IL NUOVO CIMENTO Vol. 28 C, N. 3 Maggio-Giugno 2005
DOI 10.1393/ncc/i2005-10080-x

Gamma-ray burst afterglows with cylindrical jet geometry(*)

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(ricevuto il 23 Maggio 2005; pubblicato online il 3 Ottobre 2005)

Summary. — The cylindrical jet model of Gamma-ray Burst (GRB) afterglows has been suggested. The idea of massive stars as progenitors of GRBs is widely accepted. Within this notion, a density boundary probably exists along the way of the relativistic jet. We find that a cylindrical jet interacting with this boundary can explain the optical lightcurves of GRB 970508 and GRB 000301C. On the other hand, the observing prospect for cylindrical jet model for short bursts is shown to be promising. Thus in the near future, the cylindrical jet model can be tested by the coming data.

PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.
PACS `98.38.Fs` – Jets, outflows, and bipolar flows.
PACS `01.30.Cc` – Conference proceedings.

1. – Introduction

Observations of relativistic jets from many astrophysical systems involving accretion disks show that the jets are cylindrical in geometry, *i.e.* they maintain nearly constant cross sections on large scales. This gives rise to the idea of cylindrical jets from GRBs [1].

On the other hand, many numerical results show that GRB jets are conical initially. However, after some kinds of collimation process (*e.g.* magnetic forces from the central engines; external pressure) the jet becomes cylindrical asymptotically (see [2, 3]).

2. – Model

We need a unified dynamical model to describe the evolution of cylindrical jets. For an adiabatic jet, the evolution of Lorentz factor (γ), jet radius (R), and swept-up mass

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(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.

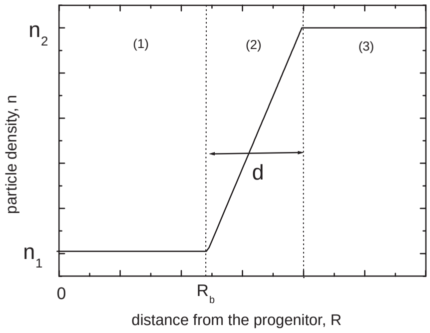

Fig. 1. – The assumed density profile of a long-duration GRB system.

(m) accords to [1,4,5]:

$$\frac{\mathrm{d}\gamma}{\mathrm{d}m} = -\frac{\gamma^2 - 1}{M_{\mathrm{ej}} + 2\gamma m}; \qquad \frac{\mathrm{d}m}{\mathrm{d}R} = \pi a^2 n m_p; \qquad \frac{\mathrm{d}R}{\mathrm{d}t} = \frac{\beta c}{1 - \beta \cos \Theta}, \tag{1}$$

where M_{ej} is the ejected mass from the progenitor, n the density of hydrogen atoms in the circumburst medium, t the observer's time, $\beta = \sqrt{1 - 1/\gamma^2}$ and Θ the viewing angle. The observed synchrotron flux density is given by [6]

$$S_\nu = \frac{1}{\gamma^3(1 - \beta\cos\Theta)^3}\frac{1}{4\pi D_L^2} P'[\gamma(1 - \beta\cos\Theta)\nu], \tag{2}$$

where D_L is the luminosity distance and $P'(\nu')$ is the synchrotron power (for details, see [7]). We assume that: 1) the magnetic energy density and electron energy density is a fraction ε_B and ε_e of the internal energy, respectively; 2) the electrons accelerated by the shocks follow a broken power law distribution. To simplify the calculations, only contributions from synchrotron radiations from forward shocks are considered. Relaxing this assumption will not affect much in the late afterglow lightcurves presented here.

3. – Signature of a density boundary in the circumburst medium

Collapse of massive stars are widely believed to trigger the majority of long GRBs. The circumburst medium is thus affected by the strong stellar winds. When the mass of swept-up gas is comparable to the wind mass, materials will accumulate at a certain radius, forming an overdense shell [8,9]. A cylindrical jet, after pushing through a low-density bubble around a massive star, meets the density boundary with the ISM. This may produce an early bump seen in several GRB afterglows [10].

To illustrate the effects of a density boundary towards the afterglow evolution, we consider a simple density profile shown in fig. 1. Region (2) corresponds to the region of nearly constant density in the simulated density profiles, as appeared in refs. [8,9].

GRB 970508 was the second burst accompanied by optical afterglow observations. The optical afterglow flux for this burst remained constant for ∼ 1 d and increases ∼ 1.3 mag in the next ∼ 1 d, followed by a PL decay in late times. Figure 2 shows the observed R-band lightcurve of GRB 970508 and GRB 000301C and the predictions by our model.

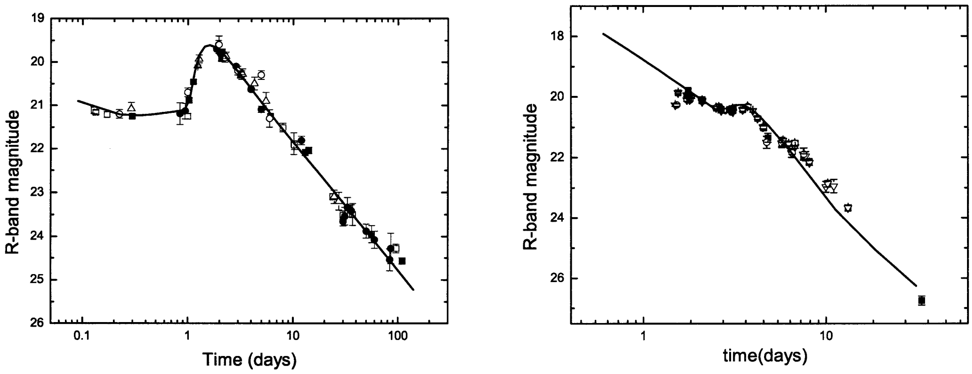

Fig. 2. – Comparison of our model (solid curve) with optical afterglows of GRB 970508 (left) and GRB 000301C (right).

We employ a simple density profile and reproduce the first bump appeared in the optical data of GRB 000301C. The two bumps may result from more complicated density fluctuations. Table I shows that parameter values we used in calculating the model lightcurves. These values are consistent with those of pressure-driven bubbles created by strong stellar winds of very massive stars at the end of their lives [8, 11].

4. – Cylindrical jets from short GRBs

Current afterglow observations limit mainly to long GRBs (an exception is GRB 040924, which we will discuss later). Short GRBs are still poorly understood due to afterglow data shortage. For conical jets, it has been argued that, due to the low fluence of short GRBs, the observation prospect for detecting the optical afterglow is unpromising. However, it was found that if the jets are cylindrical, optical afterglows can be seen even if the bursts occur in a low density (*e.g.*, $n \sim 10^{-3}\,\mathrm{cm}^{-3}$) medium [12].

One of the unresolved questions in the cylindrical jet model is: Does the jets turn from conical to cylindrical after (case A) or before (case B) the gamma-ray emitting phase? In case (A), the gamma-ray emission angle is just the opening angle of the jets θ_0; observers with viewing angles within θ_0 receive the same gamma-ray fluence as an on-axis observer. But when the jets become cylindrical, the beaming angle equals $1/\gamma$. Observers outside the cone of $1/\gamma$ will receive much dimmer afterglow light than those on the jet axis. In case (B), an observer receiving the GRB must lie in the cone of $1/\gamma$. Thus for this case, there is no off-axis afterglow. Note that in sect. **3**, we implicitly assume

Table I. – *The parameters used in our model fits to optical afterglow lightcurves of GRB 970508 and GRB 000301C.*

GRB	R_b (pc)	n_1 (cm^{-3})	n_2 (cm^{-3})	d (pc)	M_ej ($10^{-8}M_\odot$)	p	ξ_B^2	ξ_e	Θ (rad)
970508	22	1.6	100	5	26	2.0	10^{-4}	0.1	0.006
000301C	2.95	10	60	1.5	0.19	2.5	10^{-3}	0.01	0.01

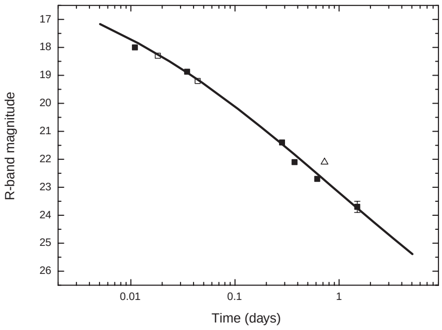

Fig. 3. – Model fit with optical afterglow of GRB 040924 (case B). The parameters used: $M_{\rm ej} = 10^{-9} M_{\odot}$, $p = 2.3$, $\gamma_0 = 100$, $\varepsilon_e = 0.1$, $\varepsilon_B = 4 \times 10^{-5}$, $n = 1\,{\rm cm}^{-3}$, $a = 2 \times 10^{15}\,{\rm cm}$.

case (B) in our calculations to fit the afterglow data.

It is found that current observations of short GRBs are consistent with the cylindrical jet model as long as $\Theta \geq 0.02$ (case A) or $a \geq 10^{15}\,{\rm cm}$ (case B) [12]. Recently, a short burst GRB 040924 was detected and found to be located at $z = 0.859$ [13]. It has been satisfactorily explained by conical jet model [14]. We found that the data is also consistent with the cylindrical jet model (fig. 3). Our poor knowledge on the values of a and whether case (A) or (B) is more realistic prevent us from drawing stronger constraints on the circumburst environments. Nevertheless, more observations on short bursts will certainly bring us towards a better understanding of these mysterious events.

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