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THEORETICAL INTERPRETATION OF THE LUMINOSITY AND SPECTRAL PROPERTIES OF GRB 031203

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ABSTRACT

The X-ray and gamma-ray observations of the source GRB 031203 by *INTEGRAL* are interpreted within our theoretical model. In addition to a complete spacetime parameterization of the GRB, we specifically assume that the afterglow emission originates from a thermal spectrum in the comoving frame of the expanding baryonic matter shell. By determining the two free parameters of the model and estimating the density and filamentary structure of the ISM, we reproduce the observed luminosity in the 20–200 keV energy band. As in previous sources, the prompt radiation is shown to coincide with the peak of the afterglow, and the luminosity substructure is shown to originate in the filamentary structure of the ISM. We predict a clear hard-to-soft behavior in the instantaneous spectra. The time-integrated spectrum over 20 s observed by *INTEGRAL* is well fitted. Despite the fact that this source has been considered "unusual," it appears to us to be a normal low-energy GRB.

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

1. INTRODUCTION

GRB 031203 was observed by IBIS on board the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) (Mereghetti & Göts 2003), as well as by *XMM-Newton* (Watson et al. 2004) and *Chandra* (Soderberg et al. 2004) in the 2–10 keV band and by the Very Large Telescope (Soderberg et al. 2004) in the radio band. It appears as a typical long burst (Sazonov et al. 2004) with a simple profile and a duration of ≈40 s. The burst fluence in the 20–200 keV band is $(2.0 \pm 0.4) \times 10^{-6}$ ergs cm^{-2} (Sazonov et al. 2004), and the measured redshift is $z = 0.106$ (Prochaska et al. 2004). We analyze in the following the gamma-ray signal received by *INTEGRAL*. The observations in other wavelengths, in analogy with the case of GRB 980425 (Pian et al. 2000; Ruffini et al. 2004b), could be related to the supernova event, as also suggested by Soderberg et al. (2004), and they will be examined elsewhere.

The *INTEGRAL* observations find a direct explanation in our theoretical model (see Ruffini et al. 2001a, 2001b, 2003, 2005a; Bianco & Ruffini 2005a, 2005b and references therein). We determine the values of the two free parameters that characterize our model: the total energy stored in the dyadosphere $E_{\rm dya}$ and the mass of the baryons left by the collapse $M_Bc^2 \equiv BE_{\rm dya}$. We follow the expansion of the pulse, composed by the electron-positron plasma initially created by the vacuum polarization process in the dyadosphere. The plasma propels itself outward and engulfs the baryonic remnant left over by the collapse of the progenitor star. As the pulse reaches transparency, the proper gamma-ray burst (P-GRB) is emitted (Ruffini et al. 1999, 2000, 2001b). The remaining accelerated baryons, interacting with the interstellar medium (ISM), produce the afterglow emission. The ISM is described by the two additional parameters of the theory: the average particle number density $\langle n_{\rm ISM}\rangle$ and the ratio $\langle \mathcal{R}\rangle$ between the effective emitting area and the total area of the pulse (Ruffini et al. 2004a), which take into account the ISM filamentary structure (Ruffini et al. 2005c).

We reproduce correctly in several GRBs and in this specific case (see, e.g., Fig. 1) the observed time variability of the prompt emission (see, e.g., Ruffini et al. 2002, 2003, 2005a and references therein). The radiation produced by the interaction of the accelerated baryons with the ISM agrees with observations for both intensity and time structure.

The progress in reproducing the X-ray and gamma-ray emission as originating from a thermal spectrum in the comoving frame of the burst (Ruffini et al. 2004a) leads to the characterization of the instantaneous spectral properties, which are shown to drift from hard to soft during the evolution of the system. The convolution of these instantaneous spectra over the observational timescale is in very good agreement with the observed power-law spectral shape.

As shown in previous cases (see Ruffini et al. 2003, 2005b), so for GRB 031203 as well, when using the correct equations of motion there is no need to introduce a collimated emission to fit the afterglow observations (see also Soderberg et al. 2004, who find this same conclusion starting from different considerations).

2. THE INITIAL CONDITIONS

The best fit of the observational data leads to a total energy of the dyadosphere $E_{\rm dya} = 1.85 \times 10^{50}$ ergs. Assuming a black hole mass $M = 10\ M_\odot$, we then have a black hole charge-to-mass ratio $\xi = 6.8 \times 10^{-3}$; the plasma is created between the radii $r_1 = 2.95 \times 10^6$ cm and $r_2 = 2.81 \times 10^7$ cm, with an initial temperature of 1.52 MeV and a total number of pairs $N_{e^+e^-} = 2.98 \times 10^{55}$. The amount of baryonic matter in the remnant is $B = 7.4 \times 10^{-3}$.

After the transparency point and the P-GRB emission, the initial Lorentz gamma factor of the accelerated baryons is $\gamma = 132.8$ at an arrival time at the detector $t_a^d = 8.14 \times 10^{-3}$ s and a distance from the black hole $r = 6.02 \times 10^{12}$ cm. This corresponds to an apparent superluminal velocity along the line of sight of $2.5 \times 10^4 c$. The ISM parameters are $\langle n_{\rm ISM}\rangle = 0.3$ particles cm^{-3} and $\langle \mathcal{R}\rangle = 7.81 \times 10^{-9}$.

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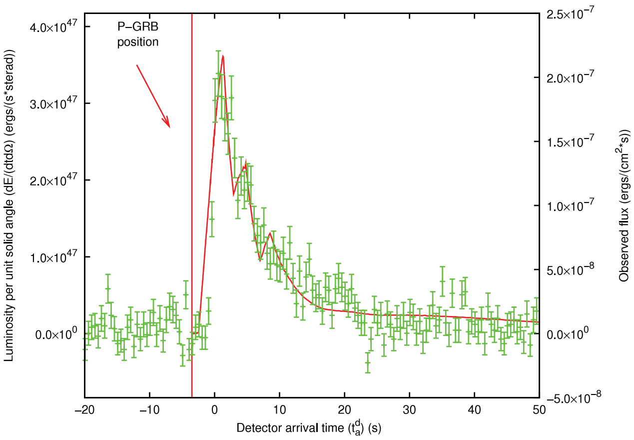

FIG. 1.—Theoretically simulated light curve of the GRB 031203 prompt emission in the 20–200 keV energy band (*solid red curve*) is compared with the observed data (*green points*) from Sazonov et al. (2004). The vertical red line indicates the time position of the P-GRB.

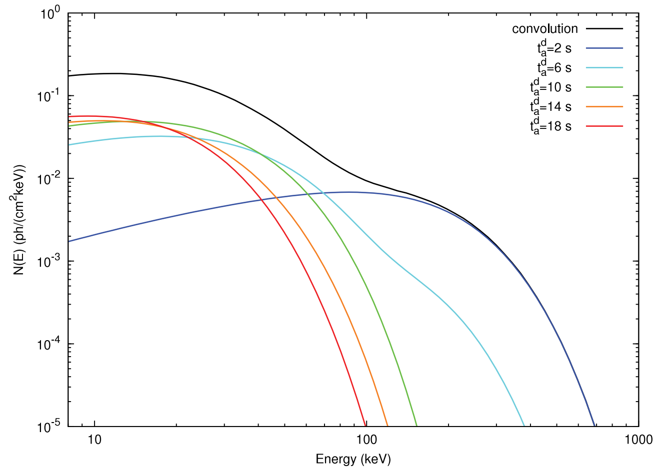

FIG. 2.—Five different theoretically predicted instantaneous photon number spectrums $N(E)$ for $t_a^d = 2$, 6, 10, 14, and 18 s are here represented (*colored curves*), together with their own temporal convolution (*black curve*). The shapes of the instantaneous spectra are not blackbodies, due to the spatial convolution over the EQTS (see text).

3. THE GRB LUMINOSITY IN FIXED ENERGY BANDS

The aim of our model is to derive from first principles both the luminosity in selected energy bands and the time-resolved/time-integrated spectra. The luminosity in selected energy bands is evaluated integrating over the equitemporal surfaces (EQTSs; see Bianco & Ruffini 2004, 2005a) the energy density released in the interaction of the accelerated baryons with the ISM measured in the comoving frame, duly boosted in the observer frame. The radiation viewed in the comoving frame of the accelerated baryonic matter is assumed to have a thermal spectrum and to be produced by the interaction of the ISM with the front of the expanding baryonic shell.

In order to evaluate the contributions in the band $[\nu_1, \nu_2]$, we have to multiply the bolometric luminosity with an effective weight $W(\nu_1, \nu_2, T_{\rm arr})$, where $T_{\rm arr}$ is the observed temperature; $W(\nu_1, \nu_2, T_{\rm arr})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at temperature $T_{\rm arr}$ to the total integral $aT_{\rm arr}^4$ (Ruffini et al. 2004a). The resulting expression for the emitted luminosity is

$$\frac{dE_\gamma^{[\nu_1,\nu_2]}}{dt_a^d\, d\Omega} = \int_{\rm EQTS} \frac{\Delta\epsilon}{4\pi} v \cos\vartheta\, \Lambda^{-4} \frac{dt}{dt_a^d} W(\nu_1, \nu_2, T_{\rm arr})\, d\Sigma, \quad (1)$$

where $\Delta\epsilon = \Delta E_{\rm int}/V$ is the energy density released in the interaction of the accelerated baryons with the ISM measured in the comoving frame, $\Lambda = \gamma[1 - (v/c)\cos\vartheta]$ is the Doppler factor, and $d\Sigma$ is the surface element at detector arrival time t_a^d on which the integration is performed (details in Ruffini et al. 2004a).

4. THE GRB 031203 PROMPT EMISSION

In order to compare our theoretical prediction with the observations, it is important to note that there is a shift between the initial time of the GRB event and the moment in which the satellite instrument has been triggered. In fact, in our model the GRB emission starts at the transparency point when the P-GRB is emitted. If the P-GRB is under the threshold of the instrument, the trigger starts a few seconds later with respect to the real beginning of the event. Therefore it is crucial, in the theoretical analysis, to estimate and take into due account this time delay. In the present case it results in $\Delta t_a^d = 3.5$ s (see Fig. 1, *vertical red line*). In what follows, the detector arrival time refers to the onset of the instrument.

The structure of the prompt emission of GRB 031203, which is a single peak with a slow decay, is reproduced assuming an ISM that does not have a constant density but presents several density spikes with $\langle n_{\rm ISM}\rangle = 0.16$ particles cm^{-3}. Such density spikes corresponding to the main peak are modeled as three spherical shells with width Δ and density contrast $\Delta n/n$: we adopted for the first peak $\Delta = 3.0 \times 10^{15}$ cm and $\Delta n/n = 8$, for the second peak $\Delta = 1.0 \times 10^{15}$ cm and $\Delta n/n = 1.5$, and for the third one $\Delta = 7.0 \times 10^{14}$ cm and $\Delta n/n = 1$. To describe the details of the ISM filamentary structure we would require intensity versus time information with an arbitrarily high resolving power. With the finite resolution of the *INTEGRAL* instrument, we can only describe the average density distribution compatible with the given accuracy. Only structures at scales of 10^{15} cm can be identified. Smaller structures would need a stronger signal and/or a smaller time resolution of the detector. The three clouds here considered are necessary and sufficient to reproduce the observed light curve: a smaller number would not fit the data, while a larger number is unnecessary and would be indeterminable.

The result (see Fig. 1) shows good agreement with the light curve reported by Sazonov et al. (2004), and it provides further evidence of the possibility of reproducing light curves with a complex time variability through ISM inhomogeneities (Ruffini et al. 2002, 2003, 2005a; see also the analysis of the prompt emission of GRB 991216 in Ruffini et al. 2002).

5. THE GRB 031203 INSTANTANEOUS SPECTRUM

As outlined in § 3, in addition to the luminosity in fixed energy bands we can derive also the instantaneous photon number spectrum $N(E)$. In Figure 2 are shown samples of time-resolved spectra for five different values of the arrival time that cover the whole duration of the event.

It is manifest from this picture that although the spectrum in the comoving frame of the expanding pulse is thermal the shape of the final spectrum in the laboratory frame is clearly nonthermal. In fact, as explained in Ruffini et al. (2004a), each single instantaneous spectrum is the result of an integration of

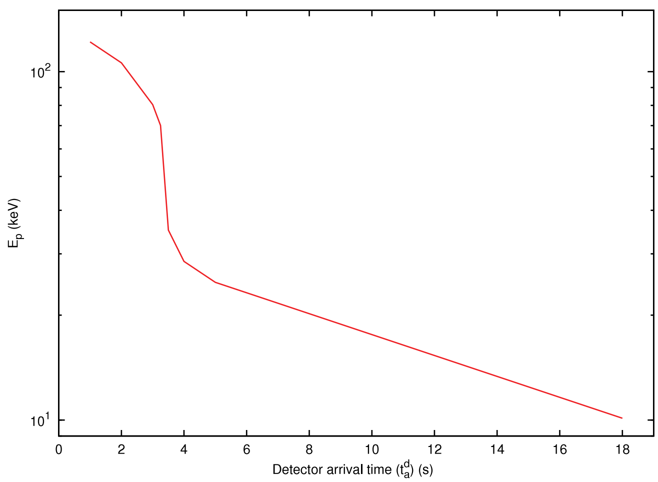

FIG. 3.—Energy of the peak of the instantaneous photon number spectrum $N(E)$ is here represented as a function of the arrival time during the prompt-emission phase. The clear hard-to-soft behavior is shown.

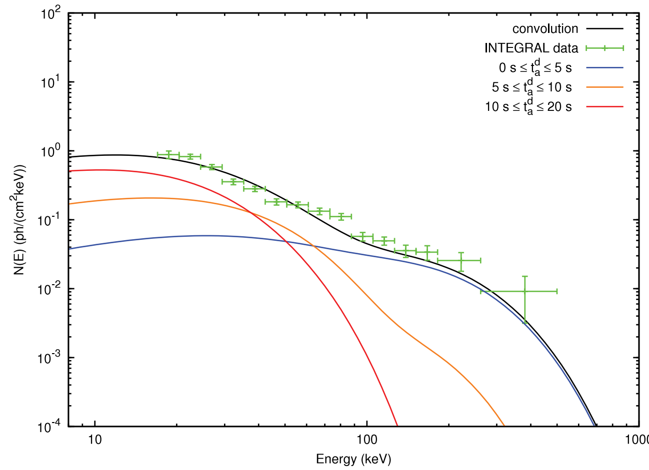

FIG. 4.—Three theoretically predicted time-integrated photon number spectra $N(E)$ are here represented for $0\ \mathrm{s} \le t_a^d \le 5\ \mathrm{s}$, $5\ \mathrm{s} \le t_a^d \le 10\ \mathrm{s}$, and $10\ \mathrm{s} \le t_a^d \le 20\ \mathrm{s}$ (*colored curves*). The hard-to-soft behavior presented in Fig. 3 is confirmed. Moreover, the theoretically predicted time-integrated photon number spectrum $N(E)$ corresponding to the first 20 s of the prompt emission (*black curve*) is compared with the data observed by *INTEGRAL* (*green points*; see Sazonov et al. 2004; S. Y. Sazonov et al. 2004, private communication). This curve is obtained as a convolution of 108 instantaneous spectra, which are enough to get a good agreement with the observed data.

hundreds of thermal spectra over the corresponding EQTS. This calculation produces a nonthermal instantaneous spectrum in the observer frame (see Fig. 2).

Another distinguishing feature of the GRB's spectra that is also present in these instantaneous spectra, as shown in Figure 2, is the hard-to-soft transition during the evolution of the event (Crider et al. 1997; Piran 1999; Frontera et al. 2000; Ghirlanda et al. 2002). In fact, the peaks of the energy distributions E_p drift monotonically to softer frequencies with time (see Fig. 3). This feature explains the change in the power-law low-energy spectral index α (Band et al. 1993), which at the beginning of the prompt emission of the burst ($t_a^d = 2$ s) is $\alpha = 0.75$ and progressively decreases for later times (see Fig. 2). In this way the link between E_p and α identified by Crider et al. (1997) is explicitly shown. This theoretically predicted evolution of the spectral index during the event unfortunately cannot be detected in this particular burst by *INTEGRAL* because of the insufficient quality of the data (poor photon statistics; see Sazonov et al. 2004).

6. THE GRB 031203 TIME-INTEGRATED SPECTRUM AND THE COMPARISON WITH THE OBSERVED DATA

The time-integrated observed GRB spectra show a clear power-law behavior. Within a different framework N. I. Shakura, R. A. Sunyaev, and Ya. B. Zel'dovich (see, e.g., Pozdniakov et al. 1983 and references therein) argued that it is possible to obtain such power-law spectra from a convolution of many non–power-law instantaneous spectra evolving in time. This result was recalled and applied to GRBs by Blinnikov et al. (1999) by assuming for the instantaneous spectra a thermal shape with a temperature changing with time. They showed that the integration of such energy distributions over the observation time gives a typical power-law shape possibly consistent with GRB spectra.

Our specific quantitative model is more complicated than the one considered by Blinnikov et al. (1999): as pointed out in § 5, the instantaneous spectrum here is not a blackbody. Each instantaneous spectrum is obtained by an integration over the corresponding EQTS (Bianco & Ruffini 2004, 2005a): it is itself a convolution, weighted by appropriate Lorentz and Doppler factors, of $\sim 10^6$ thermal spectra with variable temperature. Therefore, the time-integrated spectra are not plain convolutions of thermal spectra; they are convolutions of convolutions of thermal spectra (see Fig. 2).

The simple power-law shape of the integrated spectrum is more evident if we sum tens of instantaneous spectra, as in Figure 4. In this case we divided the prompt emission into three different time intervals, and for each one we integrated the energy distribution over time. The resulting three time-integrated spectra have a clear nonthermal behavior and still present the characteristic hard-to-soft transition.

Finally, we integrated the photon number spectrum $N(E)$ over the whole duration of the prompt event (see again Fig. 4); in this way we obtain a typical nonthermal power-law spectrum that is in good agreement with the *INTEGRAL* data (see Sazonov et al. 2004; S. Y. Sazonov et al. 2004, private communication) and that gives clear evidence of the possibility that the observed GRB spectra originated from a thermal emission.

7. CONCLUSIONS

Applying our model to the GRB 031203, we show how we are able to predict the whole dynamic of the process in which the GRB emission originates, fixing univocally the two free parameters of the model, $E_{\rm dya}$ and B. Moreover, it is possible to obtain the exact temporal structure of the prompt emission by taking into account the effective ISM filamentary structure.

The important point we would like to emphasize is that we can get both the luminosity emitted in a fixed energy band and the photon number spectrum starting from the hypothesis that the radiation emitted in the GRB process is thermal in the comoving frame of the expanding pulse. It has been clearly shown that after the correct spacetime transformations, both the time-resolved and the time-integrated spectra in the observer frame strongly differ from a Planckian distribution and have a power-law shape, although they originate from strongly time-varying thermal spectra in the comoving frame. We obtain a good agreement of our prediction with the photon number spectrum observed by *INTEGRAL* and, in addition, we predict a specific hard-to-soft behavior in the instantaneous spectra. Due to the possibility of reaching a precise identification of the emission process in GRB afterglows by observation of the instantaneous spectra, it is hoped that further missions with larger collecting area and higher time-resolving power can be conceived and that systematic attention can be given to nearer GRB sources.

Despite the fact that this GRB is often considered "unusual" (Watson et al. 2004; Soderberg et al. 2004), in our treatment we are able to explain its low gamma-ray luminosity in a natural way, giving a complete interpretation of all its spectral features. In agreement with what has been concluded by Sazonov et al. (2004), it appears to us to be a low-energy GRB ($E_{\rm dya} \approx 10^{50}$ ergs) and is well within the range of applicability of our theory, between 10^{48} ergs for GRB 980425 (Ruffini et al. 2004b) and 10^{54} ergs for GRB 991216 (Ruffini et al. 2003).

The precise knowledge that we have acquired here on GRB 031203 will help in clarifying the overall astrophysical system composed of GRB 031203, SN 2003lw, and the 2–10 keV *XMM-Newton* and *Chandra* data (see, e.g., Ruffini et al. 2005a).

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