SWIFT OBSERVATIONS OF GRB 070110: AN EXTRAORDINARY X-RAY AFTERGLOW POWERED BY THE CENTRAL ENGINE.

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ABSTRACT

We present a detailed analysis of Swift multi-wavelength observations of GRB 070110 and its remarkable afterglow. The early X-ray light curve, interpreted as the tail of the prompt emission, displays a spectral evolution already seen in other gamma-ray bursts. The optical afterglow shows a shallow decay up to ∼2 d after the burst, which is not consistent with standard afterglow models. The most intriguing feature of the observed decay is a very steep decay in the X-ray flux at ∼2×10^4 s after the burst, ending an apparent plateau. The abrupt drop of the X-ray light curve rules out an external shock as the origin of the plateau in this burst and implies long-lasting activity of the central engine. The temporal and spectral properties of the plateau phase point towards a continuous central engine emission rather than the episodic emission of X-ray flares. We suggest that the observed X-ray plateau is powered by a spinning down central engine, possibly a millisecond pulsar, which dissipates energy at an internal radius before depositing energy into the external shock.

Subject headings: gamma rays: bursts; X-rays: individual (GRB 070110)

1. INTRODUCTION

The Swift Gamma Ray Burst Explorer (Gehrels et al. 2004) is a multi-wavelength observatory specifically designed to study gamma-ray burst (GRB) evolution from their early stages. It is equipped with a wide-field instrument, the Burst Alert Telescope (BAT; Barthelmy et al. 2005a), covering the 15-350 keV energy band, and two narrow field instruments, the X-Ray Telescope (XRT; Burrows et al. 2005a) and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005), covering the 0.2-10 keV band and the 1700-6500 Å wavelength range, respectively.

During the first two years of its mission Swift detected ∼200 bursts, providing well-sampled X-ray and optical afterglow light curves. Nousek et al. (2006) and Zhang et al. (2006a) identified a common pattern in the X-ray light curves, described as consisting of three power law segments: an early steep decay with a temporal slope 3≤α≤5 lasting up to ∼300 s, followed by a shallower phase (0.5≤α≤1); the slope of the light curve steepens again (1.0≤α≤1.5) at ∼10^3-10^4 s after the burst onset. X-ray flares, overlaid on the underlying power law decay, have been detected up to 10^5 s after the BAT trigger (Burrows et al. 2005b; Chincarini et al. 2007).

O’Brien et al. (2006) modeled the observed shape of early X-ray light curves with an exponential decay that relaxes into a power law and, in most cases, presents the shallow phase. They showed that the initial rapid decay is a smooth extension of the prompt emission, probably due to emission from large angles relative to the observer’s line of sight (Kumar & Panaitescu 2000). A long-lasting energy injection into the forward shock, due either to a late internal activity or to a radial distribution of Lorentz factors, has been invoked to interpret the shallower stage of the X-ray light curve (Rees & Mészáros 1998; Zhang & Meszaros 2002b; Granot & Kumar 2006). This explanation is consistent with the final smooth steepening into the “standard afterglow” decay (Mészáros & Rees 1997).

The afterglow of GRB 070110 cannot be easily traced back to this well-known scenario. Its early X-ray light curve seems to display a canonical shape, with an initial steep decay and then a very flat plateau phase (α ∼0.05), but ∼2×10^4 s after the trigger the count rate drops abruptly by more than one order of magnitude with a slope α>7 (Sbarufatti et al. 2007; Krimm et al. 2007a). The behavior of the optical afterglow seen by the UVOT is very different, showing a shallow smooth decay remaining fairly bright at later times.

In the light of the unique properties of its afterglow, the Swift team identified GRB 070110 as a ‘burst of interest’ encouraging a follow-up campaign (Krimm et al. 2007b).

The optical afterglow of GRB 070110 (Krimm et al. 2007a) was also detected by the ESO VLT equipped with...
the FORS2 instrument. A redshift of $z=2.352±0.001$ has been inferred on the basis of several absorption features in the spectra (Jaunsen et al. 2007). Further VLT observations, performed $\sim$10.7 d after the burst, detected a fainter than predicted afterglow, suggesting the presence of an optical break (Malesani et al. 2007a).

In this paper we report on the $\gamma$-ray, X-ray and optical observations performed by Swift. The paper is organized as follows: in § 2 we present a multiwavelength timing and spectral analysis of both the prompt and the afterglow emission; in § 3 we discuss our results. Finally, in § 4 we summarize our findings and conclusions.

Throughout the paper, times are given relative to the BAT trigger time $T_0$, $t=T-T_0$, and the convention $F_{\nu,\lambda} \propto \nu^\beta t^{-\alpha}$ has been followed, where the energy index $\beta$ is related to the photon index $\Gamma = \beta + 1$. We have adopted a standard cosmology model with Hubble constant $H_0=70$ km s$^{-1}$ Mpc$^{-1}$ and cosmological constants $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$ (Spergel et al. 2006). The phenomenology of the burst is presented in the observer time frame, unless otherwise stated.

All the quoted errors are given at 90% confidence level for one interesting parameter ($\Delta \chi^2=2.706$, Lampton et al. 1976).

2. DATA ANALYSIS

2.1. Observations

GRB 070110 triggered the Swift BAT at 07:22:41 UT on 10th January, 2007. The Swift narrow field instruments, XRT and UVOT, began observing 93 s and 85 s after the trigger, respectively. An accurate afterglow position was rapidly determined by the UVOT at R.A.$=00^h03^m39.20^s$, Dec.$=-52^\circ58'26.3''$ (J2000, Krinn et al. 2007a), with an uncertainty of 1 arcsec.

XRT observations began with an initial 2.5 s image mode frame and then, as the source was bright ($\sim$40 cts s$^{-1}$), collecting data in Window Timing (WT) mode. The XRT automatically switched to Photon Counting (PC) mode when the source decreased to $\sim$2 cts s$^{-1}$. Follow-up observations lasted 26 days for a total net exposure of 165 s in WT mode and 330 ks in PC mode.

The UVOT took a short exposure with the V filter while the spacecraft was settling at the end of the initial slew. This exposure was followed by a “finding chart” exposure with the White filter lasting 100 s and then an exposure with the V filter lasting 400 s. UVOT then began its usual procedure of cycling through its 3 visible filters (V, B, and U) and 3 UV filters (UVW1, UVW2, and UVM2). The optical afterglow was detected in the White, U, B, and V filters, but not in the UV filters. The lack of detection of the afterglow in the UV filters is consistent with the measured redshift. A total of 219 UVOT exposures were taken in the first 6.7 days, after which the afterglow fell below the detection thresholds.

2.2. Gamma-ray data

We analyzed BAT event data using the standard BAT analysis software included in the NASA’s HEASARC software (HEASOFT, version 6.1.2). Fig. 1 presents the BAT mask-weighted light curve in the 15-150 keV energy band. It shows a first main peak at $t\sim0$ s and then a decay on which several peaks are superposed; emission is visible until $t\sim100$ s. We estimated the burst duration, defined as the interval containing 90% of the total observed fluence, to be $T_{90}$ (15-150 keV)$=89\pm7$ s.

Spectra were created using the task batbinevt, updating relevant keywords with batupdatephakw. The corresponding response matrices were generated by the task batdrmgen. Systematic errors were properly added to the spectra. Since the spacecraft slew started $\sim40$ s after the trigger, we created two different spectra (before and during the slew) with the appropriate response matrices and performed a joint fit.

The time-averaged $T_{90}$ spectrum (from -0.4 s to 89 s) can be fitted with a simple power law of photon index 1.57$\pm0.12$. A cut-off power law or a Band model (Band et al. 1993) do not provide a better description and cannot constrain the peak energy value. In the hardness ratio light curves, comparing different BAT energy bands, no sign of a significant spectral evolution is present throughout the prompt emission.

The fluence over the 15-150 keV band is $(1.8^{+0.2}_{-0.3})\times10^{-6}$ erg cm$^{-2}$, from which we derive an observed isotropic energy of $2.3\times10^{52}$ erg. This value can be considered as a lower limit to the isotropic energy, $E_{\gamma,iso}$, which is defined over a larger energy band (1 keV-10 MeV in the source rest frame). Extrapolating our best fit model over the whole 1 keV-10 MeV (source rest frame) we estimate an upper limit of $E_{\gamma,iso}\leq1.3\times10^{53}$ erg. This value is derived under the extreme assumption that the best description of the spectrum is Band law (Band et al. 1993) with a peak energy $E_p > 10$ MeV in the source rest frame.

2.3. X-ray data

XRT data were processed using the XRTDAS software package (v. 2.0.1) distributed within HEASOFT. We used the latest release of the XRT Calibration Database (CALDB 2.6) and applied standard screening criteria to obtain the final cleaned event list. We selected only events with grades 0-12 for PC mode data and 0-2 for WT mode data. Such a selection provides the best combination of spectral resolution and detection efficiency. Our analysis has been performed over the 0.3-10 keV energy band.
Temporal analysis

We extracted WT data in a rectangular region, 40×20 pixels wide, centered on the source position. The background contribution was estimated from a region, with the same shape and size, sufficiently offset (>2 arcmin) from the source position to avoid contamination from the PSF wings and free from contamination by other sources.

The first 300 s of PC observations were affected by pile-up. To account for this, we chose an annular extraction region centered on the source, having an inner radius of 4 pixels and an outer radius of 30 pixels. From the second orbit on (t≥3×10^4 s), when pile-up is no longer present, the source count rate was estimated in a circular region with a 30 pixels radius. The count rate evolution in the later observations (t>3×10^5 s) was obtained using the task sosta of the ximage package, using an extraction region that optimizes the signal to noise ratio of the detection.

All the light curves presented here are background subtracted and corrected for Point Spread Function (PSF) losses, vignetting effects and exposure variations.

The 0.3-10 keV light curve is shown in Fig. 2 (upper panel). WT and PC data were binned to achieve a minimum signal to noise ratio of 8 and 5, respectively. Late points (t≥10^5 s) are 3σ detections. We also included the detection taken in Image (IM) mode, converting Digital Number (DN) units into count rate (Hill et al. 2006; Mangano et al. 2007b).

The light curve has been modeled with power law segments of different slopes, whose best fit parameters are reported in the second column of Table 1. The best fit model is shown by the solid line in the upper panel of Fig. 2. We also performed a fit of the light curve with a simple broken power law, excluding from the analysis the plateau and the following steep drop. The bump at t~530 s is modeled with a Gaussian function, the late one at t~5×10^4 s with a FRED profile. The four phases of the X-ray light curve are marked: (I) an early decay, (II) an apparent plateau followed by (III) a rapid drop, and (IV) a final shallow decay. Middle panel: Hardness ratio (H/S) light curve. It compares source counts in the hard band (H: 1-10 keV) and in the soft band (S: 0.3-1 keV). Lower panel: Photon index ΓXRT temporal variations. These values were derived fitting the X-ray spectra with an absorbed power law model.

### Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model 1 Multiple broken PL</th>
<th>Model 2 Simple broken PL</th>
</tr>
</thead>
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<tr>
<td>α1</td>
<td>2.44±0.13</td>
<td>2.45±0.13</td>
</tr>
<tr>
<td>t_break,1 (s)</td>
<td>570±50</td>
<td>730±270</td>
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<tr>
<td>α2</td>
<td>0.09±0.07</td>
<td>0.72±0.06</td>
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<tr>
<td>t_break,2 (ks)</td>
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<td>–</td>
</tr>
<tr>
<td>α3</td>
<td>9.0±1.0</td>
<td>–</td>
</tr>
<tr>
<td>t_break,3 (ks)</td>
<td>29±2</td>
<td>–</td>
</tr>
<tr>
<td>α4</td>
<td>0.71±0.08</td>
<td>–</td>
</tr>
</tbody>
</table>
source counts in the soft band (S: 0.3–1 keV). An initial hard-to-soft evolution is present followed by a hardening in the X-ray light curve at \( \sim 530 \) s. The hardness ratio shows an increasing trend at the beginning of the observed plateau and spectral variations throughout it. The very steep drop displays a hard-to-soft evolution. Later points (\( t \geq 10^5 \) s) have a harder spectrum, maybe due to a late flaring activity, as the fluctuations in the light curve suggests. At times later than \( 2 \times 10^3 \) s the afterglow evolution does not show any further spectral variation.

2.3.2. Spectral analysis

In order to quantify the spectral variations seen in the hardness ratio light curve, we performed a time-resolved spectral analysis.

Source and background spectra were extracted from the same regions used to create light curves (§ 2.3.1). The relevant ancillary response files were generated using the task \texttt{xrtmkarf}. Time intervals were selected according to light curve phases and to have at least 400 net counts each. Only the first PC orbit spectrum (from 266 s to 644 s) has a lower statistical quality ( \( \sim 200 \) source counts), due to the presence of pile-up. Spectral channels were grouped so to have at least 20 counts each. The \( \chi^2 \) statistic was applied.

All the X-ray spectra can be modeled with an absorbed power law. The Galactic absorption component was kept fixed at the value of \( 1.86 \times 10^{20} \) cm\(^{-2}\) (Dickey & Lockman 1990); an additional redshifted absorption component, modeling the host intrinsic absorption, was also included. In order to estimate the host absorption we extracted a WT (from 100 s to 265 ks) and a PC spectrum (from 4 ks to 30 ks). Since at low energies (\( \sim 0.5 \) keV) XRT spectra may be affected by calibration uncertainties\(^1\), we performed our analysis excluding energy channels in the range 0.45–0.55 keV. From the joint spectral fit we obtained an intrinsic absorption value \( N_{\text{H}}^{\text{host}} = (2.6 \pm 1.1) \times 10^{21} \) cm\(^{-2}\).

We then performed time-resolved spectral fits keeping the absorption fixed as above and leaving only the photon index \( \Gamma_X \) and the normalization as free parameters. We also tested whether the initial softening of the spectrum could be due to a decreasing intrinsic absorption, as previously witnessed in other GRBs (Cusumano et al. 2007, Campana et al. 2006), but the low number of counts did not allow us to constrain the \( N_{\text{H}}^{\text{host}} \) behavior.

In order to estimate the spectral index during the final shallow decay, we extracted a spectrum in the time interval from 5.8 \( \times 10^3 \) s to 1.4 \( \times 10^6 \) s, using a circular region of 5 pixels radius centered on the source position. Because of the low number of counts (\( \sim 120 \)) and the negligible background contamination, the Cash statistic was applied (Cash 1979). We obtained \( \Gamma_X = 2.17 \pm 0.20 \).

The selected time intervals and results from the spectral fit are listed in Table 2. The photon index variations with time are reported in the lower panel of Fig. 2.

2.4. Ultraviolet/Optical data

Independent measurements of the position of the afterglow were made after summing the images taken during the first day after the trigger for the White, \( V \), \( B \), and \( U \) filters. The mean position is R.A. = \( 00^\circ 03^\prime 39.23^\prime \), Dec. = \( 52^\circ 58^\prime 26.9^\prime \) with an estimated 1\( \sigma \) uncertainty of 0.25" in each direction, based on the rms deviation of the four measurements. This position is consistent with the ground-based position given in Malesani et al. (2007b).

We performed photometry using a circular aperture of radius 3.5" centered on the position of the optical afterglow. This choice allows us to minimize the background contribution. Aperture corrections were computed us-

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\( ^1 \) http://heasarc.gsfc.nasa.gov/docs/swift/analysis/
Fig. 3.— Combined BAT, XRT and UVOT light curves. BAT and XRT count rates were converted into monochromatic fluxes using the results from the spectral analysis. UVOT magnitudes were corrected for the Galactic extinction and converted into flux densities at the central wavelength of each filter. In the plot UVOT flux values have been scaled by a factor $10^{-3}$. The optical best fit models, discussed in the text, are shown by solid lines. The dashed line shows the broken power law model (model 2). The vertical dashed-dotted lines mark the times at which SEDs were computed.

The Galactic reddening in the burst direction is $E(B-V) = 0.014$ (Schlegel et al. 1998). Using the value from the extinction curve in Pei (1992) for the Milky Way at the central wavelength of each filter, we estimated the extinction for the UVOT filters to be $A_V = 0.04$ mag, $A_B = 0.06$ mag and $A_U = 0.07$ mag.

With the exclusion of the first detection in the $U$ and in the $V$ filter, the UVOT light curves show a decaying behavior that can be well described by a simple power law. An independent fit of the three light curves gives the following temporal slopes: $\alpha_V = 0.60 \pm 0.13$, $\alpha_B = 0.43 \pm 0.10$, $\alpha_U = 0.57 \pm 0.14$. Including in the fit also the late VLT detection in the $V$ band, reported in Malesani et al. (2007a), the slope $\alpha_V$ steepens to $0.77 \pm 0.05$. Alternatively, we attempted a fit with a broken power law, which gives an initial decay of $0.6 \pm 0.2$, steepening at $\sim 150$ ks to $1.1 \pm 0.2$. Both models provide a good description of the light curve in the $V$ band.

A joint fit of the three UVOT light curves has been performed using the functional form of Willingale et al. (2007). We allowed the normalizations to vary independently, tying other parameters. Upper limits and the VLT detection were not considered in the fit. We found that our light curves follow a power law decay with a common slope of $0.57 \pm 0.13$.

Fig. 3 presents the multi-wavelength light curve of GRB 070110, including $\gamma$-ray, X-ray and UV/optical data. Both BAT and XRT light curves were converted into flux units using the best fit spectral models. The $V$, $B$ and $U$ magnitudes were corrected for Galactic extinction along the line of sight and then converted to monochromatic fluxes at the central wavelength of each filter. The best fit model of the three UVOT light curves with the Willingale et al. (2007) function are shown by solid lines. For a comparison we report the broken power law model (model 2), described in § 2.3.1 (dashed line in Fig. 3).

2.5. Optical/X-ray Spectral Energy Distributions

We calculated the Spectral Energy Distribution (SED) at four representative times: $t=400$ s during the initial decay, $t=5.5$ ks and $t=17$ ks at the beginning and at the end of the plateau phase, and $t=100$ ks during the
Fig. 4.— Optical, ultraviolet and X-ray SEDs at 400 s, 5.5 ks, 17 ks, and 100 ks. UVOT points have been corrected for the Galactic extinction $A_V = 0.04$ along the line of sight (empty symbols) and for a host extinction of $A_V = 0.12$ with an SMC-like extinction curve (filled symbols). The dashed line is the best fit of the optical data corrected only for $A_V = 0.04$. The dot-dashed line is the best fit of the optical data corrected for both the Galactic and the host intrinsic extinctions. The solid black lines define the cone corresponding to the 90% uncertainty on the spectral slope in the X-ray band. This cone is extrapolated to the optical band through the dotted lines. The X-ray fluxes, extrapolated at $t=5.5$ ks and $t=17$ ks according to our model 2, and the corresponding error cones are also shown (grey solid lines).

shallower decay. The four times are marked by vertical lines in Fig. 3.

Fig. 4 shows the four SEDs derived from the optical and X-ray light curves. Flux values in the UVOT filters at the selected times are corrected for Galactic extinction (empty symbols) and were derived from the best fit models shown in Fig. 3. X-ray data were converted into flux units for each time selecting the appropriate photon index value from Table 2. X-ray fluxes and their error regions are shown by the black cones. The contribution of the host galaxy to extinction have been estimated as the additional extinction required to have optical and X-ray data roughly lying on the same power law at $t=100$ ks. Accounting for a host extinction of $A_V=0.12$ mag with the extinction curve for the Small Magellanic Cloud (SMC; Pei 1992) provides a better match between optical and X-ray data. The entire data set at the later times is consistent with a common physical origin. UVOT fluxes corrected for both the Galactic and the intrinsic extinctions are shown by filled symbols. The best fit power law of the optical SED is shown by the dot-dashed line.

At 400 s the optical data are consistent with the extrapolation of the X-ray spectrum to low energies, but the spectral slope in the optical does not extrapolate to the X-ray band, implying a spectral break near the UV, and suggesting different origins for the optical and X-ray photons. At 5.5 ks and 17 ks, during the apparent plateau, the optical and X-ray spectral distributions are completely inconsistent with one another, implying different origins.

In § 2.3.1 we have shown that the X-ray light curve, excluding the plateau, can be fitted with a simple two component broken power law plus flares. Since the slope of this power law is marginally consistent with that observed in the optical bands, it follows that the SED consistency observed at late times also applies to this component.

This is illustrated in Fig. 4 (top right panel and bottom left panel), where we have extrapolated the late-time SED to 5.5 and 17 ks, using light curve model 2 (third
column in Table 1) to evaluate the X-ray count rates. These values were derived using the photon index value at late times (t>580 ks). The extrapolated values and their error regions are shown by the grey cones.

If we assume for the host galaxy of GRB 070110 the same gas-to-dust ratio measured in the SMC, N_H/A_V=1.6×10^{22} cm^{-2} mag^{-1} (Weingartner & Draine 2000), an intrinsic hydrogen column density of 2×10^{21} cm^{-2} can be derived from the estimated A_V. Accounting for the low SMC metallicity (∼Z/⊙/8), the intrinsic absorption required from X-ray spectra is (1.6±0.7)×10^{22} cm^{-2}, higher than the one expected from a SMC-like gas-to-dust relationship.

3. DISCUSSION

3.1. The Early X-Ray Tail

As shown in Fig. 2 (upper panel), the X-ray light curve is composed of four distinct components. It starts with (I) an early steep decay component with α = 2.44±0.13 following the prompt gamma-rays. The early decay is followed by (II) a plateau with an essentially constant flux which extends up to t~20 ks. Luminosity fluctuations are seen throughout the plateau phase. Following the plateau is (III) a remarkable steep drop with a temporal index of ∼−9.0. After this steep fall the afterglow light curve rises again, showing a late flare, then enters (IV) a more normal decay segment with α ~0.7.

The hardness ratio light curve (Fig. 2, middle panel) shows an initial hard-to-soft spectral evolution during the early decay. Our spectral analysis confirms a softening of the spectral index β_X from a value of 0.8 to 1.2. The early X-ray decay has been generally interpreted as the prompt emission tail, due to the delay of propagation of photons from high latitudes with respect to the line of sight (Tagliaferri et al. 2005; Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2006a).

The curvature effect alone, which suggests α=2+β (Kumar & Panaitescu 2000), cannot explain both the spectral evolution feature and the shallower than expected temporal slope. Such behavior has been seen in other GRBs detected by Swift and, as reported by Zhang et al. (2006b), spectral evolution seems a common feature in early, bright GRB tails (e.g. GRB 060614, Mangano et al. 2007a). Phenomenological models involving an underlying central engine afterglow with a steep spectral index or an internal shock afterglow with a cooling frequency passing through the XRT window may be candidates to interpret these spectral evolutions (Zhang et al. 2006b).

3.2. The Plateau Phase

The observed plateau is a feature of great interest. This component displays an apparently constant intensity extending up to t~20 ks, followed by an abrupt drop with a very steep decay index. Compared with the canonical XRT light curves GRBs observed by Swift (Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2006a; Willingale et al. 2007), such a steep decay following a plateau is unique.

In most other Swift GRBs, the plateau is followed by a “normal” decay which could be generally interpreted as the standard external forward shock afterglow. The plateau in those cases is therefore consistent with a refreshed shock (Rees & Meszaros 1998; Zhang et al. 2006a; Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2006b). Phenomenological models involving an internal shock afterglow with a cooling frequency passing through the XRT window may be candidates to interpret these spectral evolutions (Zhang et al. 2006b).

Several other GRBs have previously shown similar, but not exactly the same, behavior. The afterglow of GRB 051117A (Goad et al. 2007) shows a sharp drop of the X-ray flux at ~10^4 s, followed by a shallower decay (α~0.7). However, in this case the early X-ray light curve seems dominated by flaring activity and it does not show any evident plateau. Fig. 5 compares the rest frame light curves of both GRB 050904 and GRB 070110. GRB 050904 (Cusumano et al. 2006, 2007) shows a remarkably similar behavior to GRB 070110, with a rapid decay following the multiple episodic X-ray flares. However, GRB 070110 displays a much smoother emission...
eral discussion of a central engine with decaying luminosity taking place over an extended period of time (Shapiro & Teukolsky 1983; Zhang & Mészáros 2001). The duration of the plateau depends on the unknown pulsar parameters, but given a reasonable radiation efficiency, the luminosity (∼10^{48} \text{ ergs}^{-1}) and the observed duration (∼16 ks) of the plateau are consistent with the parameters of a new-born magnetized millisecond pulsar as the GRB central engine.

According to Zhang & Mészáros (2001), the continuous injection luminosity $L_{\text{em},0}$ and the characteristic time scale $\tau_{\text{em}}$, when the plateau breaks down, are related to the pulsar initial parameters:

$$L_{\text{em},0} \sim 10^{69} B_{p,15}^2 P_{0,-3}^{-4} R_6^6 \text{ erg s}^{-1}. \quad (1)$$

$$\tau_{\text{em}} \sim 2.05 \times 10^3 I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6} \text{ s}. \quad (2)$$

where $B_p = B_{p,15} \times 10^{15}$ G is the dipolar field strength at the poles, $P_{0,-3}$ is the initial rotation period in milliseconds, $I_{45}$ is the moment of inertia in units of 10^{45} g cm^2, and $R_6$ is stellar radius in units of 10^6 cm.

If we assume that a significant fraction of the spin-down luminosity is emitted in the X-ray band and take standard values of $I_{45} \sim 1$ and $R_6 \sim 1$, from the plateau parameters we can infer a pulsar initial period of $P_0 \lesssim 1$ ms and a magnetic field $B_p \gtrsim 3 \times 10^{14}$ G. The energy of the plateau puts only a lower limit to the real energy of the central pulsar $L_{\text{em},0}$ and without a good estimate of the radiation efficiency it is not possible to constrain better the pulsar parameters. It is worth to note that our estimate of $P_0$ is very close to the break-up period for a neutron star, $P_{\text{min}} = 0.96$ ms (Lattimer & Prakash 2004), so the derived pulsar parameters can be taken as good approximations of the right values.

The observed decay slope following the plateau is much steeper than the model prediction ($\alpha \sim 2$). However, accounting for detailed energy dissipation mechanisms and possible magnetic field decay at the central engine can steepen the decay (Zhang et al., in preparation). The energy dissipation mechanism of a spinning-down pulsar before deceleration is not well studied, but it may be related to the breakdown of the magneto-hydrodynamic condition in the magnetized outflow (Usov 1994; Spruit et al. 2001; Zhang & Mészáros 2002a) and powered by magnetic reconnections (Drenkhahn & Spruit 2002). Instability inside the energy dissipation regions would induce fluctuations in the emission region, giving rise to the flickering light curve and the hardness ratio variations on the plateau.

### 3.3. The Final Shallow Decay

The late X-ray light curve shows a shallow power law decay, on which a flare at ∼55 ks and mini-flares up to ∼200 ks are superimposed. These flares could be again interpreted as late central engine activities (Burrows et al. 2005b; Romano et al. 2006; Falcone et al. 2006; Zhang et al. 2006a; Fan & Wei 2005) which are likely related to the episodic accretion processes and may be different from the spin-down-powered plateau.

From the SEDs analysis (§ 2.5) we derived that in the time interval 5-20 ks we observe an internal afterglow component, which contributes strongly to the X-ray but not the optical band, and a second afterglow component, likely of external shock origin, which tracks the

We propose that the engine powering the plateau could be a spinning-down pulsar, which has a constant luminosity lasting for an extended period of time (Shapiro & Teukolsky 1983; Zhang & Mészáros 2001). The duration of the plateau depends on the unknown pulsar parameters, but given a reasonable radiation efficiency, the luminosity (∼10^{48} \text{ ergs}^{-1}) and the observed duration (∼16 ks) of the plateau are consistent with the parameters of a new-born magnetized millisecond pulsar as the GRB central engine.

According to Zhang & Mészáros (2001), the continuous injection luminosity $L_{\text{em},0}$ and the characteristic time scale $\tau_{\text{em}}$, when the plateau breaks down, are related to the pulsar initial parameters:

$$L_{\text{em},0} \sim 10^{69} B_{p,15}^2 P_{0,-3}^{-4} R_6^6 \text{ erg s}^{-1}. \quad (1)$$

$$\tau_{\text{em}} \sim 2.05 \times 10^3 I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6} \text{ s}. \quad (2)$$

where $B_p = B_{p,15} \times 10^{15}$ G is the dipolar field strength at the poles, $P_{0,-3}$ is the initial rotation period in milliseconds, $I_{45}$ is the moment of inertia in units of 10^{45} g cm^2, and $R_6$ is stellar radius in units of 10^6 cm.

If we assume that a significant fraction of the spin-down luminosity is emitted in the X-ray band and take standard values of $I_{45} \sim 1$ and $R_6 \sim 1$, from the plateau parameters we can infer a pulsar initial period of $P_0 \lesssim 1$ ms and a magnetic field $B_p \gtrsim 3 \times 10^{14}$ G. The energy of the plateau puts only a lower limit to the real energy of the central pulsar $L_{\text{em},0}$ and without a good estimate of the radiation efficiency it is not possible to constrain better the pulsar parameters. It is worth to note that our estimate of $P_0$ is very close to the break-up period for a neutron star, $P_{\text{min}} = 0.96$ ms (Lattimer & Prakash 2004), so the derived pulsar parameters can be taken as good approximations of the right values.

The observed decay slope following the plateau is much steeper than the model prediction ($\alpha \sim 2$). However, accounting for detailed energy dissipation mechanisms and possible magnetic field decay at the central engine can steepen the decay (Zhang et al., in preparation). The energy dissipation mechanism of a spinning-down pulsar before deceleration is not well studied, but it may be related to the breakdown of the magneto-hydrodynamic condition in the magnetized outflow (Usov 1994; Spruit et al. 2001; Zhang & Mészáros 2002a) and powered by magnetic reconnections (Drenkhahn & Spruit 2002). Instability inside the energy dissipation regions would induce fluctuations in the emission region, giving rise to the flickering light curve and the hardness ratio variations on the plateau.

### 3.3. The Final Shallow Decay

The late X-ray light curve shows a shallow power law decay, on which a flare at ∼55 ks and mini-flares up to ∼200 ks are superimposed. These flares could be again interpreted as late central engine activities (Burrows et al. 2005b; Romano et al. 2006; Falcone et al. 2006; Zhang et al. 2006a; Fan & Wei 2005) which are likely related to the episodic accretion processes and may be different from the spin-down-powered plateau.

From the SEDs analysis (§ 2.5) we derived that in the time interval 5-20 ks we observe an internal afterglow component, which contributes strongly to the X-ray but not the optical band, and a second afterglow component, likely of external shock origin, which tracks the
optical light curves. This component dominates after the late steep drop, when the emission from the central engine switched off. The late optical/X-ray spectrum ($t=100$ ks) can be described by a continuous power law ($\beta_{opt}=0.98\pm0.10, \beta_X=1.17\pm0.19$), indicating that the optical and the late X-ray afterglow arise from the same physical component.

The shallow temporal slopes in the X-ray band ($\alpha_X\sim0.7$) and in the optical bands ($\alpha_{opt}=0.57\pm0.13$) are consistent. However we note that the observed temporal decays are not in agreement with the standard closure relations (e.g. Zhang & Mészáros 2004), which predict a temporal slope $\alpha\gtrsim1$ for both the X-ray and the optical light curves. Such shallow behavior at late times is seen in $\sim50\%$ of the X-ray light curves observed by Swift, as noted by (Willingale et al. 2007), and it may suggest that the external shock is kept refreshed by a long-lasting energy injection.

We note that the peak time of the optical light curves, $t_{peak}\sim900$ s, derived by the best fit model with the Willingale et al. (2007) function, can be interpreted as the time of the afterglow onset, as in GRB 060418 and GRB 060607A (Molinari et al. 2007). Standard afterglow models allow the initial Lorentz factor of the expanding fireball, $\Gamma_0$, to be evaluated if the peak time, $t_{peak}$, and the released isotropic-equivalent energy, $E_{\gamma,iso}$, are known parameters (Sari 1997). However, since those models does not take into account refreshing processes, in the case of GRB 070110 we are able to estimate only an upper limit to $\Gamma_0$. According to Molinari et al. (2007), $\Gamma_0\lesssim2[3E_{\gamma,iso}(1+z)^3/32\pi n m_{p}c^2\eta^3]^{1/8}$, where $n$ is the circumburst particle number density, $m_p$ is the proton mass, and $\eta$ is the radiative efficiency. Using the values of $E_{\gamma,iso}$ derived in § 2.2 and typical values of density, $n=1$ cm$^{-3}$, and radiative efficiency, $\eta=0.2$, we evaluate for this burst $\Gamma_0<230$.

4. Conclusion

GRB 070110 is a long burst ($T_{90}\sim90$ s) with a standard behavior in the $\gamma$-ray band, that shows extraordinary properties of the X-ray afterglow. The presence of a plateau followed by an unexpected steep decay implies a new emission component from a long-lasting central engine. Such constant emission may be generated by a spinning down pulsar. This mechanism indeed allows us a better interpretation of the GRB070110 phenomenology than the superposition of multiple flares. However the naive picture we discussed cannot account for the rapid decay at the end of the plateau, indicating that a more detailed theoretical study is needed. A drop of the radiation efficiency, caused by the pulsar deceleration, or a decaying magnetic field of the new-born system could help to explain the steep decay rate.

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