GRB 050904: the oldest cosmic explosion ever observed in the Universe

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Abstract. Swift discovered the high redshift (z=6.29) GRB 050904 with the Burst Alert Telescope and began observing with its narrow field instruments only 161 s after the burst onset. GRB 050904 was a long, multi-peaked, bright GRB with a presence of flaring activity lasting up to 1-2 hours after the burst onset. The spectral energy distribution shows a clear softening trend along the burst evolution with a photon index decreasing from -1.2 up to -1.9. The observed variability is more dramatic than the typical Swift afterglow, the amplitude and rise/fall times of the flares are consistent with the behavior of nearby (z $\leq$1) long GRBs and suggest the interpretation of the BAT and XRT data as a single continuous observation of long lasting prompt emission.

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INTRODUCTION

The Swift ([1]) X-ray Telescope (XRT, [2]) is providing a growing number of unprecedented observations of the early stages of GRB afterglows in the 0.2-10 keV X-ray band.

The XRT rapid ($\leq$ 2 min) response to the Swift Burst Alert Telescope (BAT, [3]) triggers has already led to the discovery of rapid early declines followed by the smoother "standard" afterglow components and dramatic flaring in the early X-ray light curves ([4, 5, 6, 7]), as well as simultaneous peaks in the final part of the soft gamma-ray (15-350 keV) light curve observed by BAT and in the initial part of the X-ray light curve for several bursts. Thanks to its fast response, and precise (about 5$''$) source localization Swift is able to alert immediately the ground-based telescopes to locate the optical counterpart and get redshift measurements before the object becomes too faint.

Here we report on the gamma-ray and X-ray observation of GRB 050904. The GRB triggered the BAT on 2005 September 4 at 01:51:44 UT ([8]). The burst was located onboard at RA_{J2000}=00h54m41s, Dec_{J2000}=+14° 08' 17" with an uncertainty of 3' radius (90% confidence level) and was quickly pointed towards by Swift. Early photometry indicated a high redshift (z>5, [9]). A photometric redshift $z = 6.1^{+0.37}_{-0.12}$ was measured by the MISTICI collaboration ([10]) and confirmed by a Subaru spectroscopic measurement of 6.29± 0.01 ([11]). A break at T_b = 2.6±1.0 days was also found in the J-band light curve by the MISTICI collaboration ([10]). Such a high redshift translates to a distance of 12.8 billion light-years from Earth. This gave GRB 050904 the distinction of being the most distant cosmic explosion ever observed.

GRB 050904 was observed by the XRT from 161 seconds up to 10 days after the burst onset, overlapping the BAT observations for about 300 seconds, before the end of the high energy prompt emission. During the first 598 seconds, data were accumulated in WT mode, while all the other data were accumulated in PC mode (see Hill et al. 2005 for an exhaustive discussionj on XRT operative modes). Hereafter, errors are reported with a 90% single parameter confidence level. The afterglow position derived with *xrtcentroid* (v0.2.7) and including the boresight correction ([12]) is RA_{J2000} = 00h54m50s.8, Dec_{J2000} = +14°05'08"2, with an uncertainty of 3"2.

For the measured redshift $z = 6.29$, the 15-350 keV BAT band corresponds to a 109-2551 keV band while the 0.2-10 keV XRT band corresponds to a 1.4-73 keV band. The observed timescales are instead streched by a factor $(1+z)$ with respect to the rest frame ones. In the following the GRB phenomenology is presented and discussed from the point of view of the source rest frame and referred to the GRB050904 onset T =2005 Sep 4, 01:51:44.3 UT.

DATA ANALYSIS

Timing Analysis

Fig. 1 (top panel) shows the evolution of the GRB flux and luminosity in the source rest frame. The observed BAT count rates were extrapolated into the XRT 0.2-10 keV band using a conversion factor evaluated from the BAT best fit spectral model (Table 1). The observed XRT count rates were converted into flux using the best fit spectral parameters listed in Table 1.

The BAT light curve displays three main peaks: two ~2-seconds long peaks at T+3.8 and at T+7.7 seconds, respectively, and a main long-lasting peak at ~T+13.7 seconds, where T is the time of the burst onset. Emission in the BAT energy range continues up to

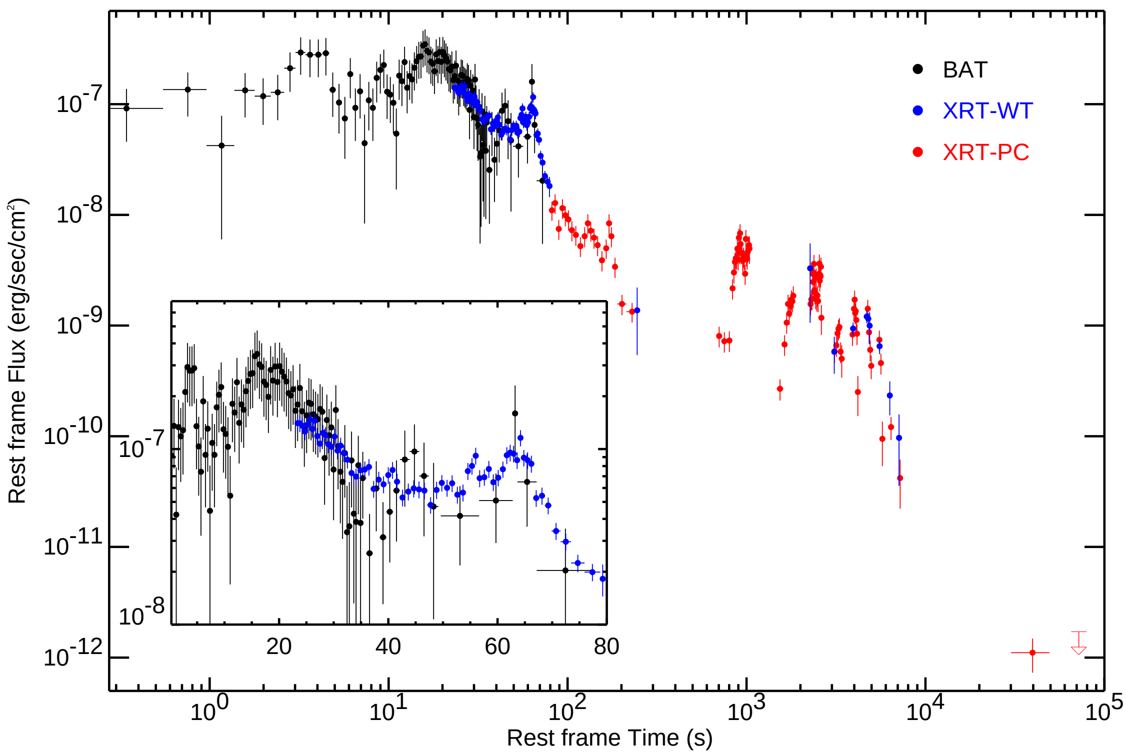

FIGURE 1. (Top panel) Light curve of GRB 050904 as observed by the BAT and XRT. Fluxes were then converted to rest frame by multiplying by $(1+z)^2$ with $z = 6.29$, and corresponds to flux emitted in the 1.4-73 keV energy band. (Bottom panel)Spectral evolution of GRB 050904 shows aphoton index Γ changing during the observation. As a guide to the reader, the intervals are highlighted with different shading.

almost T+69 seconds with a weak peak at ~T+65 seconds, coincident with the first peak of the XRT light curve. The BAT and XRT light curves overlap between T+23 and T+69 seconds. The early XRT light curve shows a steep decay with a slope $\alpha = -2.07 \pm 0.03$ with three flares superimposed at T+65 seconds, T+126 seconds and T+171 seconds. These flares can be modeled by a linear rise lasting 26.6, 5.3 and 4.7 seconds, plus an exponential decay with decay time of 4.5, 10.98 and 5.2 seconds, respectively. Although interrupted by low Earth orbit observing constrains, the light curve from GRB 050904 reveals highly irregular rate variations likely due to the presence of flares up to T+1.5 hours. At later times the flaring activity is not detected and only a residual emission, 10^5 times lower than the initial intensity, is visible.

Spectral Analysis

The spectral analysis of GRB 050904 was performed by selecting two sets of time intervals for the BAT and XRT observations, corresponding to characteristic phases of the light curve evolution. The BAT spectra were accumulated in the 14-150 keV observed band in six time intervals up to 42 seconds from the burst onset. The XRT spectra were accumulated in twelve time intervals. Instrumental energy channels below 0.2 keV and 0.7 keV for PC and WT spectra, respectively, were ignored and the background was evaluated in regions free of contamination from other sources in the field of view. The BAT spectra were modeled with a power law with photon index Γ ($F(E) \propto E^{\Gamma+1}$) while the XRT spectra were modeled with a power law plus two absorption components: one for the intrinsic absorption in the host galaxy and one for the Galactic absorption. The latter was fixed to the line-of-sight value of 4.93×10^{20} cm^{-2} **(ref)**. As a preliminary step, the intrinsic absorption column was evaluated from the PC spectra by leaving the red-shifted N_H as a free parameter. We obtained a mean value of $(2.30\pm0.50)\times10^{22}$ cm^{-2}. The spectrum of each interval was then fitted with an absorbed power law with both the Galactic column density fixed to 4.93×10^{20} cm^{-2} and the intrinsic absorption column fixed to 2.30×10^{22} cm^{-2}. More complex models, such as a Band function ([13]), cannot be constrained by the data. Fig. 1 (bottom panel)shows the evolution with time of the photon index Γ. The BAT spectra have $\Gamma \sim -1.2$, consistent with typical values of the α_{Band} parameter of the Band model ([14]). This strongly suggests that the BAT observes the low energy part of the Band function and that the peak energy of the GRB spectrum is above $150 \times (1+z)$ keV in the source rest frame. If we exclude the spectrum of the first XRT flare at T+65 seconds, the XRT photon indices show a clear decreasing trend from about -1.2 to about -1.9 in the first T+200 seconds. No further spectral evolution is present in later XRT data, in agreement with the hardness ratio curve. The BAT and XRT photon indices are in good agreement in the overlapping region. Table 1 shows the best fit parameters for each of the selected time intervals.

We also evaluated the contribution to the total fluence in the 1.4-73 keV band of the three flares (T+65, T+126 and T+171 seconds) superimposed on the early XRT light curve. The fluence over the continuum is $(1.2\pm0.08)\times10^{-6}$, $(4.7\pm0.5)\times10^{-8}$ and $(5.8\pm0.6)\times10^{-8}$ erg cm^{-2}, respectively. The fluence of the XRT continuum over the first orbit (i.e. from 23.2 to 244.4 s) is $(4.9\pm0.3)\times10^{-6}$ erg cm^{-2}. The extrapolated 1.4-73 keV BAT fluence in the time interval from the burst onset to the start of the XRT observation is $(4.1\pm xx)\times10^{-6}$ erg cm^{-2}. The three XRT flares are 5%, 1% and 1% of the total 1.4-73 keV emission observed up to T+244 s, respectively. The 1.4-73 keV fluence in the remaining part of the XRT observation is 1.8^{-6} erg cm^{-2}. This value is only a lower limit because of the observational gaps.

DISCUSSION

GRB 050904 was a long, multi-peaked, bright GRB with strong X-ray flaring activity lasting up to 1-2 hours in the source rest frame. While the variability is more dramatic than the typical Swift afterglow, the amplitude and rise/fall times of these flares are consistent with the behavior of nearby (z $\leq$1) long GRBs and suggest the interpretation of the BAT and XRT data as a single continuous observation of long lasting prompt emission. The flares in the XRT light curve could be interpreted as late internal shocks related to central engine activity. In this scenario they would have the same origin as the prompt gamma-ray emission ([15, 16, 17]). This would require that the central engine remains active up to at least 5000 seconds, consistently with the collapsar model ([18]), which allows central engine activity for up to a few hours.

In the time interval from T+23 to T+ 244 seconds, the observed intensity underlying the XRT flares decays as t^{α} with $\alpha \sim -2$. An initial steep decay of the X-ray emission has been observed in many other GRBs detected by Swift ([4, 15]). The measured decay slope together with the XRT energy index $\beta = \Gamma + 1 \sim -0.2$ are in good agreement with the interpretation of the observed emission as due to high-latitude emission ([19]). This effect arises because of the Doppler delay of radiation emitted at large angles with respect to the observer's line of sight. Radiation observed as the tail of a peak is expected to be the off-axis emission of the shocked surface arriving at the observer at later times, and would decay as t^{α} with $\alpha = \beta - 2$. After T+50 seconds, due to the decrease of β to about -1, the predicted slope would be steeper than the measured -2. This deviation could be reconciled with the high-latitude emission assuming that the delayed radiation from the outer parts of the emitting curved shell is softer than the radiation along our line of sight and that a second soft component contributes to compensate for the expected steeper decay ([16]). This additional component might be an emergent afterglow. The observational gaps after T+250 seconds do not allow us to confirm the presence of an underlying continuum at later times. The decrease of the photon index after T+50 seconds could be interpreted as an indication of a shift of E_p towards lower energies, but poor statistics and the narrowness of the XRT energy range do not allow us to verify this hypothesis.

Our lack of knowledge concerning the peak energy of the BAT and XRT spectra does not allow a precise estimate of the total energy released by GRB 050904. However, we can calculate lower and upper limits to the isotropic-equivalent radiated energy E_{iso} up to 244 seconds from the burst onset, i.e. including contributions from the first three XRT flares. To evaluate the lower limit to E_{iso} we integrated the best fit power law spectral energy distributions in the $1-200\times$(1+z) keV band and in the $1-10\times$(1+z) keV band for BAT and XRT, respectively, instead of the standard energy range 1-10^4 keV (rest frame). The upper limit was obtained in the full 1-10^4 keV band. We obtained 6.6×10^{53} erg $< E_{iso} < 3.2 \times 10^{54}$ erg. Additional contributions from the later flare portions are only a few percent. The large X-ray and gamma-ray isotropic equivalent energy of this burst is in agreement with the Amati relation ([20]) with an E_p of about 1500 keV in the rest frame.

The break observed in the optical and infrared afterglows by the MISTICI collaboration ([10]) at T_b = 2.6$\pm$1.0 days (observer frame) implies the half opening of the jet to be in the 3-4 degrees range. This corresponds to a collimation-corrected energy E_{γ} between 1.2 and 4×10^{51} erg. This is well within the E_{γ} distribution of GRBs with known redshift ([21, 22]). Consistency with the Ghirlanda relation ([23]) constrains the rest frame peak energy of the average spectrum to be within 560 and 1300 keV.

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TABLE 1. BAT and XRT spectral analysis results.

	Interval	Time Start	Time End	Γ	χ^2_ν
BAT	1	-1.43	2.69	-1.2 ±0.4	1.2 (57)
	2	2.69	4.89	-1.05±0.16	0.86 (57)
	3	4.89	10.1	-1.36±0.21	0.97 (57)
	4	10.1	20.4	-1.17±0.08	0.95 (57)
	5	20.4	30.6	-1.22±0.10	0.93 (57)
	6	30.6	41.6	-1.5 ±0.3	0.88 (57)
XRT	1	23.2	28.7	-1.13±0.07	0.70 (59)
	2	28.7	36.9	-1.31±0.06	1.13 (87)
	3	36.9	50.6	-1.34±0.06	0.81 (81)
	4	50.6	58.8	-1.78±0.07	1.23 (56)
	5	58.8	67.1	-1.50±0.07	1.18 (66)
	6	67.1	79.8	-1.88±0.12	0.78 (30)
	7	79.8	159.4	-1.80±0.10	1.00 (25)
	8	159.4	244.4	-1.96±0.19	0.82 (9)
	9	628	848	-1.81±0.22	1.51 (9)
	10	848	1040	-1.82±0.08	1.07 (37)
	11	1452	1863	-1.91±0.13	0.68 (14)
	12	2275	2618	-1.72±0.08	1.40 (35)
	13	3045	8173	-1.96±0.09	1.12 (36)

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