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GRB afterglows: Deep Newtonian phase and its application(*)

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Summary. — Gamma-ray burst afterglows have been observed for months or even years in a few cases. It is worth noting that at such late stages, the remnants should have entered the deep Newtonian phase, during which the majority of shock-accelerated electrons will no longer be highly relativistic. To calculate the afterglows, we must assume that the electrons obey a power law distribution according to their kinetic energy, not simply the Lorentz factor.

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1. – Introduction

Gamma-ray bursts (GRBs) have been recognized as the most relativistic phenomena in the Universe. In 1997, Wijers *et al.*once discussed GRB afterglows of the non-relativistic phase [1]. However, for quite a long period, many authors were obviously beclouded by the energetics of GRBs and emission in the non-relativistic phase was generally omitted. In 1998, Huang *et al.*stressed the importance of the Newtonian phase for the first time [2]. In fact, the Lorentz factor of GRB blastwave evolves as $\gamma \approx (200 - 400)E_{51}^{1/8} n_0^{-1/8} t_s^{-3/8}$ in the ultra-relativistic phase. It is clear that the shock will no longer be ultra-relativistic within tens of days. Today, the importance of non-relativistic phase has been realized by more and more authors [3-12]. For example, in the famous case of GRB 030329, the transition to the non-relativistic regime is believed to be detected, since its X-ray and radio afterglow light curves flattened achromatically at $t \sim 40$–50 day [11, 12].

Recently it was further noted that GRB afterglows may enter the deep Newtonion phase typically in a few months [13], when the minimum Lorentz factor of shock-accelerated electrons ($\gamma_{\mathrm{e,min}} \sim \xi_{\mathrm{e}}(\gamma - 1)m_{\mathrm{p}}/m_{\mathrm{e}}$) becomes less than a few. At this stage,

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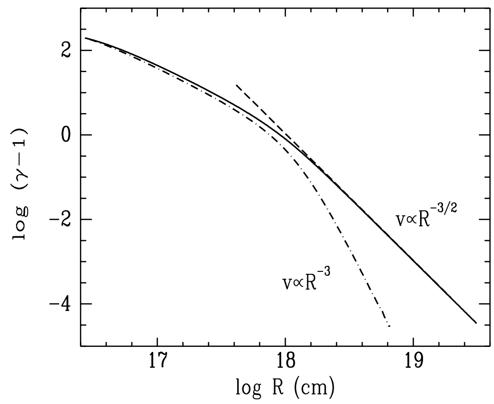

Fig. 1. – Evolution of the bulk Lorentz factor (γ) *vs.* radius for an isotropic fireball [15]. The dashed line illustrates the famous Sedov solution for a Newtonian fireball. The solid line is plot according to Huang *et al.*'s generical dynamical model, which is correct in both the relativistic and the Newtonian phases [14]. The dash-dotted line shows the result of an older dynamical model, which is not correct in the Newtonian phase.

most electrons will cease to be ultra-relativistic and their distribution function needs to be reconsidered [13].

2. – Model

To describe the deceleration of GRB ejecta, we use the refined generic dynamical model proposed by Huang *et al.* [14], which is mainly characterized by

$$\frac{\mathrm{d}\gamma}{\mathrm{d}m} = -\frac{\gamma^2 - 1}{M_{\mathrm{ej}} + \epsilon m + 2(1-\epsilon)\gamma m}. \tag{1}$$

Figure 1 shows clearly that this equation is applicable in both the ultra-relativistic phase and the Newtonian phase. Detailed description concerning the overall dynamical evolution of isotropic fireballs as well as collimated jets can be found in Huang *et al.* [14,16,17].

Shock-accelerated electrons are usually assumed to distribute as $\mathrm{d}N'_{\mathrm{e}}/\mathrm{d}\gamma_{\mathrm{e}} \propto \gamma_{\mathrm{e}}^{-p}$. However, in the deep Newtonian phase, most electrons are non-relativistic. To calculate afterglows, the distribution function now needs to be revised as [13]

$$\mathrm{d}N'_{\mathrm{e}}/\mathrm{d}\gamma_{\mathrm{e}} \propto (\gamma_{\mathrm{e}} - 1)^{-p}. \tag{2}$$

Optical afterglows can then be calculated conveniently by integrating synchrotron emission from those electrons with Lorentz factors above a critical value ($\gamma_{\mathrm{e,syn}}$) [13].

Detailed numerical results for isotropic fireballs and highly collimated conical or cylindrical jets have been presented by Huang and Cheng [13]. Here we show some exemplar results in fig 2. Figure 2a illustrates optical afterglows from isotropic fireballs. Note that the deep Newtonian phase typically begins at about 10^7 s. The light curves steepen slightly after that. Our results are consistent with analytical solutions. On the contrary, afterglow light curves of conical jets (fig. 2b) flatten in the deep Newtonian phase, which is also consistent with analytical solutions.

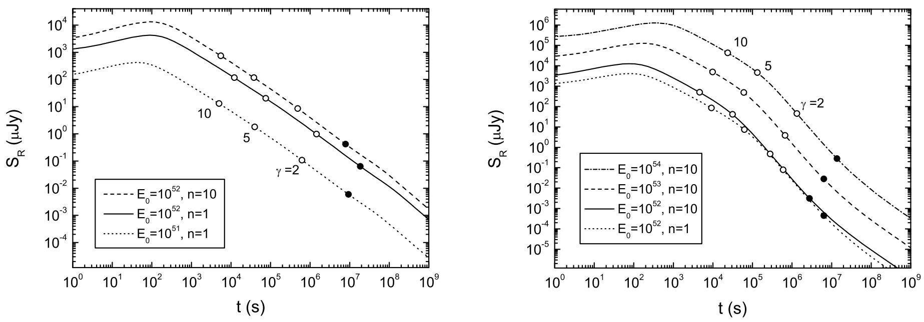

Fig. 2. – R-band optical afterglows from isotropic fireballs (**a**, left panel) and conical jets (**b**, right panel) [13]. The black dot on each light curve indicates the moment when $\gamma_{\mathrm{e,min}} = \gamma_{\mathrm{e,syn}} \equiv 5$, and open circles mark the time when the bulk Lorentz factor $\gamma = 2$, 5 and 10, respectively.

3. – Application

It has been shown clearly that GRB ejecta enters the deep Newtonian phase typically in about 3 months. Afterglows in the deep Newtonian phase are thus very important, especially in the following three cases. Case 1, late afterglows. Optical afterglows from some GRBs have been detected for more than six months. Radio afterglows are detectable even three years later. The deep Newtonian phase is unavoidable when such observations are to be accounted for. Case 2, GRBs with a dense medium. For some GRBs, the density of circum-burst medium may be as large as 10^3 cm^{-3}, or even 10^6 cm^{-3} in some rare cases. The GRB ejecta will then decelerate very rapidly and may enter the deep Newtonian phase in less than 20 days. Case 3, fireballs with relatively small initial Lorentz factor. This includes failed GRBs and the two-component jet model of GRBs, which will be discussed in more details below.

Failed GRBs [18], or dirty fireballs as named by Dermer *et al.* [19], are relativistic fireballs with initial Lorentz factor $\gamma_0 \ll 100 - 1000$. They cannot produce normal GRBs, but may give birth to X-ray flashes and contribute to orphan afterglows. The simple discovery of orphan afterglows then does not necessarily mean that GRBs are highly

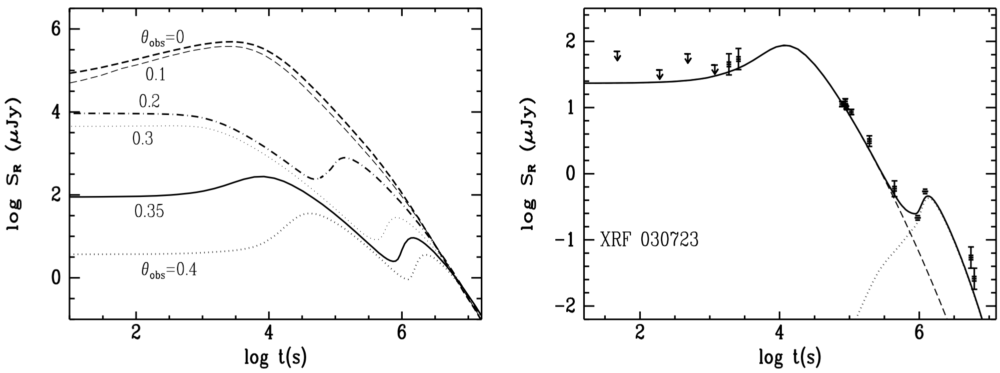

Fig. 3. – Effects of the viewing angle on the afterglow from a two-component jet (**a**, left panel), and its fit to the optical afterglow of XRF 030723 (**b**, right panel) [23].

collimated [18], although this was once regarded as a hopeful method for measuring the beaming angle of GRBs [20, 21]. To judge whether an orphan afterglow comes from a failed GRB or a jetted but off-axis GRB, Huang *et al.* suggested that the most important thing is to monitor the orphan for a relatively long period [18]. Obviously, the calculation of afterglows in the deep Newtonian phase is necessary in such studies.

Recently it was proposed that some GRB jets may have two components: a central narrow ultra-relativistic outflow and an outer, wider, mildly relativistic ejecta [22, 23]. This two-component jet model can potentially give a unified description for GRBs and X-ray flashes [23]: if our line of sight is within the narrow component, a normal GRB will be observed; On the contrary, if the line of sight is outside the narrow component but within the wide component, an X-ray flash will be witnessed. In both cases, long-lasting afterglows can be detected. In such a model, since the outer ejecta is midly relativistic at the beginning, radiation in the deep Newtonian phase will be inevitably involved in calculating its afterglows. Afterglow behaviors of two-component jets have been studied detailedly by Huang *et al.* [23]. Here, as an example, we illustrates the effects of the viewing angle on the optical light curves in fig 3a. Figure 3b shows clearly that the two-component jet model can give a perfect explanation for the observed optical afterglows from the X-ray flash XRF 030723.

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