ON THE STRUCTURES IN THE AFTERGLOW PEAK EMISSION OF GAMMA-RAY BURSTS

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ABSTRACT

Using GRB 991216 as a prototype, we show that the intensity substructures observed in what is generally called the “prompt emission” in gamma-ray bursts (GRBs) do originate in the collision between the accelerated baryonic matter pulse with inhomogeneities in the interstellar medium (ISM). The initial phase of such process occurs at a Lorentz factor $\gamma \sim 310$. The crossing of ISM inhomogeneities of sizes $\Delta R \sim 10^{15}$ cm occurs in a detector arrival time interval of $\sim 0.4$ s, implying an apparent superluminal behavior of $\sim 10^{8}$c. The long-lasting debate between the validity of the external shock model versus the internal shock model for GRBs is solved in favor of the first.

Subject headings: black hole physics — gamma rays: bursts — gamma rays: observations — gamma rays: theory — ISM: clouds — ISM: structure

To reproduce the observed light curve of GRB 991216, we have adopted, as initial conditions (Ruffini et al. 2002a) at $t = 10^{-20}$ s $\sim$ 0 s, a spherical shell of electron-positron-neutral plasma lying between the radii $r_0 = 6.03 \times 10^5$ cm and $r_1 = 2.35 \times 10^6$ cm: the temperature of such a plasma is 2.2 MeV, the total energy $E_{\text{tot}} = 4.83 \times 10^{51}$ ergs, and the total number of pairs $N_{\text{ee}} \sim 1.99 \times 10^{38}$.

Such initial conditions follow from the electromagnetic black hole (EMBH) theory we have recently developed based on energy extraction from a black hole endowed with electromagnetic structure (Ruffini 1998; Preparata, Ruffini, & Xue 1998; Ruffini et al. 1999a, 1999b, 2000, 2001a, 2001b, 2001c, 2002a; Bianco, Ruffini, & Xue 2001), $r_0$ being the horizon radius, $r_1$ being the dyadosphere radius, and $E_{\text{sd}}$ coinciding with the dyadosphere energy $E_{\text{sd}}$. The above set of parameters is uniquely determined by the value of $E_{\text{sd}}$. The EMBH energy (Christodoulou & Ruffini 1971) is carried away by a plasma of electron-positron pairs created by the vacuum polarization process (Damour & Ruffini 1975) occurring during the gravitational collapse leading to the EMBH (Cherubini, Ruffini, & Vitagliano 2002; Ruffini & Vitagliano 2002). Such an optically thick electron-positron plasma self-propels itself outward reaching ultrarelativistic velocities (Ruffini et al. 1999a, 1999b), interacts with the remnant of the progenitor star, and by further expansion becomes optically thin (Ruffini et al. 2000). The physical reason for such an extraordinary process of self-acceleration, achieving in a tenth of a second in arrival time an increase in the Lorentz gamma factor from $\gamma = 1$ to $\gamma \sim 300$, has been shown to be critically dependent on $E_{\text{sd}}$, and on the amount of baryonic matter engulfed by the plasma in its expansion (see Ruffini et al. 1999a, 1999b, 2000). It is interesting that this process is extremely efficient even in the present case, regardless of the relatively slow random thermal motion of the 2.2 MeV $e^+e^-$ plasma (see Ruffini et al. 2002a). As the transparency condition is reached, a proper gamma-ray burst (P-GRB) is emitted as well as an extremely relativistic shell of accelerated baryonic matter (ABM). It is this ABM pulse that, interacting with the interstellar medium (ISM), gives origin to the afterglow (see Ruffini et al. 2001b, 2002a).

One of the most novel results of the EMBH model has been the identification of what is generally called the “prompt emission” (see, e.g., Piran 1999 and references therein) as an integral part of the afterglow: the extended afterglow peak emission (E-APE; Ruffini et al. 2001a, 2001b, 2002a). This result is clearly at variance with the models explaining the prompt emission with ad hoc mechanisms distinct from the afterglow process (see, e.g., Rees & Mészáros 1994, 1998, 2000; Mészáros & Rees 1997, 2001; Kobayashi, Piran, & Sari 1997; Kumar & Piran 2000; Mészáros 2002). The fact that the EMBH model, using GRB 991216 as a prototype, has allowed the computation of the temporal separation of the P-GRB and the E-APE to an accuracy of a few milliseconds and also to predict their relative intensities within a few percent can certainly be considered a major success of the model (see Ruffini et al. 2001a, 2001b, 2002a).

The aim of this Letter is to report a further extension of the EMBH model in order to identify the physical processes giving origin to the intensity variability observed in the E-APE on timescales as short as a fraction of a second (Fishman & Meegan 1995), which contrasts with the smoother emission in the last phases of the afterglow (see, e.g., Costa, Frontera, & Hjorth 2001).

In our former work on the EMBH model (Ruffini et al. 2001b, 2002a), we have assumed a homogeneous ISM with a density $n_{\text{ISM}} = \langle n_{\text{ISM}} \rangle = 1$ particle cm$^{-3}$ and we have also assumed that during the collision of the ABM pulse with the ISM the “fully radiative condition” applies. These assumptions have led to the theoretical prediction of the power-law index of the afterglow slope $n = -1.6$, in excellent agreement with the observational data $n = -1.616 \pm 0.067$ (Halpern et al. 2000). Our goal here is to show that the variability in the E-APE can indeed be traced back to inhomogeneities in the ISM. We again consider, as in the previous work, the case of an ABM pulse expanding with spherical symmetry (i.e., no beaming), and for simplicity we describe the ISM inhomogeneities as spherical shells concentric to the ABM pulse. Each shell has a selected density and a constant thickness $\Delta R = 1.0 \times 10^{15}$ cm.

We recall now the relation between the relativistic beaming angle and the arrival time of the emitted photon on the detector. The visible part of the ABM pulse spherical surface is con-
The arrival time interval has been chosen to encompass the E-APE emission, dashed lines are the boundaries of the ABM pulse visible area. Note the different scale on the two axes, indicating the very high EQTS “effective eccentricity.” The arrival time interval has been chosen to encompass the E-APE emission, occurring between ~15 and ~40 s (see Figs. 4 and 5 and Table 1).

strained by

$$\cos \vartheta \geq \frac{v}{c}, \quad (1)$$

where $\vartheta$ is the angle in the laboratory frame between the radial direction of each point on the ABM pulse surface and the line of sight and $v$ is the expansion speed (Ruffini et al. 2002b). This follows from the requirement that in the comoving frame the component of the photon momentum along the radial expansion velocity direction be positive, in order to escape. There exists then a maximum allowed $\vartheta$-value $\vartheta_{\text{max}}$ defined by $\cos \vartheta_{\text{max}} = v/c$ (see Fig. 1a).

Owing to the high value of the Lorentz $\gamma$ factor (~310) for the bulk motion of the ABM pulse, the spherical waves emitted from its external surface do appear extremely distorted to a distant observer. To show this, we need to express the photon arrival time at the detector $t_{\text{arr}}^d$ as a function of its emission time $t$ and angle $\vartheta$. We set $t = 0$ when the plasma starts to expand, so that $r(0) = r_0$. We then have (see Ruffini et al. 2002b)

$$t_{\text{arr}}^d = (1 + z) \left[ t - \left( \frac{\vartheta}{\cos \vartheta} + \frac{\vartheta_{\text{max}}}{c} \right) \right], \quad (2)$$

where $z$ is the redshift of the source. Then, in order to compute the arrival time of the emitted radiation, we must know all the previous values of the source velocity starting from $t = 0$. The great advantage of the EMBH model is that for the first time we have been able to obtain the precise values of the gamma Lorentz factor as a function of the radial coordinate or equivalently of the laboratory time (see Fig. 2). This allows us, for the first time, to evaluate equation (2) and correspondingly determine the surfaces that emit the photons detected at a fixed arrival time $t_{\text{arr}}^d$, which we will call in the following “equitemporal surfaces” (EQTSs). The profiles of such surfaces are reported in Figure 1b. We emphasize once again the direct connection between the evaluation of the EQTSs and the entire past history of the source.

We have created an ISM inhomogeneity “mask” (see Fig. 3 and Table 1) with the main criteria that the density inhomogeneities and their spatial distribution still fulfill $\langle n_{\text{ism}} \rangle = 1$ particle cm$^{-3}$.

The source luminosity in a detector arrival time $t_{\text{arr}}^d$ and per unit solid angle $d\Omega$ is given by (details in Ruffini et al. 2002b)

$$\frac{dE_{\text{arr}}}{dt_{\text{arr}}^d d\Omega} = \int_{\text{EQTS}} \frac{\Delta \xi}{4\pi} v \cos \Delta \vartheta \frac{dt}{dt_{\text{arr}}^d} d\Sigma, \quad (3)$$

where $\Delta \xi$ is the energy density released in the interaction of the ABM pulse with the ISM inhomogeneities measured in the comoving frame, $\Delta = \gamma[1 - (v/c) \cos \vartheta]$ is the Doppler factor, and $d\Sigma$ is the surface element of the EQTS at detector arrival time $t_{\text{arr}}^d$ on which the integration is performed. In the present case, the Doppler factor $\Delta$ in equation (3) enhances the apparent luminosity of the burst, as compared to the intrinsic luminosity.
TABLE 1
ISM Density Mask Parameters

| Peak | \( r \) \((\times 10^{10} \text{ cm})\) | \( \tau \) (s) | \( t' \) \((\times 10^8 \text{ s})\) | \( d' \) (cm) | \( \Delta t'_p \) (s) | \( d' \) (cm) | \( \gamma \) | Superluminal \( v \equiv \gamma r_h/c \) \((\times 10^5 \text{ s})\) |
|------|----------------|---------|----------------|---------|----------------|---------|-------|----------------|
| A    | 4.50           | 4.88    | 1.50           | 15.8    | 2.95 \times 10^4 | 0.400   | 303.8 | 9.5 |
| B    | 5.20           | 5.74    | 1.73           | 19.0    | 3.89 \times 10^4 | 0.622   | 265.4 | 9.1 |
| C    | 5.70           | 6.54    | 1.90           | 22.9    | 5.83 \times 10^4 | 1.13    | 200.5 | 8.3 |
| D    | 6.20           | 7.64    | 2.07           | 30.1    | 9.03 \times 10^4 | 5.16    | 139.9 | 6.9 |
| E    | 6.50           | 9.22    | 2.17           | 55.9    | 2.27 \times 10^3  | 10.2    | 57.23 | 3.9 |
| F    | 6.80           | 1.10    | 2.27           | 87.4    | 2.42 \times 10^3  | 10.6    | 56.24 | 2.6 |

Note.—For each ISM density peak represented in Fig. 3, we give the initial radius \( r \), the corresponding comoving time \( \tau \), laboratory time \( \tau' \), arrival time at the detector \( t'_p \), diameter of the ABM pulse visible area \( d' \), Lorentz factor \( \gamma \), and observed duration \( \Delta t'_p \) of the afterglow luminosity peaks generated by each density peak. In the last column, the apparent motion in the radial coordinate, evaluated in the arrival time at the detector, leads to an enormous superluminal behavior, up to \( 9.5 \times 10^5 c \).

The results are given in Figure 5. We obtain, in perfect agreement with the observations (see Fig. 4):

1. the theoretically computed intensity of the A, B, and C peaks as a function of the ISM inhomogeneities;
2. the fast rise and exponential decay shape for each peak;
3. a continuous and smooth emission between the peaks.

Interestingly, the signals from shells E and F, which have a density inhomogeneity comparable to A, are undetectable. The reason is due to a variety of relativistic effects and partly to the spreading in the arrival time, which for A, corresponding to \( \gamma = 303.8 \), is 0.4 s, while for E (F), corresponding to \( \gamma = 57.23 \) (56.24), is 10.2 s (10.6 s) (see Table 1 and Ruffini et al. 2002b).

In the case of D, the agreement with the arrival time is reached, but we do not obtain the double-peaked structure. The ABM pulse visible area diameter at the moment of interaction with the D shell is \( \sim 1.0 \times 10^{13} \) cm, equal to the extension of the ISM shell (see Table 1 and Ruffini et al. 2002b). Under these conditions, the concentric shell approximation does not hold anymore: the disagreement with the observations simply makes manifest the need for a more detailed description of the three-dimensional nature of the ISM cloud.

The physical reasons for these results can be simply summarized: we can distinguish two different regimes corresponding in the afterglow of GRB 991216, respectively, to \( \gamma > 150 \) and to \( \gamma < 150 \). For different sources, this value may be slightly different. In the E-APE region (\( \gamma > 150 \)), the GRB substructure intensities indeed correlate with the ISM inhomogeneities. In this limited region (see peaks A, B, and C), the Lorentz gamma factor of the ABM pulse ranges from \( \gamma \sim 304 \) to \( \gamma \sim 200 \). The boundary of the visible region is smaller than the thickness \( \Delta R \) of the inhomogeneities (see Fig. 1 and Table 1). Under this condition, the adopted spherical approximation is not only mathematically simpler but also fully jus-

![Fig. 4.—BATSE data on the E-APE of GRB 991216 (source: BATSE GRB light curves; see http://gammaray.msfc.nasa.gov/batse/grb/lightcurve) together with an enlargement of the P-GRB data (source: BATSE rapid burst response; see http://gammaray.msfc.nasa.gov/~kippen/batserb). For convenience, each E-APE peak has been labeled by a different uppercase Latin letter.](image-url)

![Fig. 5.—Source luminosity connected to the mask in Fig. 3 given as a function of the detector arrival time (solid “spiky” line), with the corresponding curve for the case of constant \( n_{\text{p}} = 1 \) particle cm\(^{-3}\) (smooth dashed line) and the BATSE noise level (horizontal dotted line). The “noise” observed in the theoretical curves is due to the discretization process adopted, described in Ruffini et al. (2002b), for the description of the angular spreading of the scattered radiation. For each fixed value of the laboratory time, we have summed 500 different contributions from different angles. The integration of the equation of motion of this system is performed in 22,314,500 contributions to be considered. An increase in the number of steps and in the precision of the numerical computation would lead to a smoother curve.](image-url)
curves are tomographic images of the density distributions of an idealized process occurring at a fixed, have reached activity of an unspecified “inner engine” (Sari & Piran 1997; see time variability has to be envisioned within the protracted ac-

Fenimore et al. 1999). In their opinion, the solution of the short shell interacting with the ambient material (“external shocks”; ally connected variations in a single, symmetric, relativistic

Dermer & Mitman 1999) on the other.

and collaborators (see, e.g., Sari & Piran 1997; Piran 1999, 2000, 2001) on one side and the one by Dermer and collabor-
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cy metric and making the computation more difficult. However,

do not need to perform this more complex analysis for

Panaitescu, A., & Mészáros, P. 1998, ApJ, 492, 683

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tified. The angular spreading is not strong enough to wipe out the signal from the inhomogeneity spike.

As we descend in the afterglow (γ < 150), the Lorentz gamma factor decreases markedly. In the borderline case of peak D, we have γ ∼ 140. For peaks E and F, we have γ ∼ 50, and, under these circumstances, the boundary of the visible region becomes much larger than the thickness ∆R of the in-

homogeneities (see Fig. 1 and Table 1). A three-dimensional description would be necessary, breaking the spherical sym-

metry and making the computation more difficult. However, the initial Lorentz factor of the ABM pulse γ ∼ 310 decreases very rapidly to γ ∼ 150 as soon as a fraction of a typical ISM cloud is engulfed (see Fig. 2 and Table 1). We conclude that the “tomography” is indeed effective but uniquely in the first ISM region close to the source and for GRBs with γ > 150.

One of the most striking features in our analysis is clearly represented by the fact that the inhomogeneities of a mask of radial dimension of the order of 1017 cm give rise to arrival time signals of the order of 20 s. This outstanding result implies an apparent “superluminal velocity” of ∼10c (see Table 1). The superluminal velocity here considered, first introduced in Ruffini et al. (2001a), refers to the motion along the line of sight. This effect is proportional to γ. It is much larger than the one usually considered in the literature, within the context of radio sources and microquasars (see, e.g., Mirabel & Rodriguez 1994), referring to the component of the velocity at right angles to the line of sight (see details in Ruffini et al. 2002b). This second effect is in fact proportional to γ (see Rees 1966). We recall that this superluminal velocity was the starting point for the enunciation of the relative spacetime transformation paradigm (Ruffini et al. 2001a), emphasizing the need of the knowledge of the entire past worldlines of the source. This need has been further clarified here in the determination of the EQTSs (see Fig. 1b), which indeed depend on an integral of the Lorentz gamma factor extended over the entire past worldlines of the source. In turn, therefore, the agreement between the observed structures and the theoretical predicted ones (see Figs. 4 and 5) is also an extremely stringent additional test on the values of the Lorentz gamma factor determined as a function of the radial coordinate within the EMBH theory (see Fig. 2).