THE PROMPT OPTICAL/NEAR-INFRARED FLARE OF GRB 050904: THE MOST LUMINOUS TRANSIENT EVER DETECTED

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ABSTRACT

With a redshift of \( z = 6.295 \), GRB 050904 is the most distant gamma-ray burst (GRB) ever discovered. It was an energetic event at all wavelengths, and the afterglow was observed in detail in the near-infrared (NIR) bands. We gathered all available optical and NIR afterglow photometry of this GRB to construct a composite NIR light curve spanning several decades in time and flux density. Transforming the NIR light curve into the optical, we find that the afterglow of GRB 050904 was more luminous at early times than any other GRB afterglow in the pre- \textit{Swift} era, making it at these wavelengths the most luminous transient ever detected. Given the intrinsic properties of GRB 050904 and its afterglow, we discuss whether this burst is markedly different from other GRBs at lower redshifts.

Key word: gamma rays: bursts

Online material: color figure

1. INTRODUCTION

The detection of an extremely bright prompt optical flash accompanying GRB 990123 (Akerlof et al. 1999) highlighted the possibility of using gamma-ray burst (GRB) afterglows as backlighting sources to probe the high-redshift universe and the reionization era (Lamb & Reichart 2000; Inoue et al. 2004; Totani et al. 2006). This promise was finally fulfilled with the discovery of GRB 050904 by the \textit{Swift} satellite (Cusumano et al. 2006, 2007), lying at a redshift of \( z = 6.295 \) (Kawai et al. 2006). Not only was a bright NIR afterglow discovered for this GRB (Haislip et al. 2006; Tagliaferri et al. 2005), a prompt flash contemporaneous to the gamma-ray emission was seen by the robotic 25 cm TAROT telescope (Böer et al. 2006).

Had the prompt optical flash of GRB 990123 been at a redshift of \( z = 1 \) and had it been unextinguished by any dust, it would have peaked at an apparent magnitude of \( R = 7.6 +0.04 \) (Kann et al. 2006, hereafter K06). This corresponds to an absolute \( R \)-band magnitude \( M_R = -36.5 \) (2.3 \( \times 10^{16} \) \( L_{\odot} \), assuming the \( V - R \) color for a G2 V star from Ducati et al. 2001), making this the most luminous optical source ever detected at that time. In this paper we compile all available data on the afterglow of GRB 050904 and construct a synthetic light curve for a hypothetical perfectly ionized universe showing no Lyman dropout up to the redshift of the GRB. We then derive light-curve parameters and use the spectral energy distribution (SED) of the afterglow to extrapolate the afterglow light curve into the \( R \) band assuming \( z = 1 \). We find that the prompt flash of GRB 050904 is the most luminous optical/NIR transient ever detected, even exceeding the \( R \)-band luminosity of GRB 990123 at peak by more than 1 mag.

2. THE COMPOSITE LIGHT CURVE OF THE GRB 050904 AFTERGLOW

2.1. Data Mining and Fitting Methods

The optical/NIR afterglow of GRB 050904 was observed by different telescopes over almost five decades in time and more than six decades in flux density. Due to its very high redshift, it was not detected at wavelengths shorter than the \( I_C \) band. We compiled all data from the following papers: Haislip et al. (2006), Tagliaferri et al. (2005), Böer et al. (2006), Kawai et al. (2006), Gendre et al. (2007), and Berger et al. (2006). All data were corrected for Galactic extinction assuming \( E(B-V) = 0.060 \) (Schlegel et al. 1998) and then transformed into AB magnitudes (Oke & Gunn 1983). To transform the magnitudes into flux densities, we used the zero points given in Haislip et al. (2006) to transform their data and standard zero points for all other data. Data in Kawai et al. (2006), Berger et al. (2006), and \( z' \) data from Tagliaferri et al. (2005) are already AB magnitudes.

The highest data density is available in the \( J \) band. Therefore, we started with the \( J \) band to construct a synthetic light curve by achromatically shifting the other bands to the \( J \)-band light curve. This method is justified, as no systematic color evolution was found in the data set. For the normal forward shock evolution of the afterglow (once the cooling frequency \( v_c \) has passed the optical/NIR bands), such achromacy is expected. While the early steep-to-shallow transition at \( t = 0.35 \) days may be chromatic, we only have \( J \)-band data at this time anyway. In the following, we always assume an achromatic evolution of the afterglow.

We fitted the \( J \)-band data with a broken power law (for more details on the fitting procedure, see Zeh et al. 2006, hereafter Z06). As Haislip et al. (2006) have noted, the early \( J \)-band data before 0.3 days are brighter than the extrapolation of later data to these times, indicating the steeper decline from what could be a reverse shock flash. Initially, we excluded these early data from our fit. We used the derived light-curve parameters from the fit to the \( J \)-band light curve as a reference light curve and fitted the \( H \)-band data with this reference curve. We thus found a color \( J - H \). Assuming \( J - H = \text{const.} \), we shifted the \( H \)-band data to the \( J \) zero point, merging the light curves. We then fitted the combined \( JH \) light curve again and shifted the \( H \)-band data points in small increments until the \( \chi^2 \) was minimized, thus deriving the true \( J - H \) color and the light-curve parameters of the joint light curve, which spans a longer time range (0.3–12 days in the observer frame) and gives a better constraint on the postjet break (after 2.6 days) decay slope \( \alpha_2 \) (it is \( F_v \propto r^{-\alpha_2} \)). The \( K \)-band data (in which we make no distinction between \( K \), \( K_s \), and \( K' \)) and the \( Y \)-band data were added in the same way. These additional shifts were not larger than 0.03 mag.
We transformed the Hubble Space Telescope (HST) NICMOS F160W (AB) data point from Berger et al. (2006) to $H$ (AB) by using the conv$_{AB}$ value from the hyperZ package$^4$ (Bolzonella et al. 2000), $m_{AB}(H) = m_{AB}(F160W) + 0.069$. As the final HST data point is corrected for host contribution, we also corrected the other data points in the same way. From the synthetic host spectrum presented in Berger et al. (2006) we derived for the host galaxy a $J$-band flux density of 0.055 μJy, which transforms into $J_{AB} = 27.0$. We assumed conservative errors of 0.3 mag. The effect of host subtraction is very small, at most 0.03 mag, since the last afterglow data point at 5 days is still 4 mag brighter than the host galaxy.

2.2. Fitting the Light Curve

The $YJHK$ composite light curve consists of an early steep decay (Haislip et al. 2006), which goes over into a typical afterglow decay, followed by a further break, which is identified as a jet break (Tagliaferri et al. 2005). We fitted the two breaks separately, using the equation from Z06 (fixing the host flux to zero, as the data have been corrected for host contribution). For the first fit, we excluded all data beyond 3 days from the fit. The break smoothness parameter $n$ (see Z06) had to be fixed to $n = -10$ (a negative value, as the break is from steep to shallow). The jet break was fitted with $n$ left as a variable in the fit. For this fit, data earlier than 0.3 days were excluded. We thus derived three decay constants, which we label $\alpha_0$ (the steep early decay), $\alpha_1$, and $\alpha_2$ (the typical prejet and postjet break decay). We then transformed all data from AB back to Vega magnitudes using standard zero points.

The $z'$ data (Böer et al. 2006; Haislip et al. 2006; Tagliaferri et al. 2005; Kawai et al. 2006) are already affected by Lyα damping. While we used the composite reference light curve to find the $z'$ – $J$ color, we did not implement the $z'$ data in the derivation of the light-curve parameters. We also did not implement the subluminous $Z$ measurement from Haislip et al. (2006). Böer et al. (2006) give the TAROT measurements both as flux density at 9500 Å and as $I_C$ magnitudes. We used the flux density and transformed it to $z'$ magnitudes. Comparing these with the $I_C$ magnitudes of Böer et al. (2006) we find $I_C - z' = 2.49$ mag. This is in very good agreement with the $I_2 - z'$ color of 2.48 mag derived from late afterglow data at 1.2 days, where $I_2$ is the Very Large Telescope FORS2 $I$-band filter (for details on the $I_1$ and $I_2$ filters, see Tagliaferri et al. 2005). The $z' - J$ color derived at late times was then used to shift all $z'$ data points to the $J$ zero point (as always, we assume achromaticity, i.e., a constant spectral slope). The result is a final composite light curve that includes all data from the early prompt emission to the late HST detection. In the following, when we speak of the $J$-band light curve, we always refer to this composite light curve.

2.3. Results of the Light-Curve Fitting

The results of the light-curve fits using the $YJHK$ light curve are given in Table 1, and the complete composite light curve is shown in Figure 1. As expected, $\alpha_1$ derived from the two different fits (see §2.2) agrees within the errors. There is some scatter in the light-curve data, which leads to the high values of $\chi^2$. This is due to either additional measurement uncertainties or small deviations from a power-law decay, as it has been found that the X-ray afterglow was extremely variable (Cusumano et al. 2006, 2007; Watson et al. 2006). The values we derived are in full agreement with those of other authors (Table 1). These light-curve parameters are typical for afterglows (see Z06 for a compilation of light-curve parameters of all pre-Swift afterglows). The light-curve steepening $\Delta \alpha = \alpha_2 - \alpha_1 = 1.6 \pm 0.2$ is high but also not extraordinary (Fig. 3 of Z06). We note that this is one of the few light curves that allow the smoothness of the jet break to be fitted as a free parameter, and the result is in full agreement with the potential relationship between $\alpha_1$ and $n$ found by Z06 (their Fig. 8).

![Fig. 1: Composite $z'YJHK$ light curve of the afterglow of GRB 050904, as it has been constructed with the procedure outlined in §§2.1 and 2.2. Triangles show significant upper limits. The solid line represents the fit with the two broken power laws, and the dotted lines represent the 1σ confidence interval of the fit. The dashed lines indicate the times of the two light-curve breaks at 0.35 and 2.63 days, and the three decay slopes are labeled. The residuals $\Delta m$ represent observed minus fitted magnitudes. The residuals have been zoomed to show the scatter in the data. The afterglow is seen to peak at $J \approx 10$, almost 3 mag above the extrapolation of the fit from 0.2 days, assuming a simple power-law decay.](http://webast.ast.obs-mip.fr/hyperz/)

Table 1: Results of the Composite YJHK Light-Curve Fitting

| Fit | $\chi^2$ | Degrees of Freedom | $m_0$ | $\alpha_0$ | $\alpha_1$ | $\alpha_2$ | $I_0$ | $I_2$ | $n_1$ | $n_2$ |
|-----|---------|-------------------|------|-----------|-----------|-----------|------|------|------|------|
| 1   | 59.2    | 17                | 18.80 ± 0.47 | 1.39 ± 0.13 | 0.92 ± 0.05 | ... | 0.35 ± 0.14 | ... | −10  |
| 2   | 59.7    | 17                | 20.65 ± 0.17 | ... | 0.85 ± 0.08 | 2.45 ± 0.18 | ... | 2.63 ± 0.37 | ... | 1.82 ± 1.02 |
| H06 | ...     | ...               | 1.36$^{+0.06}_{-0.07}$ | 0.82$^{+0.04}_{-0.04}$ | ... | ... | ... | 0.5  | ... | ... |
| T05 | ...     | ...               | 0.72$^{+0.13}_{-0.20}$ | 2.4 ± 0.4 | ... | 2.6 ± 1.0 | ... | 1.0  | ... | ... |

$^a$ The first fit uses data from 0.1 to 3 days after the burst, while the second fit uses only data after 0.3 days. H06 denotes the results from Haislip et al. (2006) and T05 those of Tagliaferri et al. (2005).

$^b$ The apparent $J$-band magnitude at the respective break time is denoted as $m_0$ (see eq. [1] of Z06).

$^c$ The break at which the forward shock afterglow begins to dominate over the prompt flash emission is $I_0$, while $I_2$ denotes the jet break time. Break times are given in units of days after the burst trigger.

$^d$ The values of $n_1$ and $n_2$ are the break smoothness parameters of the first and second breaks, respectively.
First, we found an observed spectral slope arbitrarily chosen. While the MW (solid line) and LMC (dashed line) fits are indistinguishable, the slight upturn of the SMC fit (dotted line) is seen. The Lyman absorption cutoff is not modeled; the gray fit curves are extrapolations. Only upper limits (triangles) have been found in the $R_C$, $r'$, and $V$ bands. The flux density scale is arbitrarily chosen.

For our fit, the extrapolation to very early times meets the earliest TAROT detection at 0.002 days, similar to what Böer et al. (2006) find. However, the following plateau phase around 0.004 days and the flare are much brighter than the extrapolated light curve (1 and almost 3 mag, respectively). This implies that the decay after the optical flare must be steep. Taking into account the upper magnitude limit at 0.009 days (Gendre et al. 2007), we find $\alpha_{\text{flare}} \geq 3$. Such a steep decay implies that the flare could be due to either reverse shock emission or internal shocks from late central engine activity (Böer et al. 2006; Gendre et al. 2007; Wei et al. 2006; Zou et al. 2006). Since this is even steeper than $\alpha_0$, an additional break must exist, but no data are available during this time span. In particular, we find that the afterglow peaks at $J \approx 10$, which is among the brightest NIR afterglows ever detected and is a first hint at its extreme luminosity.

3. THE LUMINOSITY OF THE PROMPT FLASH

3.1. Results of the Spectral Energy Distribution Fitting

To construct the SED, we used the colors $J - H$, $J - K$, and $Y - J$ that were derived in § 2.1 ($Y$, $J$, $H$, and $K$ data are not affected by $Ly\alpha$ damping). The SED is fitted as described in K06. First, we found an observed spectral slope $\beta_0$. Then the SED was fitted with an additional dust extinction curve, using dust models for the Milky Way (MW) and the Large and Small Magellanic Clouds (LMC and SMC) (Pei 1992). This gives us the extinction in the $V$ band in the host galaxy frame $A_V^{\text{host}}$ and an intrinsic spectral slope $\beta$, corrected for the host extinction.

To extend the SED farther into the optical bands (in the observer frame), we used reported $R_C$, $r'$, and $V$ upper limits. By shifting the composite light curve to these limits, we produced additional $R_C - J$, $r' - J$, and $V - J$ colors, which are lower limits on these colors. Instead of a flat or downward-curved SED, we actually found a slight upward curvature, mainly due to the $V$-band data (which have large errors) being slightly too bright (Fig. 2; this can also be seen in Figs. 2 and 3 of Haislip et al. 2006). This results in a fit with SMC dust, which is typically favored for GRB host galaxies (K06 and references therein), finding a negative extinction, which is unphysical. The best result is actually obtained for MW dust, even though this does not imply that the host galaxy of GRB 050904 has dust resembling that of the MW. While SMC dust is characterized by strong far-ultraviolet extinction, MW dust has a much flatter extinction curve at these wavelengths. Indeed, Maiolino et al. (2004) have found dust with flat far-ultraviolet extinction in a quasar at almost the same redshift as GRB 050904, and Stratta et al. (2005) have found that the optical and X-ray afterglow of GRB 020405 can be explained by dust with similar properties, although this GRB lies at a much closer redshift. The characteristic 2175 Å bump of MW dust is not visible due to the very low extinction value we derive. We thus conclude that the extinction in the host galaxy is very low and the dust is dissimilar to SMC-type dust. In the following, we use the values derived from the MW dust fit, deeming this to be a conservative approach.

The results of the SED fitting are given in Table 2. Once again, our fits are in good agreement with those of other authors, except for Price et al. (2006), who ascribe the low value they derive to possible short-term fluctuations. Haislip et al. (2006) and Tagliaferri et al. (2005) also note that while source-frame dust extinction may be present, it must be low. The hydrogen column density along the line of sight in the host galaxy derived via optical spectroscopy is large ($\log N_H^{\text{host}} = 21.3$; Kawai et al. 2006). Coupled with the very low extinction, this implies a dust-to-gas ratio that is even lower than that for the SMC. The result is similar to GRB 990123, and in this case also the prompt flash may have burned dust along the line of sight (see Fig. 6 in K06 and references therein).

3.2. The Circumburst Environment of GRB 050904

Knowledge of the light-curve parameters and the intrinsic spectral slope allows us to derive conclusions on the nature of the circumburst environment via closure relations (Price et al. 2002; Berger et al. 2002). We find that, when using $\alpha_1$ and $\beta$, a model is strongly favored in which the cooling break frequency $\nu_c$ lies redward of the source-frame ultraviolet after 0.4 days. This is substantiated by the spectral slope of the late X-ray afterglow, which is identical to that in the ultraviolet within the errors. Watson et al. (2006) find $\beta_X = 0.88 \pm 0.04$, and Cusumano et al. (2006, 2007) find $\beta_X \approx 0.9 \pm 0.1$. Furthermore, Frail et al. (2006) used their radio detections of the afterglow of GRB 050904 to perform broadband modeling and arrived at the same conclusion. In this case one cannot draw any conclusion on whether the GRB environment is of constant density (interstellar medium [ISM]) or is shaped by a progenitor wind. The observed very soft jet break ($\nu_2$; Table 1) may be indicative of a wind environment (Chevalier & Li 1999), whereas Frail et al. (2006) use an ISM model. Finally, Gendre et al. (2007) propose that the afterglow passes through a termination shock somewhere before 0.5 days in the observer frame, switching from an early wind medium to a late ISM medium.
Given the location of $\nu_c$, redward of the optical/NIR bands, an electron spectral index of $\beta = 2 \beta = 1.97 \pm 0.29$ is found, which is typical for GRB afterglows (e.g., Zhang & Mészáros 2004 and references therein). The standard fireball model predicts $\beta = \alpha_2$ (Zhang & Mészáros 2004), consistent with the $\alpha_2$ we find within 1.4 $\sigma$ (Table 1).

3.3. Derivation of the $R_C$-Band Light Curve

In the observer frame $R_C$ band, the afterglow was unobservable due to Lyman damping. Typically, GRB afterglows have the highest data density in the $R_C$ band, and all afterglows that were examined in K06 were $R_C$-band afterglows. Because of the synchrotron nature of the afterglow radiation (described by a power law, $F_\nu \propto \nu^{-\beta}$, with $\beta$ being the spectral slope), and assuming $\beta = \text{const.}$, we can construct the $R_C$-band light curve from the $J$-band light curve. The spectral slope we derived from the observer frame NIR data can be extrapolated into the observer frame optical, allowing us to find an $R_C - J$ color without the damping influence of $Ly\alpha$. For this purpose, we used the observed spectral slope that has not yet been corrected for host galaxy extinction, $\beta_0$. Since the host galaxy extinction is very low, the spectral curvature is negligible and we can use a simple power law for the extrapolation. This power law has an error from the fitting process, which we added in quadrature to the measurement errors of the data points.

3.4. The $R_C$-Band Luminosity of the Prompt Flash

In order to place the afterglow of GRB 050904 in the context of the afterglow sample discussed in K06, we shifted the afterglow to a redshift $z = 1$. Using the derived intrinsic spectral slope $\beta$, the source-frame extinction $A_{R_C}^{\text{host}}$ (both from the MW dust fit), and the redshift, we computed the magnitude shift denoted $dR_C$ in K06. This shift takes into account the extinction correction, the redshift difference, and the cosmological $k$-corrections (Sandage 1988) when moving the source from its original redshift to $z = 1$. The magnitude shift creates a further error (from $\Delta \beta$ and $\Delta A_{R_C}$), which we again add in quadrature to the errors of the data. We find $dR_C = -5.05^{+0.12}_{-0.13}$ mag, which is higher than any value found in K06. Applying this correction to the $R_C$-band afterglow, we finally arrive at our main result: had GRB 050904 lain at $z = 1$ and been unaffected by any line-of-sight extinction (including $Ly\alpha$ damping), the optical flare detected by TAROT would have peaked at $R_C = 6.55^{+0.27}_{-0.28}$ almost visible to the naked eye. This is more than 1 mag brighter than the reverse shock peak of GRB 990123 (the flux density is higher by a factor of 2.8), making the afterglow of GRB 050904 the most luminous optical transient ever detected. Böer et al. (2006), neglecting $k$-correction, find a peak flux density of 1080 mJy (in the $I'$ band) for the afterglow of GRB 990123 and 1300 mJy (in the $L$-band) for the afterglow of GRB 050904 after scaling it to the redshift of GRB 990123, but they do not remark on this further except to call the two events comparable. For $\beta = 0.99$, the absolute $R_C$-band magnitude is $M_R = -37.6 \pm 0.3 \pm 0.0$ ($6.4 \times 10^{48} L_{\odot}$), making the afterglow in the $R_C$ band alone between 60 and 600 times brighter than the intrinsic bolometric luminosity of the gravitationally lensed hyperluminous broad absorption line quasar APM 08279+5255, the most luminous persistent source known (Ibata et al. 1999).

The complete composite $R_C$-band light curve is shown in comparison with other afterglows in Figure 3. It is immediately apparent that the optical afterglow of GRB 050904 was much brighter than any other afterglow over almost two decades in time. At the peak of the prompt flash, it was 6 mag brighter than GRB 021004, which is the brightest afterglow at late times, and another 6 mag brighter than GRB 041006, one of the faintest GRBs in the sample. This span is much larger than at 1 day after the GRB, where the afterglow luminosities tend to cluster (K06; Liang & Zhang 2006; Nardini et al. 2006). At later times, however, it resembles other afterglows. At 1 and 4 days after the burst (Fig. 3), we find $R_C = 18.13$ and 21.50, respectively, which transform to absolute magnitudes $M_B = -24.51 \pm 0.20$ and $-21.14 \pm 0.20$, respectively (see Figs. 9 and 10 of K06). This ranks it among the brightest afterglows at 1 day, but it is not the brightest, as it has also been noted by Tagliaferri et al. (2005). At 4 days after the burst, it lies close to the center of the luminosity distribution.

3.5. The Spectral Slope during the Flare

Since no multicolor data for the prompt emission phase are available, we shifted the early optical emission achronically, assuming no spectral changes between this phase and the late afterglow phase (where no color evolution is evident). The assumption of achromacy for the first 100 s after a GRB is surely an oversimplification. Strong spectral changes are expected within this time (Sari et al. 1998). However, does this imply that the true luminosity of the flare was actually lower than what we have derived?

The spectral slope of the late optical/NIR afterglow, consistent with the cooling break lying at longer wavelengths than the optical, is very steep, $\beta \approx 1$. During the prompt emission, the forward shock afterglow is expected to be in the fast cooling phase (Wu
et al. 2005 and references therein). If the medium surrounding the GRB progenitor is of constant density (ISM model), and the optical band lies between the cooling frequency $\nu_c$ (at longer wavelengths) and the peak frequency $\nu_{\nu_p}$, the expected spectral slope is $\beta = 0.5$. In case even the cooling frequency has not yet passed the optical bands, the spectral slope in the optical actually rises, with $\beta = -1/3$ (Zhang & Mészáros 2004 and references therein). A similar situation would be seen if the early optical emission were dominated by the low-energy tail of the prompt emission, a situation that was seen for GRB 041219A and GRB 050820A (Vestrand et al. 2005, 2006). This has also been suggested for GRB 050904 (Wei et al. 2006), although the optical flux in the flare is much brighter than the extrapolation of the X-ray spectrum for GRB 050904 (Böer et al. 2006), in contrast to the cases of GRB 041219A and GRB 050820A (Vestrand et al. 2005, 2006). We thus conclude that the spectrum in the optical bands during the prompt emission was not steeper than at late times and was possibly shallower, i.e., $\beta < 1$.

On the one hand, this implies that the $R_C$ magnitude of the afterglow at $z = 6.295$ would be brighter than what we derived with the spectral slope of the late afterglow. On the other hand, when we apply the cosmological shift to $z = 1$, the $dR_C$ shift becomes smaller. We find $dR_C = -4.26$ mag for $\beta = 0.5$ and $dR_C = -3.10$ mag for $\beta = -1/3$ (also correcting for the small host extinction), resulting in $R_C = 6.93$ and $7.52$, respectively. Thus, for $\beta = -1/3$, the extrapolated $R_C$-band magnitude at $z = 1$ of the flare would be comparable to that of GRB 990123. However, we should also note that the same argument may apply to the flare of GRB 990123, so that the flare of GRB 050904 truly is brighter with a high probability.

4. IS GRB 050904 DIFFERENT FROM OTHER LONG GRBs?

In the literature on GRB 050904, consensus is not reached on whether GRB 050904 is, apart from its redshift, a special event. Let us review some aspects of both the prompt emission and the afterglow.

In many ways GRB 050904 does not differ from the typical mean values found for GRBs. In the source frame $T_90 = 31$ s, with gamma-ray emission detected up to 69 s after the trigger, including the flare seen prominently in the X-ray and the optical (Böer et al. 2006; Cusumano et al. 2006, 2007). The intrinsic luminosities of the X-ray (Watson et al. 2006), the late optical (as shown in this work), and the radio afterglow (Frail et al. 2006) are typical, as are the light-curve decay parameters and the jet break time in the rest frame (Zöf; K06).

But some aspects of GRB 050904 do stand out. The peak energy $E_p$ lies beyond the Swift Burst Alert Telescope (BAT) energy range. From joint fitting of Swift BAT and Suzaku Wideband All-sky Monitor data, Sugita et al. (2006) report a preliminary $E_p = 366^{+500}_{-140}$ keV, translating into $E_p = 2670^{+414}_{-104}$ keV in the rest frame. This peak energy is the highest found in the compilation of 56 bursts (Amati 2006); only GRB 050717 (observer frame $E_p = 2101^{+1934}_{-1394}$ keV, time-integrated spectrum; Krimm et al. 2006) very probably has a higher peak energy (the redshift is not known but is assumed to be high). The isotropic energy is not exactly known. Cusumano et al. (2006, 2007) derive $E_{iso} = 6.6 \times 10^{53}$ to $3.2 \times 10^{54}$ ergs. The upper end of the range is higher than for any other burst, including GRB 990123 (Amati 2006), and even the lower value is higher than for most GRBs with well-determined $E_{iso}$. Using a jet break time of $t_b = 2.6 \pm 1.0$ days, Tagliaferri et al. (2005) derive log $E_i(\text{ergs}) = 51.6-52.1$. This is the second-highest beaming-corrected energy ever found (Friedman & Bloom 2005), after GRB 050820A [log $E_i(\text{ergs}) = 51.7-52.2$; Cenko et al. 2006]. The X-ray afterglow is the most variable ever seen by Swift (Cusumano et al. 2006, 2007; Watson et al. 2006), implying that, in the source frame, the central engine was active for several hours after the burst (Zou et al. 2006). We have shown in this paper that the early optical/NIR emission is brighter than for any other GRB detected so far. Frail et al. (2006) derive a high circumburst density of $680 \text{ cm}^{-3}$ from broadband afterglow modeling, noting that a density typical for GRB environments ($10 \text{ cm}^{-3}$) is ruled out by the absence of a bright, early radio afterglow.

There is no aspect of GRB 050904 that exceeds the typical GRB parameters so much that one could claim that the progenitor of GRB 050904 was markedly different from those of all other long GRBs, e.g., a Population III star. However, it is clear that GRB 050904 is one of the most extreme GRBs ever observed, comparable only to GRB 990123 (cf. Böer et al. 2006), and exceeding even this seminal event in some aspects.

5. CONCLUSIONS AND OUTLOOK

We have shown that the early flare of GRB 050904 detected by the TAROT telescope is the most luminous optical/NIR transient ever detected, exceeding even the peak magnitude of the prompt optical flash of GRB 990123. While GRB 050904 is not markedly different from other GRBs in any single aspect, it is among the most extreme GRBs ever detected.

So far, only a single GRB at the end of the reionization era has been detected. It is thus not possible to decide whether GRB 050904 is typical for GRBs at a very high redshift, or if it is simply observational bias that the first GRB to be found at $z > 6$ is one of the most extreme events ever detected. More typical events would not have sufficient follow-up to determine the necessary parameters, especially the redshift. The Swift satellite, with its high sensitivity in an energy band that is typical for highly redshifted hard bursts and its possibility of long-duration image triggers, is a very powerful instrument for detecting these very distant events. It is likely that more very high redshift GRBs will be detected during the lifetime of Swift, possibly even breaking the redshift records for quasars (Fan et al. 2003) and galaxies (Jye et al. 2006). Indeed, a GRB at a higher redshift than GRB 050904 may have already been found: GRB 060116 (Grazian et al. 2006).

While the detection of a GRB by Swift is the first and most important step, most parameters characterizing the event can only be obtained by ground-based telescopes. The determination of the true burst energetics depends on the measurement of the redshift and the jet break time, and GRBs at $z > 6$ are bright only in the NIR. While optical spectroscopy is still feasible to $z \approx 7$, any higher redshifts will move the metal lines that are used for an exact determination of $z$ beyond the typical limit of optical spectroscopy (and the region beyond 0.7 $\mu$m is already strongly affected by sky lines). NIR spectroscopy even at large facilities needs bright sources, and thus far NIR spectroscopy of a GRB afterglow has never been successful in detecting any lines. The dilemma is that observing time at large facilities is precious, and observations are only triggered when there is already a strong suspicion that the event lies at a very high redshift. This implies the need for rapid photometric redshift determinations that use the Lyα trough, as it has been successfully applied to GRB 050904 (Haislip et al. 2006; Tagliaferri et al. 2005; Price et al. 2006). One telescope that is already in use and has the capability for rapid multicolor photometry is the MAGNUM telescope, which also observed GRB 050904 (Price et al. 2006). A key element would be the deployment of more moderately large robotic NIR

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6 However, see also Piranomonte et al. (2006) and Tanvir et al. (2006).
telescopes such as PAIRITEL (Bloom et al. 2006) and REM (Zerbi et al. 2001), which also has an optical camera.

More rapid follow-up of high-redshift bursts will finally allow GRBs to fulfill their promise as the ultimate probes of the very early universe.

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