack of observations.

3.2. Prediction for GRB 030329

GRB 030329 is the nearest cosmological GRB ($z = 0.1685$) and has a bright afterglow at all wavelengths. Berger et al. (2003) have reported its bright radio afterglow up to $\sim 70$ days after the burst. Since no radio flattening (due to the transition to NR evolution) appears yet, we ought to calculate $t_{nR}$ using $E_{51}/h$ derived from available data.

The early breaks ($\sim 0.5$ days) in the R band (Price et al. 2003) and X-ray (Tiengo et al. 2004) light curves infer a small jet opening angle leading to a small jet-corrected energy release in GRB 030329, which is more than 1 order of magnitude below the average value of 200 days; therefore, the RRB may arise at $\sim 200$ days. At first glance, the radio light curves of Figure 1 of Frail et al. (2000) report an extensive monitoring of the radio afterglow of GRB 970508, lasting 450 days after the burst. In this work we suggest that RRBs are common for GRBs with double-sided jets and are the natural consequence of the transition of RJ to NR evolution. If we assume the same properties for both PJ and RJ, and also for the ambient medium on both sides, the RRB should arise at a time $t_{nR} = 5_{-0.5}^{+1.0} E_{51}/h^{1/3}$ yr after the burst, with a flux comparable to that at the time $t_{nR}$. Assuming the same temporal slope for the late time, an extrapolation of the available radio light curves (Berger et al. 2003) to $\sim 120$ days gives a flux of $\sim 0.6$ mJy at 15 GHz, or $\sim 0.3$ mJy at 44 GHz. A dense monitoring campaign around 1.7 yr after GRB 030329 outburst is required to obtain a well-observed RRB profile.

4. Summary and Discussion

In this work we suggest that RRBs are common for GRBs with double-sided jets and are the natural consequence of the transition of RJ to NR evolution. If we assume the same properties for both PJ and RJ, and also for the ambient medium on both sides, the RRB should arise at a time $t_{nR} = 5_{-0.8}^{+1.0} E_{51}/h^{1/3}$ yr after the burst, with a flux comparable to that at the time $t_{nR}$. Assuming the same temporal slope for the late time, an extrapolation of the available radio light curves (Berger et al. 2003) to $\sim 120$ days gives a flux of $\sim 0.6$ mJy at 15 GHz, or $\sim 0.3$ mJy at 44 GHz. A dense monitoring campaign around 1.7 yr after GRB 030329 outburst is required to obtain a well-observed RRB profile.

Although the X-ray afterglow shows flattening at around day 37 (Tiengo et al. 2004), we believe this is not relevant to the NR transition of the radio jet, because there is no simultaneous radio flattening (Berger et al. 2003), and also because it conflicts with the still superluminal expansion in the radio angular size measurement (Taylor et al. 2004). The X-ray flattening may need other explanations, e.g., an IC component or NR transition for the narrow jet in the two-component model (Berger et al. 2003).
Unfortunately, no radio data were collected when RRBs occurred for GRB 970508 and GRB 980703, the two longest observed GRBs so far. We suppose the RRB of GRB 030329 to be around 1.7 yr after the burst, with \( \sim 0.6 \) mJy at 15 GHz (\( \sim 0.3 \) mJy at 44 GHz), and we encourage a dense monitoring campaign during that time. It should be noted that for a weakly spreading jet, the RRB might be more delayed, since \( r_{\text{NR}} \) is much larger (see the end of § 2.1).

There has been growing evidence for collimated jets in GRBs over the past several years, coming mainly from observations of achromatic breaks in the afterglow light curves (e.g., Kulkarni et al. 1999; Stanek et al. 1999). However, there are still other explanations for the light curve breaks; for example, the transition from the relativistic to the NR phase of the blast wave after a few days, due to a highly dense medium (Dai & Lu 1999; Wang et al. 2000); the effects of IC scattering, flattening, or steepening of the light curves (Wei & Lu 2000); a sudden drop in the external density (Kumar & Panaitescu 2000); or a break in the energy spectrum of radiating electrons (Li & Chevalier 2001). On the other hand, although a black hole–disk system with twin jets is generally assumed in GRBs, magnetized, rapidly rotating neutron stars remain contenders, and an off-center dipole could lead to a one-sided jet. Since RRBs are only associated with collimated, double-sided, relativistic outflows, the detection of RRBs would provide straightforward evidence of double-sided jets in GRBs and prove black hole–disk system formation in the cores of progenitors. This makes RRB observations significantly important.

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