IL NUOVO CIMENTO Vol. 28 C, N. 4-5 Luglio-Ottobre 2005
DOI 10.1393/ncc/i2005-10093-5

Testing density profile in Gamma-Ray Burst(*)

A. Galli and L. Piro
IASF, INAF-CNR - Via del Fosso del Cavaliere, I-00113 Rome, Italy

(ricevuto il 23 Maggio 2005; pubblicato online il 9 Settembre 2005)

Summary. — The GRB afterglow evolution strictly depends on the properties of the external medium in which the fireball expands. Studying afterglow emission, we tried to constrain the nature of the medium. We studied afterglow evolution either in a homogeneous external medium and in a wind ejected by the GRB progenitor (probably a Wolf-Rayet Star) during the final phases of its life. We also extended this analysis to a medium characterized by a discontinuous density profile. Such discontinuities can be due to a variable activity of wind emission by massive star progenitors or to the interaction of the wind with the external medium. We numerically integrated the equations of the Standard Fireball Model, and applied it to GRB011121 and XRF011030, two events detected by the BeppoSAX satellite. These two objects show a late X-ray burst (reburst) at about few hundred seconds after the main pulse. We tried to explain the reburst as the onset of the external shock and we found that it can be successfully explained under this assumption if the fireball is expanding in a thick shell.

PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 97.10.Me – Mass loss and stellar winds.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The delayed emission (afterglow) observed in Gamma-Ray Bursts (GRB) is strongly influenced by the medium in which the fireball expands. Studying the afterglow evolution is possible to constrain the nature of the medium and finally the kind of progenitor. Observations and the theoretical developments of the latest years suggest that GRBs are produced by extremely massive stars losing mass during their evolution, due to their stellar wind. In fact, Fe emission or absorption lines were observed in the spectrum of the main event and in those of the X-ray afterglow of several events. These lines can be produced only if the medium around the central engine has high density and is rich in metals, like that observed in the surroundings of very massive stars. These objects have a fast evolution and during their life they remain near the region of formation. This is in agreement with the fact that in several cases the GRB counterparts are localized near the

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

centre of the host galaxy. Finally, the optical light curves of some GRB afterglows are similar to those of a supernova; the most evident cases are GRB980425 [1], GRB030329 [2, 3] and GRB031203 [4].

Besides, on the theoretical point of view, the collapsar model predicts that the star loses its external layers to allow the relativistic jet to penetrate it and then to expand outside [5-7]. If GRB progenitors are massive stars we expect that a large number of events should manifest a wind density profile. On the other hand, the studies of afterglow show that for the most of events the external environment has a density profile consistent with a uniform interstellar medium [8-10]. In this paper we present new evidence of two events that show a wind profile.

2. – Observational data

We analysed two events observed with BeppoSAX: GRB011121 and XRF011130. Afterglow observations of XRF011030 were performed by CHANDRA and the public data were analyzed by our group [11]. For GRB011121 we had indications that the fireball expands in a wind density profile [12]. Instead, for XRF011030 there was not yet indication about the medium. The light curves of these two bursts are characterized also by the presence of an unusual revival of emission in the X-ray range, called reburst, which occurs after the prompt emission phase. In the October burst the reburst took place about 1280 s after the main event, while in the November burst it appeared about 240 s later.

3. – Fireball with a thin shell: the Standard Fireball Model and models with discontinuous density profile

At first we tried to reconcile the observations with the theoretical expectations and to explain the reburst using the prescriptions of the Fireball Model [13], which is based on a fireball with a thin shell expanding with spherical symmetry into a homogeneous medium or into a wind. We remember that a shell is considered thin if $\Delta < (E/nm_pc^2)^{1/3}\Gamma_0^{-8/3}$, where Δ is the thickness of the shell and Γ_0 is its initial Lorentz factor [14]. To generalize and to apply this model we performed the numerical integration of its equations. We use the Standard Fireball Model to study XRF011030 and GRB011121 in the cases of both a uniform interstellar medium and wind. We found that the calculated light curves do not accommodate the data. Then we explored the possibility of a discontinuous density profile. This idea is supported by the fact that the duration of wind emission is finite. Besides, several simulations [15] show that if the pressure of the external environment is larger than the pressure associated with the shock front of the wind bubble, then the expansion of the bubble is stopped before the total evolution of the progenitor. In this case a final shock occurs and a region of approximately uniform density is formed. For typical values of parameters this region is located at a distance of the order of 0.1–1 parsec, that is the scale of distance of interest. Thus the external medium could be formed by two regions, the first one with a wind density profile and the second one of constant density, higher with respect to the first one (see fig. 1 of [15]). We expect that when the fireball interacts with the discontinuity between the two regions a major number of photons is produced and the flux increase significantly explaining the reburst. However the increase of the flux corresponding to this discontinuity is not large enough to account for the observed reburst in GRB011121 and XRF01130. This is mostly due to the fact that when the observational frequency ν_{obs} becomes smaller than the cooling frequency ν_c the emission is not affected anymore by the density profile in which the fireball expands [13].

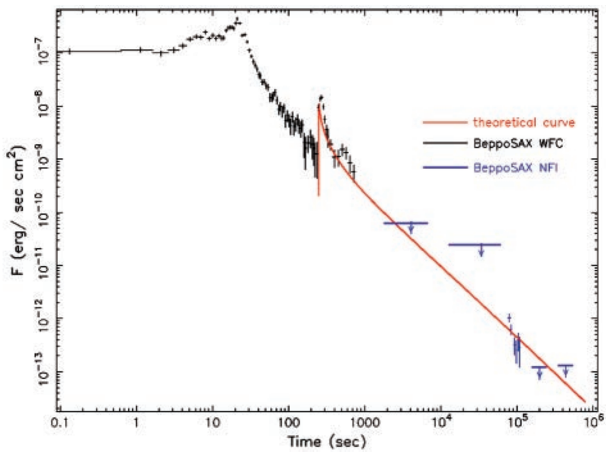

Fig. 1. – Light curve of GRB011121 in a wind assuming that the shell is thick. The parameters are $E_{53} = 0.28$, $\Gamma_0 = 130$, $A_* = 0.003$, $\varepsilon_e = 0.01$, $\varepsilon_B = 0.5$, $p = 2.5$ and $t_0 = 250$ s.

4. – A fireball with a thick shell

In this case the reverse shock is still crossing the shell when the latter reaches the deceleration radius. Therefore the external shock keeps being energized for a longer time and the origin of time is shifted at the instant of the reburst [12]. Adopting a fireball with a thick shell we found that GRB011121 and XRF011030 environments can be described by a wind density profile (fig. 1 and fig. 2). In the case of XRF011030 we have only the X data, and it is not sufficient to constrain all the parameters of the model, namely the energy of the fireball E_{53} in unity of 10^{53}erg, the initial value of the Lorentz factor of the relativistic shell Γ_0, the spectral index of the electron's population p, the fraction of energy going in electrons ε_e and the fraction of energy going in magnetic field ε_B. We

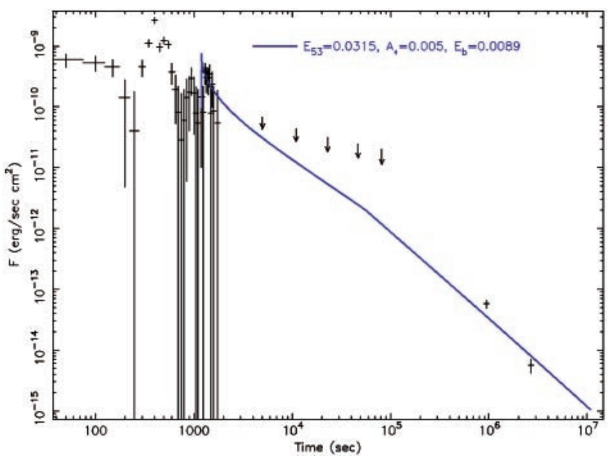

Fig. 2. – Light curve of XRF011030 in a wind assuming that the shell is thick. The parameters are $E_{53} = 0.0315$, $\Gamma_0 = 45$, $A_* = 0.005$, $\varepsilon_e = 0.03$, $\varepsilon_B = 0.0089$, $p = 2.2$ and $t_0 = 1200$ s.

determined E_{53} from the fluence value assuming that all the kinetic energy is converted in γ-rays and that the redshift is $z = 1$. Γ_0 has been constrained because it, and also E_{53}, determine the shape of the reburst emission. Finally, from our spectral analysis we found $p = 2.2$. not well constrained. For ε_e we adopted the typical value $\varepsilon_e = 0.01$, while ε_B and A_* were constrained in order to explain the break. To this aim we required that the cooling frequency ν_c, which increases as $T^{1/2}$ for a fireball expanding in a wind, becomes greater than the observational frequency ν_{obs} between 10^4 and 10^6 s. In fact, when $\nu_c < \nu_{obs}$ the flux goes as $\nu^{-(p-1)/2}$, while when $\nu_c > \nu_{obs}$ it goes as $\nu^{-p/2}$. Thus we found a family of solutions. In fig. 2 we show one of these solutions which fit the data.

In the case of XRF011030 the reburst spectrum is softer with respect to that of the prompt and is consistent with the spectrum of the afterglow about 1 day after the burst. Similar outcomes were found by Piro *et al.* [12] for GRB011121. This leads to interpret the reburst as the beginning of afterglow.

We thus conclude that XRF011030 environment is well described by a wind density profile.

5. – Conclusions

From our analysis we found that the BeppoSAX data of XRF011030 and GRB011121 can be described only by a fireball with a thick shell. Under this assumption the onset of the afterglow needs to be shifted to the reburst time. In this case the calculated light curve well reproduce this reburst and the late afterglow emission. This suggests that the reburst represents the onset of the afterglow. We also show that both of the events can be explained if the fireball expands into a wind. In the case of GRB011121 this confirms the claim by Piro *et al.* [12]. For XRF011030 we claim for a new case in which the event light curve is explained by a wind profile environment.

Since now the research was focalized on normal bursts the next step is to search for reburst in the sample of all X-ray flash observed with BeppoSAX. The launch of SWIFT [16] satellite will also help to this hunt, because this satellite is suited to observe the afterglow emission starting from seconds after the burst to about 1 day. This will advantage the observation of reburst and details into light curves.

REFERENCES

[1] Galama T. J., Vreeswijk P. M. *et al.*, *Nature*, **395** (1998) 670.
[2] Stanek K. Z. *et al.*, *ApJ*, **591** (2003) L17.
[3] Hjorth J. *et al.*, *ApJ*, **599** (2003) 123.
[4] Malesani D. *et al.*, *ApJ*, **609L** (2004) 5.
[5] Woosley S., *ApJ*, **405** (1993) 273.
[6] Ramirez-Ruiz E. *et al.*, *MNRAS*, **337** (2002) 1349.
[7] Waxman and Meszaros, *ApJ*, **584** (2003) 390.
[8] Panaitescu A. and Kumar P., *ApJ*, **554** (2001) 667.
[9] Panaitescu A. and Kumar P., *ApJ*, **571** (2002) 779.
[10] Yost S. A. *et al.*, *ApJ*, **597** (2003) 459.
[11] D'Alessio V. and Piro L., 2005, in these proceedings.
[12] Piro L. *et al.*, *ApJ*, **623** (2005) 314P; astro-ph/0412589.
[13] Panaitescu A. and Kumar P., *ApJ*, **543** (2000) 66.
[14] Sari R. and Piran T., *ApJ*, **520** (1999) 641.
[15] Chevalier R. A., Li Z. and Fransson C., *ApJ*, **606** (2004) 369.
[16] `http://swift.gsfc.nasa.gov/docs/swift/swiftsc.html`