Induced Gravitational Collapse in the BATSE era: the case of GRB 970828

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ABSTRACT

Following the recently established “Induced Gravitational Collapse” (IGC) paradigm, we here interpret GRB 970828 in terms of the four episodes typical of such a paradigm. The “Episode 1”, up to 40 s after the trigger time, with a time varying thermal emission and a total energy of $E_{\nu,\nu=\gamma} = 2.60 \times 10^{51}$ erg, is interpreted as due to the onset of a supernova Ib/c in a tight binary system with a companion neutron star. The “Episode 2”, observed up to 90 s, is interpreted as a canonical gamma ray burst, with an energy of $E_{\nu,\nu=\gamma} = 1.60 \times 10^{53}$ erg, a baryon load of $B = 7 \times 10^{-3}$ and a bulk Lorentz factor at transparency of $\Gamma = 142.5$. From this Episode 2, we infer that the GRB exploded in an environment with a large average particle density $\langle n \rangle = 10^3$ particles/cm$^3$, and dense clouds characterized by typical dimensions of $(4 \pm 2) \times 10^{18}$ cm and $\ln n / \mu \sim 10$. The “Episode 3” is identified from 90 s all the way up to $10^{-6}$ s, despite the paucity of the early X-ray data, typical in the BATSE, pre-Swift era, we find extremely significant data points in the late X-ray afterglow emission of GRB 970828, which corresponds to the ones observed in all IGC GRBs-SNe sources. The “Episode 4”, related to the Supernova emission, does not appear to be observable in this source, due to the presence of darkening from the large density of the GRB environment, also inferred from the analysis of the Episode 2.

Key words. Gamma-ray burst: general — Gamma-ray burst: individual: GRB 970828 — Black hole physics

1. Introduction

The Gamma Ray Burst (GRB) 970828 is one of the first GRBs with an observed X-ray and radio afterglow and a determined redshift of z=0.9578 from the identification of its host galaxy (Djorgovski et al. 2001). It was detected by the All Sky Monitor (ASM) detector on board the Rossi X-ray Timing Explorer (RXTE) spacecraft (Remillard et al. 1997), and then observed also by the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (Smith et al. 1997). The crucial data on the afterglow of GRB 970828 were collected by the Advanced Satellite for Cosmology and Astrophysics (ASCA) in the (2 - 10) keV energy range, one day after the RXTE detection (Filippenko et al. 1997), and by ROSAT (Greiner et al. 1997) in the (0.1 - 2.4) keV, one week later. Observations on optical wavelengths failed to detect the optical afterglow (Odewahn et al. 1997; Groot et al. 1998). The fluence measured by BATSE implies an isotropic energy for the total emission of $E_{\nu,\nu=\gamma} = 4.2 \times 10^{53}$ erg. This source is still present today, after 15 years from its discovery, an extremely rich problematic in the identification of its astrophysical nature.

The recent joint GRBs observations made by satellites as Swift ( Gehrels et al. 2004), Fermi (Meegan et al. 2009), AGILE (Tavani et al. 2009), Konus-WIND (Aptekar et al. 1995) in hard X-rays energy range, as well as the follow-up of their afterglow emission in the (0.3 - 10) keV range by the X-Ray Telescope (XRT) (Burrows et al. 2005) on-board Swift, and the corresponding follow-up observations in the optical and radio wavelengths have made possible a new understanding of the entire GRB process. In this paper we start a procedure of revisiting previous GRBs in the BATSE, pre-Swift era, including the new understanding mentioned above. In particular, we apply to GRB 970828 the new Induced Gravitational Collapse paradigm introduced for GRBs associated with Supernovae (SNe) (Ruffini et al. 2007; Rueda & Ruffini 2012), which are composed of four different episodes (Izzo et al. 2012b; Penacchioni et al. 2012, 2013; Pisani et al. 2013).

– The “Episode 1” corresponds to the emission from the onset of a Supernova (SN), in a close binary system with a companion neutron star (NS). The initial SN expansion, on non-relativistic velocities, induces a strong matter accretion onto the NS, which reaches the critical mass (Belvedere et al. 2012) and then collapses to a black hole (BH). In the specific case of GRB 970828, this episode is clearly identified, see Fig. 1. The observed hard X-ray emission is composed of a thermal spectrum plus a power-law component, both evolving in time. The early expansion of the SN deduced from the characteristic time decay of the blackbody temperature $kT$ (from 80 to 25 keV), in the rest-frame time of 20 s, leads to the estimate of the emitter radius between 5000 and 25000 km.

– The “Episode 2”, corresponding to the observations of the GRB, is related to the collapse of the NS into a BH. The
characteristic parameters of the GRB 090618 are the Lorentz Gamma factor of $\Gamma \approx 150$, the baryon load $B = 7 \times 10^{-3}$ and a large circumburst density of the order of $10^3$ particles/cm$^3$.

- The “Episode 3”, in soft X-rays, occurs when the prompt emission from the GRB fades away and an additional component, discovered by Swift XRT (Zhang et al. 2006; Nousek et al. 2006) emerges. It has been shown (Pisani et al. 2013) that this component, in energetic ($E_{iso} \geq 10^{52}$ erg) GRBs-SNe, when referred to the rest-frame of the source, follows a standard behavior of the light curve evolution, see Fig. 2. This emission encompasses the SN shock break out and the expanding SN ejecta ($v/c \approx 0.1$). In the case of GRB 970828, the X-ray emission observed by ASCA and ROSAT perfectly overlap with the common trend observed in GRB-SN IGC systems and exemplified in Fig. 2.

- The “Episode 4” is represented by the observations of the optical emission of the SN, which has been observed in some IGC sources, with $z \leq 0.9$, (GRB 090618, GRB 060729, GRB 091127, GRB 111228, GRB 080319B, see e.g. Pisani et al. 2013). It is generally hard to detect a SN at $z \approx 0.9578$ and in the case of GRB 970828 is even more difficult due to the very large presence of circumburst material, which has also hampered the observations of the optical afterglow, making this source a ‘dark’ GRB.

The presence of an evolving thermal component in the first 20 s of the emission of GRB 090618, using BATSE data, has been indicated by Pe‘er et al. (2007), where they have considered the emission in the first 20 s of Episode 1. They then have fitted the evolution of the temperature $kT$ and the ratio $R = (\text{Flux}_{BB}/\sigma T_{obs}^4)^{1/2}$, where $\text{Flux}_{BB}$ is the observed flux of the instantaneous blackbody, $\sigma$ the Stefan constant and $T_{obs}$ the observed temperature, whose evolution in time is fitted with a broken power-law function, see Fig. 3. In their theoretical interpretation, this thermal emission was associated to the photospheric GRB emission of a relativistic expanding fireball (Mészáros 2002), and they inferred a bulk Lorentz Gamma factor of the expanding plasma, $\Gamma \approx (305 \pm 28) Y_0^{1/4}$, with $Y_0 \geq 1$ the ratio between the entire fireball energy and the energy emitted in $\gamma$-rays (Mészáros 2002). Since the fireball photospheric radius is given by $r_{ph} = 1.06 Y_0^{3/4}$, with $D$ the luminosity distance of the GRB, they obtain for $r_{ph}$ the value of $2.7 \times 10^{11} Y_0^{1/4}$ cm. In Pe‘er et al. (2007), the authors have also attributed the remaining GRB emission to an unspecified engine activity and neglected all data after 20 s. In their own words, “we neglect here late-time episodes of engine activity which occur after ~ 25 and ~ 60 s in this burst”. As we will show in the following of this article, we notice the presence of a thermal component in the first 40 s, and we attribute it to a non-relativistic initial expansion of the SN, with radius evolving from $2 \times 10^9$ to $3 \times 10^{10}$ cm, see Fig. 5. In addition, we identify the GRB emission between t$_{0}+50$ s and t$_{0}+90$ s and the third episode between $10^4$-$10^6$ s.

In Section 2 we give a summary of the observations of GRB 090618 and describe our data analysis. We proceed in Section 3 to the description of Episode 1, with the details of the expanding black body emitter, the analysis of the non-thermal component and its interpretation in the IGC paradigm. In Section 4 we describe Episode 2, the authentic GRB emission. It is well explained in the context of the fireshell scenario, see e.g. Ruffini et al. (2007) for a complete review of the model. In Section 5 we describe Episode 3, pointing out the clear overlapping of the observed late X-ray data within the theoretical expectation of a GRB-SN IGC member. In Section 6 we discuss about the theoretically expected SN emission, not observed due to the large circumburst medium. Conclusions are given in the last Section.
2. Data Analysis

GRB 970828 was discovered with the All-Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE) on 1997 August 28th (Smith et al. 1997). Within 3.6 hr the RXTE/PCA scanned the region of the sky around the error box of the ASM burst and detected a weak X-ray source (Marshall et al. 1997; Filippenko et al. 1997). GRB 970828 was also observed by the Burst and Transient Source Experiment (BATSE) and the GRB experiment on Ulysses (Smith et al. 1997). The BATSE-LAD light curve is characterized by two main emission phenomena, see Fig.1: the first lasts about 40 s and is well described by two main pulses, the second one is more irregular, being composed by several sharp pulses, lasting other 40 s.

The X-ray afterglow was discovered by the ASCA satellite 1.17 days after the GRB trigger (Murakami et al. 1997). The X-ray afterglow observations continued up to 7-10 days from the burst detection. The optical observations, which started about 4 hr after the burst, did not report any possible optical afterglow for GRB 970828 up to $R=23.8$ (Groot et al. 1998). However, the observations at radio wavelengths of the burst position, 3.5 hrs after the initial burst, succeeded in identifying a source at a good significance level of 4.5 $\sigma$ (Djorgovski et al. 2001) inside the ROSAT error circle (10$''$). The following deep searches for a possible optical counterpart of this radio source led to the identification of an interacting system of faint galaxies, successively recognized as the host galaxy of GRB 970828. The spectroscopic observations of the brightest of this system of galaxies led to the identification of their redshift, being $z=0.9578$. The lack of an optical transient associated with the afterglow of GRB 970828 can be explained as due to the presence of strong absorption, due to dusty clouds in the burst site environment, whose presence does not affect the X-ray and the radio observations of the GRB afterglow. The absence of an optical afterglow (Groot et al. 1998), together with the large intrinsic absorption column detected in the ASCA X-ray data (Yoshida et al. 2001) and the contemporaneous detection in radio-wavelengths of the GRB afterglow, imply a very large value for the circum-burst medium (CBM); the variable absorption might be an indication of a strong inhomogeneous CBM distribution.

To analyze in detail this GRB, we have considered the observations of the BATSE-LAD detector, which observed GRB 970828 in the 25-1900 keV energy range, and then we have reduced the data by using the RMFIT software package. For the spectral analysis we have considered the High Energy Resolution Burst (HERB) data, which consist of 128 separate high energy resolution spectra stored during the burst emission. The light curve, shown in Fig. 1, was obtained by using the Medium Energy Resolution (MER) data, which consist of 4,096 16-channel spectra summed from triggered detectors.

3. The Episode 1

3.1. The onset of the Supernova

In analogy to the cases of GRB 090618 (Izzo et al. 2012b), we analyze here the first emission episode in GRB 970828 to seek for a thermal signature, due to the early SN emission. We have rebinned the light curve assuming a signal-to-noise value for each time bin of 20. This large value of counts per bin allows us to consider a gaussian distribution for the photons in each bin, in the following we will use a chi-square statistic. As often done in GRB analysis, we first perform a time-integrated spectral analysis of the first 40 s of emission, which corresponds to the Episode 1, to identify the best-fit model and the possible presence of thermal features. We make use of different spectral models, see Table 1, to determine the best-fit function. We also check if nested models really improve the best-fit, as in the case of models with an extra power-law component. We find that the best-fit corresponds to a double blackbody model with an extra power-law component. The check between the Band and the double black body plus power law is minimal ($F_{\text{val}} = 9\%)$ but with this last model we note an improvement of the best fit at high energies, see Fig. 4.

It has already been emphasized that the integrated spectral analysis often misses the nature of the physical components and also the nature of the underlying physical mechanisms. We perform therefore a time-resolved spectral analysis to determine the existence and the evolution of a thermal component. We find that the double blackbody model observed in the time-integrated spectrum can be explained by the presence of an instantaneous single blackbody with a temperature $kT$ varying in intensity and time, showing a double decay trend. We note that the timing of these trends corresponds to the two main spikes in the observed light curve of this first episode, see Fig. 5. We have then analyzed this characteristic evolution of the blackbody in both time intervals, corresponding each one to an observed decay trend of the temperature. From the observed flux of the blackbody component $\phi_{BB,obs}$ for each interval, we obtain the evolution of the emitter radius in the rest-frame:

$$r_{em} = \left( \frac{\phi_{BB,obs}}{\sigma T_{obs}^4} \right)^{1/2} \frac{D}{(1 + z)^2}$$

whose evolution is shown in Fig. 5. It is very interesting that the radius monotonically increases, without showing an analog double trend which is observed for the temperature, see Fig. 5. The global evolution of the emitter radius is well-described with a power-law function $r = \alpha t^\delta$ and a best fit of the data provides for $\delta = 0.41 \pm 0.04$ and $\alpha = (5.38 \pm 0.52) 10^6$ cm, with an $R^2$ statistic value of 0.98, see Fig. 5.

It is appropriate to discuss the power law component observed in the time resolved spectra. In IGC systems, the tight geometry of the binary system implies that as the external layers of the SN core starts to expand, an accretion phenomenon is induced onto the NS companion.

3.2. Accretion onto the NS and outflow

Within the IGC paradigm (Rueda & Ruffini 2012; Izzo et al. 2012a), GRB 970828 originated following the time sequence given by the induced collapse process, which occurs in a binary system formed by a massive evolved star on the verge of a SN explosion and a NS companion. The material ejected in the early pre-SN phases expands at non-relativistic velocities and is accreted by the NS companion. This process starts at times larger than $t = t_{0,\text{accr}}$, when the material reaches the NS gravitational capture region. The emission observed in the first episode is associated to this phase. The NS grows in mass and reaches in a time $t = t_{0,\text{accr}} + \Delta t_{\text{accr}}$ its critical mass and gravitationally collapses to a black hole. This process leads to the emission of the GRB seen in Episode 2. We adopt the critical mass of a non-rotating NS, $M_{\text{crit}} = 2.67 M_{\odot}$, as given by Belvedere et al. (2012).

The rate at which the SN ejecta enters into the capture region of the NS is given by (see Rueda & Ruffini (2012) and Izzo et al. (2012a))

$$\dot{M}(t) = \pi r_{\text{cap}}(t) v_{\text{rel}}(t) R_{\text{cap}}^2(t),$$

where $r_{\text{cap}}(t)$ is the radius of the gravitational capture region of the NS.
Table 1. Spectral analysis (25 keV - 1.94 MeV) of the first 40 s of emission in GRB 970828. The following symbols represent: * temperature (keV) of the second black body; † normalization of the power law component in units of ph cm^{-2} s^{-1} keV^{-1}.

| Spectral model | $\alpha$ (y) | $\beta$ | $\gamma_{\text{rest}}$ | $E_{\text{peak}}$ (keV) | $kT$ (keV) | norm$_1$ ph cm^{-2} s^{-1} keV^{-1} | norm$_2$ ph cm^{-2} s^{-1} keV^{-1} | $\chi^2$/DOF |
|----------------|--------------|---------|-------------------------|-------------------------|------------|-------------------------------|-------------------------------|-------------|
| Power Law      | -1.38 ± 0.01 | -       | -                       | -                       | -          | 0.018 ± 0.001                 | -               | 622.3/115   |
| Cut-off PL     | -0.77 ± 0.02 | -       | -                       | -                       | -          | 0.027 ± 0.001                 | -               | 203.8/114   |
| Band           | -0.60 ± 0.03 | -       | -                       | -                       | -          | 0.031 ± 0.001                 | -               | 106.4/113   |
| Band+PL        | -0.41 ± 0.15 | -       | -1.47 ± 0.17            | 335.8 ± 17.6            | -          | 0.028 ± 0.002                 | 0.003 ± 0.002   | 104.1/111   |
| cutoff + PL    | -0.47 ± 0.17 | -       | -1.28 ± 0.16            | 338.7 ± 17.9            | -          | 0.027 ± 0.002                 | 0.004 ± 0.002   | 104.2/112   |
| BB + po        | -1.50 ± 0.01 | -       | -                       | 63.7 ± 0.92             | 3.21 ± 0.16 10^{-6} | 0.012 ± 0.001 | 228.0/113  |
| BB + BB + po   | -1.53±0.17   | -       | 0.010 ± 0.001†          | 40.01±2.05              | 106.8±6.3   | 4.85±1.15 10^{-7}           | (10.15±1.32) 10^{-6} | 101.7/111  |

Fig. 4. Time-integrated spectral fits and sigma residual plot (25-1900 keV) of the first emission episode (0-40 s) in GRB 970828 with respectively a) a blackbody plus an extra power-law model; b) a double blackbody plus an extra power-law component; c) a Band model.

Fig. 5. (Left panel) The evolution of the temperature $kT$ (red crosses) as obtained from a time-resolved spectral analysis of the first 40 s of emission of GRB 970828. The light curve of the first episode (blue dots) is shown in background. (Right panel) Evolution of the rest-frame radius of the first episode of GRB 970828. The solid line corresponds to the best fit of this dataset with a power-law function $r \propto r^\delta$, with $\delta = 0.41 \pm 0.04$.

where $R_{\text{cap}} = 2GM_{\text{NS}}(t)/v_{\text{ej}}^2(t)$ is measured from the NS center, $\rho_{\text{ej}}(t) = 3M_{\text{ej}}(t)/4\pi r_{\text{ej}}^3(t)$ is the density of the ejecta and $v_{\text{ej}}(t) = \sqrt{\frac{v_{\text{orb}}^2}{\text{NS}}(t) + v_{\text{s}}^2(t)}$ is the velocity of the ejecta relative to the NS. In this latter formulation, $v_{\text{orb}}(t) = \sqrt{GM_{\text{prog}}(t)/a}$ is the orbital velocity relative to the SN core progenitor, $a$ is the separation distance between the NS and the SN core progenitor, and

$$v_{\text{ej}} = \frac{dr_{\text{ej}}(t)}{dt} = \frac{r_{\text{ej}}(t)}{t}$$

(3) is the expansion velocity of the SN material in the early phase; we have used $r_{\text{ej}}(t) = r_{\text{em}}(t)$ as given by Eq. (1). The quantities $M_{\text{prog}}$ and $M_{\text{NS}}(t)$ are the pre-SN core progenitor mass and the NS mass.

The available mass to be accreted by the NS changes with time as $M_{\text{acc}}(t) = M_{\text{ej}}(t) - M(t)$, where $M_{\text{ej}}(t)$ is the given initial mass of the ejecta (prior to the beginning of the accretion process) and $M(t)$ is the mass of the ejecta that is lost because it passes through the capture region of the NS.

The actual mass accretion rate onto the NS, $M_{\text{acc}}(t)$, is a fraction $\eta_{\text{acc}} \leq 1$ of the rate $\dot{M}$ given by Eq. (2), so we define

$$M_{\text{acc}}(t) = \eta_{\text{acc}} \dot{M}(t),$$

(4)
which implies that there is an outflow of not accreted material at a rate

\[ M_{\text{out}}(t) = (1 - \eta_{\text{accr}})\dot{M}(t), \]

and therefore the NS mass increases with time as

\[ M_{\text{NS}}(t) = M_{\text{NS}}(0) + \int_0^t M_{\text{accr}}(\tau) \, d\tau. \]

3.3. The luminosity in the accretion process and in its outflow

As we have mentioned, we examine the possibility of explaining the power-law component in the spectrum of the Episode 1 being related to the outflow originating in the accretion process onto the NS. Since this power-law component is present from the beginning of the emission, the onset of the accretion \( t_{0,\text{accr}} \) coincides with the starting time of the first episode. This assumption imposes the following constraint

\[ a = r_0 + R_{\text{cap}}(0), \]

which is an implicit equation to the separation distance \( a \) of the binary. Here \( r_0 = r_f(0) \) and \( R_{\text{cap}}(0) \) are the radius of the early SN ejecta and the capture radius of the NS companion at the beginning of Episode 1. In the present case, \( r_0 \approx 5.0 \times 10^8 \) cm; see Fig. 5 and Eq. (1). The separation \( a \) is thus a function of the initial mass of the NS and of the SN core progenitor mass, as well as of the orbital velocity, through \( R_{\text{cap}} \).

Moreover, we must impose the constraint that the NS must reach its critical mass, \( M_{\text{crit}} \), in a time interval that ends at the beginning of the second episode, i.e., at the starting point of the GRB emission, since in this scenario it is given by the collapse of the NS to a black hole. This implies for GRB 970828 the further constraint

\[ \Delta t_{\text{accr}} \approx \frac{t_{EPL}}{1 + z} \approx 23 \text{ s}, \]

where \( t_{EPL} = 46 s \) corresponds with the onset of Episode 2.

In Table 2 we show the parameters of the binary system leading to induced gravitational collapse of the NS in a time interval equal to the duration of the first episode of GRB 970828. In this example we adopt an initial mass for the NS, \( M_{\text{NS}}(0) = 1.8 M_\odot \) and, correspondingly, a NS radius of \( R_{\text{NS}}(0) = 12.3 \) km from the mass-radius relation of Belvedere et al. (2012). From the constraint given by Eq. (6) we fix the binary separation \( a \). We then proceed with the numerical integration of the accretion rate equations by requiring that

\[ M_{\text{NS}}(t) = M_{\text{out}}(t) \]

at \( t = \Delta t_{\text{accr}} \), given by Eq. (7), from which we obtain the efficiency \( \eta_{\text{accr}} \). We repeat this procedure for different pre-SN core progenitor masses \( M_{\text{prog}} \) from 4 to 10 \( M_\odot \) and for all of them we assume that, out from the SN event, a NS remnant of 1.3 \( M_\odot \) is left.

We return now to the possible luminosity emitted during the accretion process. Assuming that the gain in gravitational energy of the accreted material onto the NS can be released from the system, we can obtain an upper limit of the luminosity

\[ L_b = \frac{GM_{\text{accr}}(t)M_{\text{NS}}(t)}{R_{\text{NS}}(t)}, \]

where we have to account for the change of the NS radius with time owing to the increment of the NS mass by accretion. The self-consistent radius is computed at each time from the mass-radius relation of Belvedere et al. (2012).

The actual luminosity depends on the efficiency \( \eta_{\text{rad}} \) in converting gravitational energy into electromagnetic radiation.

\[ L_b(t) \approx \frac{L_{PL}}{L_b}. \]

In Figs. 6 and 7 we show the evolution of the accretion luminosity \( L_b \) given by Eq. (8) and the efficiency \( \eta_{\text{rad}} \) estimated via Eq. (9) in the first seconds of emission for the binary systems shown in Table 2. We assume a constant and isotropic power-law luminosity of Episode 1, \( L_{PL} \approx 7 \times 10^{50} \text{ erg s}^{-1} \approx 4 \times 10^{-1} M_\odot \text{ s}^{-1} \). We computed the values of the efficiency for the binary systems shown in Table 2. For all the cases, we obtain the same evolution of the efficiency with time, i.e., the curves overlap. The values of \( \eta_{\text{rad}} \) are always \(< 12\% \).

Since in our model we assume that the BB component of Episode 1 is due to the early-SN expansion, we estimate the efficiency \( \eta_{\text{rad}} \) from the assumption that \( L_b \) is responsible for the power-law luminosity \( L_{PL} \), namely

\[ \eta_{\text{rad}}(t) = \frac{L_{PL}}{L_b}. \]

In Figs. 6 and 7 we show the evolution of the accretion luminosity \( L_b \) given by Eq. (8) and the efficiency \( \eta_{\text{rad}} \) estimated via Eq. (9) in the first seconds of emission for the binary systems shown in Table 2. We assume a constant and isotropic power-law luminosity of Episode 1, \( L_{PL} \approx 7.5 \times 10^{50} \text{ erg s}^{-1} \approx 4 \times 10^{-1} M_\odot \text{ s}^{-1} \), as found from the spectral analysis. For all the cases, we obtain the same evolution of the efficiency with time, i.e., the curves overlap. This is due to the fact that we constrained all the systems to have the same initial NS mass and \( \Delta t_{\text{accr}} \). There is still another possible source of radiation in the above process. In Eq. (5) we defined the amount of material not accreted by the neutron star per unit time, \( M_{\text{out}} \), introducing the
accretion efficiency parameter, $\eta_{\text{accret}}$. This parameter encloses in an effective way possible processes leading to a reduction of the Bondi-Hoyle accretion rate, Eq. (2), such as the effect of the angular momentum of the material passing by the capture region. The outflow given by $M_{\text{out}}$ could then be converted into radiation by some process which in the case of maximum conversion efficiency would lead to a maximum luminosity $L_{\text{out}}^{\max} \approx M_{\text{out}} c^2$. In Fig. 8 we plot the ratio $L_{\text{pl}}/L_{\text{out}}^{\max}$ as a function of time.

### 3.4. A possible explanation for the non-thermal component and the compactness problem

It is well known (see Piran 1999) that most of GRBs emit a large fraction of observed high-energy photons ($E \gg 1$ MeV) which can interact with low-energy photons to produce electron-positron pairs via $\gamma \gamma \rightarrow e^+ e^-$ in a compact region $R < c\delta t \approx 3000$ km. Although the high photon density, the observed spectra of GRBs are non-thermal, indicating that these sources expand relativistically with Lorentz factor $\Gamma > 1$ (Ruderman 1975; Piran 1999). A consequence of such a relativistic motion is a decrease of the estimated optical depth (Woods & Loeb 1995; Lithwick & Sari 2001; Zhang & Pe’er 2009).

The observed high-energy photon spectrum is often modeled by a single power-law $KE^{-\gamma}$, with $E_{\text{min}} < E < E_{\text{max}}$ and power-law index $\gamma$. The energy $E_{\text{max}}$ is the highest observed photon energy. In the frame of the emitting material, where the photons are assumed to be isotropic, a photon with energy $E'$ can annihilate a second photon with energy $E'_{\text{th}}$, yielding an electron-positron pair. The threshold for this process is described by

$$E'_{\text{th}} \gtrsim (m_e c^2)^2$$

where $m_e$ is the electron mass. If the source is moving toward the observer with a Lorentz factor $\Gamma$, then the photons previously analyzed have detected energy of $E = \Gamma E'/(1 + z)$ and $E_{\text{th}} \gtrsim \Gamma^2 E'_{\text{th}}/(1 + z)$, respectively. Therefore in the observer frame photons with energy $E_{\text{max}}$ annihilate only with other photons having energy $E_{\text{max},\text{th}} = [\Gamma m_e c^2/(1 + z)]^2 E_{\text{max}}^{-1}$.

Although the observed high-energy photon spectrum is a power-law, there is no observational evidence that photons with energy beyond the instrumental high-energy threshold $E_{\text{max}}$ exist. Therefore it is reasonable to assume that $E_{\text{max}}$ is also the maximum possible energy emitted in the burst event. From this assumption, it is straightforward to impose that the threshold energy $E_{\text{max},\text{th}}$ for the pair creation process has to be $E_{\text{max},\text{th}} \leq E_{\text{max}}$ (see e.g. case (III) in Gupta & Zhang 2008). It follows then an upper limit on the Lorentz factor from the observed energy $E_{\text{max}}$

$$\Gamma_{\text{max}} \leq \frac{E_{\text{max}}}{m_e c^2} (1 + z).$$

We can identify $E_{\text{max}}$ with the cut-off energy of the spectrum $E_c$, but for the moment we treat them as different energies. Following the considerations in (Gupta & Zhang 2008), we have calculated the averaged number of photons interacting with $E_{\text{max}}$ from $E_{\text{max},\text{th}}$ to $E_c \geq E_{\text{max}}$ on the cross-section of the process integrated over all the angles $\theta$

$$\langle \sigma N_{\text{max},\text{th}} \rangle = 4\pi \int_{E_{\text{max},\text{th}}}^{E_c} \int_1^{\infty} \int_{\text{pair}} \frac{3}{16} \sigma_T ds dE_{\text{max},\text{th}} = \frac{2E_{\text{max},\text{th}}^{1-\gamma} - (\gamma + 1)E_c^{1-\gamma} + (\gamma - 1)E_{\text{max}}^{2-\gamma}E_c^{-1}}{\xi}$$

and we have correspondingly evaluated the optical depth

$$\tau_{\gamma \gamma} = \frac{\langle \sigma N_{\text{max},\text{th}} \rangle}{4\pi r^2},$$

by defining the following quantities

$$d_z = \frac{D}{1 + z}, \quad s = \frac{E_{\text{max}} E(1 - \cos \theta)}{2(m_e c^2)^2}, \quad \xi = \frac{3\sigma_T d_z^2 K \Delta t}{4(\gamma^2 - 1)},$$

and using the Thomson cross-section $\sigma_T$. The radius of the emitting region $r$ in Eq. (13) is considered as an independent quantity and the condition $\tau_{\gamma \gamma} \leq 1$ yields to a lower limit on it

$$r \geq \langle \sigma N_{\text{max},\text{th}} \rangle/4\pi.$$
We have applied these considerations to non-thermal spectrum of the first episode of GRB 970828. In particular we have considered separately the non-thermal components from the two time intervals corresponding to the double decay trend for the temperature (see Fig. 1), namely from \( t_0 \) to \( t_0 + 23 \) s (in the following \( \Delta t_0 \)) and from \( t_0 + 23 \) s to \( t_0 + 43 \) s (in the following \( \Delta t_0 \)). We have considered six different values of the cut-off energy, i.e. \( E_c = 1.9, 3.0, 4.3, 5.9, 7.7 \) and 10 MeV. By imposing the condition \( E_{\text{max}} = E_c \), from Eq. (11) we have then calculated the corresponding upper limits on the Lorentz factor, i.e. \( \Gamma_{\text{max}} = 7.23, 11.5, 16.5, 22.6, 29.5 \) and 38.3 (see horizontal gray lines in Fig. A.1 in Appendix).

Therefore, a relativistic outflow of the accretion process of the SN onto the companion NS, can explain the origin of the power-law high energy component observed in Episode 1.

### 4. The Episode 2: the GRB emission

Turning now to the second emission episode, we have computed the isotropic energies emitted in this episode, by considering a Band model as the best fit for the observed integrated spectra: \( E_{\text{iso,2nd}} = 1.6 \times 10^{53} \) erg. In what follows we explain this second emission episode of GRB 970828 as a single canonical GRB emission in the context of the Fireshell scenario.

In this model (Ruffini et al. 2001b; Ruffini 2001; Ruffini et al. 2001a), a GRB originates from an optically thick \( e^+e^-\)-plasma created in the process of vacuum polarization, during the process of gravitational collapse leading to a Kerr-Newman black hole (Christodoulou & Ruffini 1971; Damour & Ruffini 1975). The dynamics of this expanding plasma is described by its total energy \( E_{\text{tot}}^{eff} = \text{baryon load} \cdot B \cdot \text{circumburst medium (CBM) distribution around the burst site.} \) The GRB light curve emission is characterized by a first brief emission, named the proper GRB or P-GRB, originating in the process of the transparency emission of the \( e^+e^-\)-plasma, followed by a multiwavelength emission due to the collisions of the residual accelerated baryons and leptons with the CBM. This latter emission is assumed in a fully radiative regime. Such a condition is introduced for mathematical simplicity and in order to obtain a lower limit on the CBM density. This condition establishes a necessary link between the inhomogeneities and filamentary CBM distribution (Ruffini et al. 2005b) with the observed structures in the \( \gamma \) and X-ray light curves in the prompt and early afterglow phase.

In the spherically symmetric approximation the interaction of the accelerated plasma with the CBM can be described by the matter density distribution \( n_{\text{CBM}} \) around the burst site and the fireshell surface filling factor \( R = R_{\text{eff}}/R_{\text{subs}} \), which is the ratio between the effective emitting area and the total one (Ruffini et al. 2005a).

The spectral energy distribution in the comoving frame of the shell is well-described by a “modified” thermal emission model (Patricelli et al. 2012), which differs from a classical blackbody model by the presence of a tail in the low-energy range.

In this context, to simulate the second episode of GRB 970828, which is the actual GRB emission, we need to identify the P-GRB signature in the early second episode light curve. From the identification of the P-GRB thermal signature, and the consequent determination of the energy emitted at transparency, we can obtain the value of the baryon load \( B \) assuming that the total energy of the \( e^+e^-\)-plasma is given by the isotropic energy \( E_{\text{iso}} \) observed for the second episode of GRB 970828, as it was done for the second episode in GRB 090618, see e.g. Izzo et al. (2012b). We have then started to seek for a possible thermal signature attributable to the P-GRB emission in the early emission of the second episode. As it is shown in Fig. 9, the early emission of the second episode is characterized by an intense spike, anticipated by a weak emission of \( 9 \) s. Our search for the P-GRB emission is concentrated in this time interval, since from the fireshell theory the expected luminosity of the P-GRB emission, in case of long GRBs for which the baryon load is in between \( 10^{-3} - 10^{-5} \), is of the order of \( 10^{-2} \) of the prompt emission. The observed fluence (10-1000 keV) in the P-GRB emission, computed from the fit with the power-law function \( S_{\text{obs}} = (1.54 \pm 0.10) \times 10^{-6} \) erg/cm\(^2\), which corresponds to an isotropic energy of the P-GRB of \( E_{\text{tot, PGRB}} = 1.46 \times 10^{51} \) erg, which is quantitatively in agreement with the energetic of the P-GRB for this GRB (it is \( \approx 0.01 \% \) the total energy of the second episode, the GRB). However, due to the paucity of photons in this time interval, we are not able to put tight constraints, e.g. about a possible observed temperature of the P-GRB.

With these results, we can estimate the value of the baryon load from the numerical solutions of the fireshell equations of motion. These solutions for four different values of the total \( e^+e^-\)-plasma energy are shown in the Fig. 4 of Izzo et al. (2012b). We find that the baryon load is \( B = 7 \times 10^{-3} \), which corresponds to a Lorentz gamma factor at transparency \( \Gamma = 142.5 \). The GRB emission was simulated with very good approximation by using a density mask characterized by an irregular behavior: all the spikes correspond to spherical clouds with a large particle density \( \langle n \rangle \sim 10^3 \) part/cm\(^3\), and with radius of the order of \( (4 - 8) \times 10^{14} \) cm, see Fig. 10. Considering all the clouds found in our analysis, the average density of the CBM medium is \( \langle n \rangle = 3.4 \times 10^3 \) particles/cm\(^3\). The corresponding masses of the
Table 3. Spectral analysis (25 keV - 1.94 MeV) of the P-GRB emission in the second episode of GRB 970828.

| Spectral model | $\gamma$ | $\beta$ | $E_{\text{cutoff}}$ (keV) | $kT$ (keV) | $\chi^2$/DOF |
|----------------|----------|---------|--------------------------|------------|--------------|
| power-law      | -1.18 ± 0.04 |         | 2251 ± 1800              | 69.6 ± 40.0 | 90.228/113   |
| cutoff PL      | -1.15 ± 0.08 |         | 958.8 ± 800.0            | 91.495/115  | 91.157/114   |
| BB + PL        | -1.16 ± 0.06 |         | 5000                      | 90.439/113  |              |
| Band           | -0.96 ± 0.44 | -1.23 ± 0.08 | 15 000                   |            |              |

Fig. 10. Radial CBM density distribution for GRB 970828. The characteristic masses of each cloud are on the order of $\sim 10^{22}$ g and $10^{15}$ cm in radii. The black line corresponds to the average value for the particle density.

blobs are of the order of $10^{24}$ g, in agreement with the clumps found in GRB 090618.

The results of the fireshell simulation are shown in Table 4 while the simulated light curve and spectrum are shown in Fig. 11.

5. The Episode 3: the late X-ray afterglow

The most remarkable confirmation of the IGC paradigm applied to GRB 970828, comes from the late X-ray afterglow emission. As shown in Pisani et al. (2013), from the knowledge of the redshift of the source, we can compute the X-ray luminosity light curve in the common rest frame energy range 0.3–10 keV after $\approx 10^4$ s from the initial GRB emission. However, while in Pisani et al. (2013) the analysis is based on the available X-ray data (0.3–10 keV) from the Swift-XRT detector, GRB 970828 occurred in the pre-Swift era. Its observational X-ray data are available in the energy range 2–10 keV, since the data were collected by three different satellites: RXTE, ASCA and ROSAT. To further confirm the IGC progenitor mechanism for GRB 970828, we verify the overlapping of the late X-ray data with the ones of the ‘Golden Sample’ (GS) sources presented in Pisani et al. (2013). To this aim, we have computed its luminosity light curve $L_{\text{ff}}$ in a common rest-frame energy range 0.3–10 keV. Since the observed energy band is different (2–10 keV), the expression for the flux light curve $f_{\text{ff}}$ in the 0.3–10 keV rest-frame energy range is not as expressed in Eq. 2 of Pisani et al. (2013), but it becomes

$$f_{\text{ff}} = f_{\text{obs}} \left( \frac{10}{12} \right)^{-2/\gamma} \frac{\Gamma (0.3)}{\Gamma (2)} \frac{1}{10^\gamma - 2^\gamma},$$

where $\gamma$ is the photon index of the power-law spectral energy distribution of the X-ray data. All the other data transformations, reported in Pisani et al. (2013), remain unchanged.

Fig. 11. Light curve (top panel) and spectrum (lower panel) with the simulation of the second episode emission in GRB 970828, in the context of the fireshell scenario. In the simulation we have assumed for simplicity a purely radial 1-dimensional distribution of the CBM, which leads at late times (when $F_{\gamma} \approx 10$), to broader structures than the observed ones. This difficulty can be overcome by a much more time-consuming 3-dimensional description of the CBM, but without any conceptual additional contribution (Izzo et al. 2010).

We made use in particular of the RXTE-PCA observations and ASCA data presented in Yoshida et al. (2001); the averaged photon indexes are taken from the text, for RXTE-PCA ($\gamma \sim 2$), and from Tab. 1, for the ASCA data, of the same paper. The last data-point by ROSAT is taken from Fig. 7 in Djorgovski et al. (2001), with a corresponding photon index $\sim 2$; the error on the observed flux is the 25% as indicated for the count rate (Greiner et al. 1997). We show in Fig. 12 the late X-ray (0.3 - 10 keV) light curve of GRB 970828 and we compare it with some GRBs of the “Golden Sample” presented in Pisani et al. (2013): GRB
U nation that the SN has the same intrinsic luminosity. Moreover, to the redshift of GRB 970828. This simple operation concerns to the presence of an underlying supernova (Cano et al. 2011), observed in the optical afterglow of GRB 090618, associated with the prototype of SNe connected with GRBs (Della Valle 2011). We have transposed the data of the “bump” Rc-band light curve of the GRB-SN-IGC sources confirms the presence of an IGC mechanism operating also in GRB 970828.

6. Limits on the Episode 4: SN-related observations

The analysis of GRB 090618 (Izzo et al. 2012b) and GRB 101023 (Penacchioni et al. 2012) represents an authentic “Rosetta Stone” for the understanding of the GRB-SN phenomenon. The presence of a supernova emission, observed ten days after the burst in the cosmological rest-frame of GRB 900618, was found to have the same luminosity of SN 1998bw (Cano et al. 2011), the SN related to GRB 980425 and which is the prototype of SNe connected with GRBs (Della Valle 2011). We have transposed the data of the “bump” Rc-band light curve observed in the optical afterglow of GRB 090618, associated to the presence of an underlying supernova (Cano et al. 2011), to the redshift of GRB 970828. This simple operation concerns only the transformation of the flux observed, under the assumption that the SN has the same intrinsic luminosity. Moreover, we have also transposed the U and R-band light curves of SN 1998bw (Galama et al. 1998), which is the prototype of a supernova associated to a GRB. From the K−correction transformation formula, the U−band light curve, transposed at z=0.9578, corresponds approximately to the observed R−band light curve, so in principle we should consider the U = 365 nm transposed light curve as the actual one observed with the Rc = 647 nm optical filter. These transposed light curves are shown in Fig. 13. We conclude that the Supernova emission could have been seen between 20 and 40 days after the GRB trigger, neglecting any possible intrinsic extinction. The optical observations were made up to 7 days from the GRB trigger, reaching a limit of R ~ 23.8 (Groot et al. 1998) and subsequent deeper images after ~ 60 days (Djorgovski et al. 2001), so there are no observations in this time interval. It is appropriate to notice that the R-band extinction value should be large since the observed column density from the X-ray observations of the GRB afterglow of the SN is high as well (Yoshida et al. 2001): the computed light curve for the possible SN of GRB 970828 should be lowered by more than 1 magnitude, leading to a SN bump below the R = 25.2 limit, see Fig. 13. The presence of very dense clouds of matter near the burst site might have darkened both the supernova emission and the GRB optical afterglow. Indeed we find the presence of clouds in our simulation at the average distances of ~10^{15}−10^{16} cm from the GRB progenitor, with average density of \langle n \rangle \approx 10^{3} \text{part/cm}^3 and typical dimensions of (4−8) \times 10^{14} cm, see Fig. 10.

7. Conclusions

In conclusion, the recent progress in the observations of X and γ-ray emission, with satellites such as Swift, Fermi, AGILE, Suzaku, Coronas-PHOTON, the possibility of observing GRB afterglows with the new generation of optical and radio telescopes, developed since 1997, and the theoretical understanding in the IGC GRBs-SNe paradigm, have allowed to revisit the data of GRB 970828 and give a new conceptual understanding of the underlying astrophysical scenario.

We verify in this paper that GRB 970828 is a member of the IGC GRBs-SNe family. This new understanding leads to a wealth of information on the different emission episodes which are observed during an IGC process. In Episode 1, we determine the evolution of the thermal component and of the radius of the blackbody emitter, given by Eq. (1), see Figs. 5, 5. The onset of the SN is here observed for the first time in an unprecedented circumstance: a SN exploding in a close binary system with a companion NS. The energetics are correspondingly much larger than the one to be expected in an isolated SN, and presents an high energy component likely associated to an outflow process in the binary accreting system. In Episode 2, the GRB, we give the details of the CBM structure, see Fig. 10, of the simulation of the light curve and the spectrum of the real GRB emission, see Fig. 11. We have also shown in Table 3 the final results of the GRB simulation, the total energy of the e^+e^− plasma, the baryon load B, the temperature of the P-GRB kT_{th} and the Lorentz Gamma factor at transparency Γ, as well the average value of the CBM density \langle n_{CBM} \rangle and the density ratio of the clouds δn/n. In Episode 3, we have shown that the late afterglow emission observed by ASCA and ROSAT, although limited to few data points, when considered in the cosmological rest-frame of the emitter, presents a successful overlap with
the standard luminosity behavior of other members of the IGC family (Pisani et al. 2013), which is the most striking confirmation that in GRB 970828 an IGC process is working. Finally, from this latter analogy with the late X-ray afterglow decay of the “Golden Sample” (Pisani et al. 2013), and with the optical bump observed in GRB 090618, see Fig. 13, associated to a SN emission (Cano et al. 2011), we have given reasons why a SN associated to GRB 970828 was not observable due to the large interstellar local absorption, in agreement with the large column density observed in the ASCA X-ray data Yoshida et al. (2001) and with the large value we have inferred for the CBM density distribution, \( n_{CBM} \approx 10^5 \) particles/cm\(^3\).

The possibility to observe the energy distribution from a GRB in a very wide energy range, thanks to the newly space missions dedicated, has allowed to definitely confirm the presence of two separate emission episodes in GRBs associated to SNe. Future planned missions, as the proposed Wide Field Monitor detector on board the LOFT mission (Feroci et al. 2012), will allow to observe the thermal decay from these objects down to \( kT = 0.5 – 1 \) keV. It is important to note the possibility that the Large Area Detector, designed for the LOFT mission, will be also able to observe the afterglow emission from times larger than \( 10^5 \) s in the rest-frame, allowing to check possible new IGC GRBs-SNe by using the overlapping method described in (Pisani et al. 2013; Izzo et al. 2013) and consequently estimate the distance, wherever an observed determination of the redshift is missing.

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Appendix A: Detailed constraints on the non-thermal outflow from observations

We reproduce in Fig. A.1 the plots of the Lorentz factor \( \Gamma \) of the non-thermal emitter at the condition \( \tau_{\gamma \gamma} = 1 \) as function of the radius \( r \).

From the following equation

\[
\tau_{\gamma \gamma} = \frac{\langle \sigma_N \rangle_{\text{max,th}}}{4\pi r^2} = 1 ,
\]

we have constructed the function \( \Gamma = \Gamma(r) \) for each choice of \( E_\gamma \). As we can see in Fig. A.1, for \( \Gamma = 1 \) the size of the emitter is quite insensitive to the value of \( E_\gamma \), being \(-2.2-3.5\) \( \times 10^5 \) cm in the \( \Delta t_4 \) time interval (solid lines), and \(-2.3-3.8\) \( \times 10^6 \) cm in the \( \Delta t_3 \) time interval (dashed lines).

To find the unique couple of values \((r, \Gamma)\) which can fit the observed properties of the non-thermal components in \( \Delta t_4 \) and \( \Delta t_3 \) time intervals, we have tried to put a constraint by requiring that the on-set of the non-thermal component starts \( \delta t_{\text{on}} = 1 \) s before the on-set of the thermal component in the observer frame. In this way we have the additional condition \( r_{\text{on}} = 2\Gamma^2 \delta t_{\text{on}} \), which is plotted in Fig. A.1 (solid black power-law) giving \( \Gamma(r) \) and \( E_\gamma \). The most stringent constraint comes from the comparison of the observed non-thermal fluxes in the energy range 25-1900 keV with the intrinsic ones in the co-moving frame of the non-thermal emitter. It is well known that the observed luminosity \( L \) of a relativistic moving, continuous and isotropic source is related to its intrinsic luminosity \( L_\text{in} \) through \( L = [D/(1+z)]^2 L_\text{in} \) (Urry & Padovani 1995), where \( D = [\Gamma(1 - \beta \cos \theta)^{-1}]^{-3} \) is the Doppler factor, \( \beta = v/c \) is the velocity of the expanding source in units of \( c \) and \( \gamma \) is the spectral index of the power-law spectrum. The spectral energy distribution (SED) of photons in the co-moving frame is a cut-off power-law with the cut-off energy \( m_e c^2 \), as it follows from Eq. (10), and photon index \( \gamma \). For isotropic emitting sources, the normalization constant of the
Fig. A.1. Plots of the Lorentz factor $\Gamma$ of the non-thermal emitter at the condition $r_{on} = 1$ as function of the radius $r$ for six values of the cut-off energy (from the lower to the upper curves): $E_c = 1.9$ (cyan), 3.0 (green), 4.3 (blue), 5.9 (purple), 7.7 (red) and 10 MeV (orange). The horizontal gray lines correspond to the asymptotic values of the Lorentz factor, corresponding to the above values of $E_c$, i.e. $E_{\text{max}} = 7.23$, 11.5, 16.5, 22.6, 29.5 and 38.3. The solid black power-law represents additional condition $r_{on} = 21 \Gamma_c$, assuming the on-set of the non-thermal component to start $\delta t_{on} = 1$ s before the on-set of the thermal component in the observer frame. The results for $\Delta t_a$ and $\Delta t_b$ time intervals are shown, respectively, with solid and dashed curves.

SED in the co-moving frame $K'$ is related to the observed one $K$ through $K' = (D/r)^2 K$. Therefore the non-thermal bolometric observed luminosity $L_{\text{bol}}$ expressed in terms of intrinsic physical quantities is

$$L_{\text{bol}} = 2\pi r^2 \int^{+\infty}_{-\infty} K'E^{-1-\gamma}e^{-E/E_c}dE' \int_{-1}^{+1} \left( \frac{D}{1+z} \right)^{3+\alpha} \mu d\mu,$$

where $\mu = \cos \theta$ and $\beta$ can be expressed as $\beta = \sqrt{1 - \Gamma}$. The non-thermal flux in the observed energy band with energies $E_1 = 25$ keV and $E_2 = 1900$ keV is a function of the Lorentz factor $\Gamma$ and can be computed as

$$F(\Gamma) = \frac{L_{\text{bol}}}{4\pi D^2} W(E_1, E_2, E_c).$$

where the effective weight $W(E_1, E_2, E_c)$ can be expressed as

$$W(E_1, E_2, E_c) = \int_{E_1}^{E_2} \int_{0}^{+\infty} E^{1-\gamma} e^{-E/E_c} dE \int_{-1}^{+1} \frac{D}{1+z}^{3+\alpha} \mu d\mu.$$

In the computation described in Eqs.(A.2)–(A.4) we have used the redshift $z = 0.9578$, the normalization constants of the non-thermal components, $K_\alpha = (6.73 \pm 0.34) \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1+\beta}$ and $K_\beta = (9.44 \pm 0.51) \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1+\beta}$, and their photon indexes $\gamma_\alpha = 1.46 \pm 0.03$ and $\gamma_\beta = 1.54 \pm 0.03$ (the subscripts $\alpha$ and $\beta$ indicate, respectively, time interval $\Delta t_a$ and $\Delta t_b$).

We have computed $F(\Gamma)$ and compared to the observed values, i.e. $F_{obs,a} = (1.04 \pm 0.05) \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$ for $\Delta t_a$ and $F_{obs,b} = (9.26 \pm 0.50) \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ for $\Delta t_b$. Correspondingly, we have inferred two values of the Lorentz factor, respectively, $\Gamma_a = 9.88 \pm 0.46$ and $\Gamma_b = 8.00 \pm 0.34$ (see Fig. A.2).

Finally, we have calculated the radius of the non-thermal emitter from the formula $r_{on} = 21 \Gamma_c$. We have found, respectively, $r_{on,a} = (5.85 \pm 0.54) \times 10^{12}$ cm in the $\Delta t_a$ time interval and $r_{on,b} = (3.84 \pm 0.33) \times 10^{12}$ cm in the $\Delta t_b$ time interval.