

## Two-component jet models of gamma-ray burst sources<sup>(\*)</sup>

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**Summary.** — Recent observational and theoretical studies have raised the possibility that the collimated outflows in gamma-ray burst (GRB) sources have two distinct components: a narrow, highly relativistic outflow, from which the  $\gamma$ -ray emission originates, and a wider, moderately relativistic surrounding flow. Using a simple synchrotron emission model, we calculate the R-band afterglow lightcurves expected in this scenario and derive algebraic expressions for the flux ratios of the emission from the two jet components at the main transition times in the lightcurve. We apply this scheme to the interpretation of the afterglow lightcurves in GRB and X-ray flash sources and show that it may significantly alleviate the radiative efficiency requirements in the internal shock model of GRBs.

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### 1. – Introduction

Recently, the possibility that at least some GRB outflows consist of two distinct components has been raised in the literature. On the observational side, this possibility was first invoked to interpret the afterglow lightcurves of certain sources. It was proposed that the  $\gamma$ -rays and early (shorter-wavelength) afterglow emission can be attributed to a narrow, ultrarelativistic outflow component and that the late (longer-wavelength) afterglow emission originates in a separate wide component that is only mildly relativistic [1,2]. A two-component model was also suggested as an explanation of the observed rebrightening of the X-ray flash (XRF) source XRF 030723 [3] as well as of the apparent peak-energy distribution of GRBs and XRFs [4] and of the origin of the blueshifted optical absorption features in the spectrum of the GRB 021004 afterglow [5].

The possibility of a two-component outflow in GRB sources has been independently indicated by theoretical considerations. In this contribution we focus on two distinct

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examples. 1) Hydromagnetically driven jet originating from a neutron star or a neutron-rich accretion disk that forms in the collapse of a massive star [6]. In this case the neutrons decouple at a moderate Lorentz factor while the protons continue to be accelerated and collimated by the electromagnetic forces, giving rise to a narrow, highly relativistic proton component and a wider and slower neutron component. 2) Collapsar jet breakout. In this model, the outflow produced when a GRB jet emerges from the progenitor star's envelope is predicted to consist of a highly relativistic core and a moderately relativistic surrounding cocoon [7]. For more details on the work reported here, see [8].

## 2. – Model afterglow lightcurves

A simple jet structure is assumed in this work, consisting of a narrow and initially faster component and a wide and initially slower component. The two components are assumed uniform with sharp edges, and noninteracting. We only consider the case of a uniform external medium (of number density  $n = n_0 \text{ cm}^{-3}$ ) and neglect the possible effects of radiative losses on the hydrodynamic evolution. The narrow and fast jet component has an initial Lorentz factor  $\eta_n (\gtrsim 10^2)$ , a half-opening angle  $\theta_{j,n}$ , and a kinetic energy (at the beginning of the afterglow phase)  $E_n$ , while the wide and slow jet component is characterized by  $\eta_w (\sim 10)$ ,  $\theta_{j,w} (> \theta_{j,n})$ , and  $E_w$ . In what follows, the subscripts “n” and “w” denote the narrow and wide jet components, respectively. The ratio of the true energy  $E$  and the isotropic-equivalent energy  $E_{\text{iso}}$  is given by the beaming factor  $f_b = 1 - \cos \theta_j \approx \theta_j^2/2$ . The true energy ratio  $E_w/E_n$  is  $\gtrsim 2$  in the hydromagnetic model but only  $\sim 0.1$  in the collapsar jet-breakout model.

In the two-component jet picture, GRB sources correspond to “on axis” ( $\theta_{\text{obs}} \lesssim \theta_n$ ) observation angles. In this case the behavior of the lightcurve changes at  $t_{\text{dec}}$ , the characteristic flow deceleration time, and at  $t_{\text{jet}}$ , the jet break time (when the Lorentz factor decreases to  $\sim 1/\theta_j$ ). For typical parameters  $t_{\text{dec,w}}/t_{\text{dec,n}} \gg 1$ : the deceleration of the narrow component would generally remain unobservable, but a bump (representing emission from the slow component) might show up in the decaying lightcurve of the fast component at  $t \approx t_{\text{dec,w}}$  if  $F_{\nu,w} > F_{\nu,n}$  at that time. The lightcurve from either of the two components steepens significantly after the respective jet break time is passed.

For typical parameters the observed R-band optical frequency is smaller than the cooling frequencies but larger than the typical synchrotron frequency for both jet components. In this frequency domain the flux ratios for an on-axis observer at the main lightcurve transition times are (denoting the power law index of the electron energy distribution by  $p$ ):

$$(1) \quad f_1 \equiv \frac{F_{\nu,w}}{F_{\nu,n}} \Big|_{t=t_{\text{dec,w}}}^{\nu < \nu_c} \simeq \begin{cases} \left( \frac{E_{\text{iso,w}}}{E_{\text{iso,n}}} \right)^{(p+3)/4}, & t_{\text{dec,w}} < t_{\text{jet,n}}, \\ \left( \frac{E_{\text{iso,w}}}{E_{\text{iso,n}}} \right)^{(p+3)/3} (\eta_w \theta_{j,n})^{-2(p+3)/3}, & t_{\text{dec,w}} > t_{\text{jet,n}}, \end{cases}$$

$$(2) \quad \hat{f}_1 \equiv \frac{F_{\nu,w}(t_{\text{jet,w}})}{F_{\nu,n}(t_{\text{jet,n}})} \Big|_{\nu < \nu_c} = \left( \frac{E_w}{E_n} \right) \left( \frac{\theta_{j,w}}{\theta_{j,n}} \right)^{-2p},$$

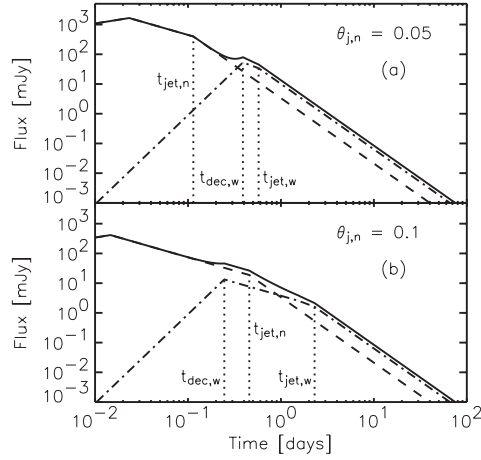


Fig. 1. – R-band afterglow lightcurve from a two-component jet. The contribution of the narrow component, wide component, and their sum is represented by the dashed, dash-dotted, and solid curves, respectively. The total outflow energy is assumed to be constant,  $E_w + E_n = 10^{51}$  ergs. The top and bottom panels correspond to  $\theta_{j,n} = 0.05$  and  $0.1$ , respectively. The other parameters are the same for both panels:  $\eta_n = 200$ ,  $\eta_w = 15$ ,  $E_w = 2 E_n$ ,  $\theta_{j,w} = 2 \theta_{j,n}$ ,  $n_0 = 1$ ,  $\epsilon_e = 0.1$ ,  $\epsilon_B = 0.01$ ,  $p = 2.2$ , and  $D_{L,28} = 1$ .

and

$$(3) \quad \tilde{f}_1 \equiv \frac{F_{\nu,w}}{F_{\nu,n}} \Big|_{t=t_{\text{jet},w}}^{\nu < \nu_c} = \left( \frac{E_w}{E_n} \right)^{(p+3)/3}.$$

The flux ratio  $f_1$  depends on whether  $t_{\text{dec},w}$  is larger or smaller than  $t_{\text{jet},n}$  because the time evolution of the jet Lorentz factor changes at the jet break time.

### 3. – Applications

**3.1. GRB afterglows and source energetics.** – For characteristic parameter values,  $t_{\text{dec},w}$  nearly coincides with  $t_{\text{jet},n}$ . This gives rise to the possibility that the jet break in the narrow outflow component remains unobservable if the flux ratio  $f_1$  (eq. (1)) is close to 1. The latter condition is typically satisfied if  $E_w \gtrsim E_n$ , which also implies that the wide component dominates the overall optical emission (see eq. (3)). The outflow would then be mistakenly interpreted as a single-component jet with an opening half-angle  $\theta_{j,w}$ , resulting in  $E_\gamma$  being *overestimated* by a factor  $\sim (\theta_{j,w}/\theta_{j,n})^2$ . Correspondingly, the inferred kinetic-to-radiative energy conversion efficiency of the narrow outflow component,  $\mathcal{E}_n \equiv E_\gamma/(E_\gamma + E_n)$ , would be overestimated, since it is determined by the ratio  $E_\gamma/E_n$ , which is overestimated by the factor  $(E_n/E_w)(\theta_{j,w}/\theta_{j,n})^2 = E_{\text{iso},n}/E_{\text{iso},w}$  if  $E \approx E_w$ . Thus, to have a reduction in the required efficiency,  $E_w/E_n$  must satisfy

$$(4) \quad 1 < E_w/E_n < (\theta_{j,w}/\theta_{j,n})^2.$$

The condition  $E_w/E_n > 1$  implies that the wide component dominates the afterglow emission at late times, whereas the requirement  $E_{\text{iso},n}/E_{\text{iso},w} > 1$  implies that the narrow

component dominates at early times. A two-component outflow with  $E_w/E_n > 1$  arises naturally in the (initially) neutron-rich, hydromagnetically accelerated jet scenario.

As the wide component gradually takes over from the narrow component to become the dominant contributor to the flux, the lightcurve exhibits a concave “flattening” (if  $t_{\text{dec,w}} > t_{\text{jet,n}}$ ; fig. 1a) or a convex “bump” (if  $t_{\text{dec,w}} < t_{\text{jet,n}}$ ; fig. 1b) of duration  $\Delta t \sim t$ . The presence of this feature may be hard to discern in practice because of insufficiently dense time coverage or the interference of other factors (the emission from the reverse shock, ambient density inhomogeneities, refreshed shocks, etc.) that could cause a similar behavior. Nonetheless, there are already several potential candidates for this feature among observed afterglows (*e.g.*, GRB 970508, GRB 021004, GRB 030329).

It is, however, worth noting that GRB 021004 and GRB 030329 exhibited variability of the late afterglow, and that it has been suggested that all these events may have a similar physical origin — such as a variable injection at the source [9]. Interestingly, a refreshed-shock scenario of this type is a natural feature of the hydromagnetic, initially neutron-rich jet model of [6]. In this picture, the decoupled neutrons that constitute the wide outflow component decay into protons on a distance scale  $\gtrsim R_\beta = 4 \times 10^{14}(\eta_w/15)$  cm, which is likely larger than the scale over which many of the shell collisions invoked in the internal shock model for GRBs take place. The faster neutron shells thus move to the front and are the first to decelerate after they decay into protons; subsequent shells will catch up with them and give rise to a repeatedly re-energized shock, with the energy injection possibly tapering off as the slowest shells finally arrive at the front-shock location.

**3.2. XRF afterglows and source energetics.** – XRFs are high-energy transients that strongly resemble GRBs except that their peak energies fall in the X-ray, rather than the  $\gamma$ -ray, spectral regime. One attractive interpretation of these sources is that they represent essentially uniform GRB jets that are observed outside the jet half-opening angle [10]. The association with GRBs is supported by the detection of afterglow emission in several XRF sources. In the context of a two-component outflow model with  $E_w > E_n$  one can identify XRFs with GRB outflows observed at  $\theta_{\text{obs}} > \theta_{\text{j,n}}$  (but with  $\theta_{\text{obs}}$  likely  $< \theta_{\text{j,w}}$ ). In this picture the wide component would dominate the overall afterglow emission, although the narrow component might appear as a bump in the late optical lightcurve around  $t_{\theta,\text{n}}$  (when  $\gamma_{\text{n}} \simeq 1/\theta_{\text{obs}}$ ). XRFs can be given an alternative interpretation in the context of the collapsar jet-breakout model, in which  $E_w \ll E_n$  [7], although in the case of a source like XRF 020903 in which a long-lasting afterglow was detected this interpretation may be problematic [8].

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