GRB 050315: A STEP TOWARD THE UNIQUENESS OF THE OVERALL GRB STRUCTURE

REMO RUFFINI1,2, MARIA GRAZIA BERNARDINI1,2, CARLO LUCIANO BIANCO1,2, PASCAL CHARDONNET1,3, FEDERICO FRASCHELLI1,2, ROBERTO GUIDA1,2, SHE-SHENG XUE1,2

Abstract

Using the Swift data of GRB 050315, we progress on the uniqueness of our theoretically predicted Gamma-Ray Burst (GRB) structure as composed by a proper-GRB (P-GRB), emitted at the transparency of an electron-positron plasma with suitable baryon loading, and an afterglow comprising the so called “prompt emission” as due to external shocks. Thanks to the Swift observations, the P-GRB is identified and for the first time we can theoretically fit detailed light curves for selected energy bands on a continuous time scale ranging over 10²⁶ seconds. The theoretically predicted instantaneous spectral distribution over the entire afterglow is presented, confirming a clear hard-to-soft behavior encompassing, continuously, the “prompt emission” all the way to the latest phases of the afterglow.

Subject headings: gamma rays: bursts — gamma rays: observations — radiation mechanisms: thermal

1. Introduction

GRB 050315 (Vaughan et al. 2006) has been triggered and located by the BAT instrument (Barthelmy et al. 2004, Barthelmy et al. 2005) on board of the Swift satellite (Gehrels et al. 2004), at 2005-March-15 20:59:42 UT (Parsons et al. 2005). The narrow field instrument XRT (Burrows et al. 2004, 2005), began observations ∼ 80 s after the BAT trigger, one of the earliest XRT observations yet made, and continued to detect the source for ~ 10 days (Vaughan et al. 2006). The spectroscopic redshift has been found to be = 1.949 (Kelson & Berger 2005).

We present here the results of the fit of the Swift data of this source in 5 energy bands in the framework of our theoretical model (see Ruffini et al. 2001a, 2001b, 2002, 2005a, Bianco & Ruffini 2004, 2005a, b, c and references therein), pointing out a new step toward the uniqueness of the explanation of the overall GRB structure. In section 1, we recall the essential features of our theoretical model; in section 2, we fit the GRB 050315 observations by both the BAT and XRT instruments; in section 3, we present the instantaneous spectra for selected values of the detector arrival time ranging from 60 s (i.e. during the so called “prompt emission”) all the way to 3.0 × 10⁷ s (i.e. the latest afterglow phases); in section 4, we present the conclusions.

2. Our Theoretical Model

A major difference between our theoretical model and the ones in the current literature (see e.g. Piran 2004, and references therein) is that what is usually called “prompt emission” in our case coincides with the peak of the afterglow for selected values of the detector arrival time ranging from 60 s (i.e. during the so called “prompt emission”) all the way to 3.0 × 10⁷ s (i.e. the latest afterglow phases); in section 5, we present the conclusions.

References

Bernardini et al. 2005, Piran et al. 2003, Piran et al. 1993, Grimsrud & Wasserman 1998, Ruffini et al. 1993, 2000, 2001, 2006, 2007; Piran et al. 2003, and references therein. The first afterglow regime corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time, corresponding to a substantially constant Lorentz gamma factor of the accelerated baryons. The second regime consists of the bolometric luminosity peak, corresponding to the “knee” in the decreasing phase of the baryonic Lorentz gamma factor. The third regime corresponds to a bolometric luminosity decreasing with arrival time, corresponding to the late deceleration of the Lorentz gamma factor. In some sources the P-GRB is under the observability threshold. In Ruffini et al. 2001b, we have chosen as a prototype the source GRB 991216 which clearly shows the existence of the P-GRB and the three regimes of the afterglow. Unfortunately, data from BATSE existed only up to 36 s, and data from R-XTE and Chandra only after 3500 s, leaving our theoretical predictions in the whole range between 36 s and 3500 s without the support of the comparison with observational data. Nevertheless, both the relative intensity of the P-GRB to the peak of the afterglow in such source, as well as their corresponding temporal lag, were theoretically predicted within a few percent (see Fig. 11 in Ruffini et al. 2003).
the peak, including the "prompt emission", all the way to the latest phases without any gap in the observational data.

3. THE FIT OF THE OBSERVATIONS

The best fit of the observational data leads to a total energy of the black hole dyadosphere, generating the $e^\pm$ plasma, $E_{dyo} = 1.46 \times 10^{53}$ erg (the observational Swift $E_{iso}$ is $> 2.62 \times 10^{52}$ erg, see Vaughan et al. 2006), so that the plasma is created between the radii $r_1 = 5.88 \times 10^6$ cm and $r_2 = 1.74 \times 10^8$ cm with an initial temperature $T = 2.05 MeV$ and a total number of pairs $N_{e^-} = 7.93 \times 10^{57}$. The second parameter of the theory, the amount $M_B$ of baryonic matter in the plasma, is found to be such that $B = M_B c^2 / E_{dyo} = 4.55 \times 10^{-3}$. The transparency point and the P-GRB emission occurs then with an initial Lorentz gamma factor of the accelerated baryons $\gamma_0 = 217.81$ at a distance $r = 1.32 \times 10^{14}$ cm from the black hole.

3.1. The BAT data

In Fig. 1 we represent our theoretical fit of the BAT observations in the three energy channels 15–25 keV, 25–50 keV and 50–100 keV and in the whole 15–350 keV energy band.

In our model the GRB emission starts at the transparency point when the P-GRB is emitted; this instant of time is often different from the moment in which the satellite instrument triggers, due to the fact that sometimes the P-GRB is under the instrumental noise threshold or comparable with it. In order to compare our theoretical predictions with the observations, it is important to estimate and take into account this time shift.

In the present case of GRB 050315 it has been observed (see Vaughan et al. 2004) a possible precursor before the trigger. Such a precursor is indeed in agreement with our theoretically predicted P-GRB, both in its isotropic energy emitted (which we theoretically predict to be $E_{P-GRB} = 1.98 \times 10^{51}$ erg) and its temporal separation from the peak of the afterglow (which we theoretically predicted to be $\Delta t_p = 51$ s). In Fig. 1, the blue line shows our theoretical prediction for the P-GRB in agreement with the observations.

After the P-GRB emission, all the observed radiation is produced by the interaction of the expanding baryonic shell with the interstellar medium. In order to reproduce the complex time variability of the light curve of the prompt emission as well as of the afterglow, we describe the ISM filamentary structure, for simplicity, as a sequence of overdense spherical regions separated by much less dense regions. Such overdense regions are nonhomogeneously filled, leading to an effective emitting area $A_{eff}$ determined by the dimensionless parameter $R = A_{eff} / A_{vis}$, where $A_{vis}$ is the expanding baryonic shell visible area (see Ruffini et al. 2004A, 2005A, for details). Clearly, in order to describe any detailed structure of...
the time variability an authentic three dimensional representation of the ISM structure would be needed. However, this finer description would not change the substantial agreement of the model with the observational data. Anyway, in the “prompt emission” phase, the small angular size of the source visible area due to the relativistic beaming makes such a spherical approximation an excellent one (see also [Ruffini et al. 2002] for details).

The structure of the “prompt emission” has been reproduced assuming three over dense spherical ISM regions with width $\Delta$ and density contrast $\Delta n/n$: we chose for the first region, at $r = 4.15 \times 10^{16}$ cm, $\Delta = 1.5 \times 10^{15}$ cm and $\Delta n/n = 5.17$, for the second region, at $r = 4.53 \times 10^{16}$ cm, $\Delta = 7.0 \times 10^{14}$ cm and $\Delta n/n = 36.0$ and for the third region, at $r = 5.62 \times 10^{16}$ cm, $\Delta = 5.0 \times 10^{14}$ cm and $\Delta n/n = 85.4$. The ISM mean density during this phase is $\langle n_{\text{ISM}} \rangle = 0.81$ particles/cm$^3$ and $\langle R \rangle = 1.4 \times 10^{-2}$. With this choice of the density mask we obtain agreement with the observed light curve, as shown in Fig. 1. A small discrepancy occurs in coincidence with the last peak: this is due to the fact that at this stage the source visible area due to the relativistic beaming is comparable with the size of the clouds, therefore the spherical shell approximation should be duly modified by a detailed analysis of a full three-dimensional treatment of the ISM filamentary structure. Such a topic is currently under investigation (see also [Ruffini et al. 2002] for details). Fig. 1 shows also the theoretical fit of the light curves in the three BAT energy channels in which the GRB has been detected (15–25 keV in Fig. 1a, 25–50 keV in Fig. 1b, 50–100 keV in Fig. 1c).

3.2. The XRT data

The same analysis can be applied to explain the features of the XRT light curve in the afterglow phase. It has been recently pointed out [Nousek et al. 2006] that almost all the GRBs observed by Swift show a “canonical behavior”: an initial very steep decay followed by a shallow decay and finally a steeper decay. In order to explain these features many different approaches have been proposed [Mészáros 2006, Nousek et al. 2006, Panaitescu et al. 2006, Zhang et al. 2006]. In our treatment these behaviors are automatically described by the same mechanism responsible for the prompt emission described above: the baryonic shell expands in an ISM region, between $r = 9.00 \times 10^{16}$ cm and $r = 5.50 \times 10^{18}$ cm, which is significantly at lower density $\langle n_{\text{ISM}} \rangle = 4.76 \times 10^{-4}$ particles/cm$^3$, $\langle R \rangle = 7.0 \times 10^{-6}$) then the one corresponding to the prompt emission, and this produces a slower decrease of the velocity of the baryons with a consequent longer duration of the afterglow emission. The initial steep decay of the observed flux is due to the smaller number of collisions with the ISM. In Fig. 2 is represented our theoretical fit of the XRT data, together with the theoretically computed 15–350 keV light curve of Fig. 1 (without the BAT observational data to not overwhelm the picture too much).

What is impressive is that no different scenarios need to be advocated in order to explain the features of the light curves: both the prompt and the afterglow emission are just due to the thermal radiation in the comoving frame produced by inelastic collisions with the ISM duly boosted by the relativistic transformations over the EQTSs.

4. THE INSTANTANEOUS SPECTRUM

In addition to the the luminosity in fixed energy bands we can derive also the instantaneous photon number spectrum $N(E)$ starting from the same assumptions. In Fig. 3 are shown samples of time-resolved spectra for eight different values of the arrival time (colored curves). The hard to soft behavior is confirmed.
nature of the spectrum during the prompt and the afterglow phases: the observed energy distribution changes from hard to soft, with continuity, from the “prompt emission” all the way to the latest phases of the afterglow.

5. CONCLUSIONS

Before the Swift data, our model could not be directly fully tested. With GRB 050315, for the first time, we have obtained a good match between the observational data and our predicted intensities, in 5 energy bands, with continuous light curves near the beginning of the GRB event, including the “prompt emission”, all the way to the latest phases of the afterglow. This certainly supports our model and opens a new phase of using it to identify the astrophysical scenario underlying the GRB phenomena. In particular:

1. We have demonstrated that the “prompt emission” is not necessarily due to the prolonged activity of an “inner engine”, but corresponds to the emission at the peak of the afterglow.

2. We have a clear theoretical prediction on the total energy emitted in the P-GRB \( E_{P-GRB} = 1.98 \times 10^{51} \) erg and its temporal separation from the peak of the afterglow \( \Delta t \sim 51 \) s. To understand the physics of the inner engine more observational and theoretical attention should be given to the analysis of the P-GRB.

3. We have uniquely identified the basic parameters characterizing the GRB energetics: the total energy of the black hole dyadosphere \( \dot{E}_{\text{dyas}} = 1.46 \times 10^{53} \) erg and the baryon loading parameter \( B = 4.55 \times 10^{-3} \).

4. The “canonical behavior” in almost all the GRB observed by Swift, showing an initial very steep decay followed by a shallow decay and finally a steeper decay, as well as the time structure of the “prompt emission” have been related to the fluctuations of the ISM density and of the \( R \) parameter.

5. The theoretically predicted instantaneous photon number spectrum shows a very clear hard-to-soft behavior continuously and smoothly changing from the “prompt emission” all the way to the latest afterglow phases.

Only the first afterglow regime we theoretically predicted, which corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time, preceding the “prompt emission”, still remains to be checked by direct observations. We hope in the near future to find an intense enough source, observed by the Swift satellite, to verify this still untested theoretical prediction.

As a byproduct of the results presented in this Letter, we can explain one of the long lasting unanswered puzzles of GRBs: the light curves in the “prompt emission” show very strong temporal substructures, while they are remarkably smooth in the latest afterglow phases. The explanation follows from three factors: 1) the value of the Lorentz \( \gamma \) factor, 2) the EQTS structure and 3) the coincidence of the “prompt emission” with the peak of the afterglow. For \( \gamma \sim 200 \), at the peak of the afterglow, the diameter of the EQTS visible area due to relativistic beaming is small compared to the typical size of an ISM cloud. Consequently, any small inhomogeneity in such a cloud produces a marked variation in the GRB light curve. On the other hand, for \( \gamma \rightarrow 1 \), in the latest afterglow phases, the diameter of the EQTS visible area is much bigger than the typical size of an ISM cloud. Therefore, the observed light curve is a superposition of the contribution of many different clouds and inhomogeneities, which produces on average a much smoother light curve (details in Ruffini et al. 2002, 2003).

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