A STRONG OPTICAL FLARE BEFORE THE RISING AFTERGLOW OF GRB 080129

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ABSTRACT

We report on GROND observations of a 40 s duration (rest-frame) optical flare from GRB 080129 at redshift 4.349. The rise and decay times follow a power law with indices +12 and −8, respectively, inconsistent with a reverse shock and a factor $10^5$ faster than variability caused by interstellar material interaction. While optical flares have been seen in the past (e.g., GRB 990123, 041219B, 060111B, and 080319B), for the first time, our observations not only resolve the optical flare into subcomponents, but also provide a spectral energy distribution (SED) from the optical to the near-infrared once every minute. The delay of the flare relative to the gamma-ray burst (GRB), its SED as well as the ratio of pulse widths suggest it to arise from residual collisions in GRB outflows. If this interpretation is correct and can be supported by a more detailed modeling or observation in further GRBs, the delay measurement provides an independent determination of the Lorentz factor $\Gamma$ of the outflow.

Key words: gamma-rays: bursts – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) emit their bulk luminosity over a time period of 2–50 s in the 100–1000 keV range (e.g., Kaneko et al. 2006). Their afterglows are generally assumed to arise from the interaction of the blast wave with the surrounding interstellar material (ISM), where a strong relativistic shock is driven (the so-called external shock). This happens about $10^2$–$10^4$ s after the burst, at distances of the order of $3 \times 10^{16}$ cm (Meszaros & Rees 1997). The shocked gas is the source of a long-lived, slowly decaying afterglow emission.

Some afterglows have shown substantial optical variability, both at early times as well as at late times. The early ones can be distinguished into a component which tracks the prompt gamma rays (GRB 041219A (Vestrand et al. 2005, Blake et al. 2005), GRB 050820A (Vestrand et al. 2006), and GRB 080319B (Racusin et al. 2008)) and an afterglow component which starts during or shortly after the prompt phase (GRB 990123 (Akerlof et al. 1999), GRB 030418 (Rykoff et al. 2004), and GRB 060111B (Klotz et al. 2006)). The former component has been attributed to internal shocks, while the latter component was interpreted as reverse shock emission (e.g., Sari & Piran 1999a, Meszaros & Rees 1999). At late times, some GRB afterglows showed bumps on top of the canonical fading, with timescales of $10^3$–$10^5$ s. Originally, these bumps have been interpreted as the interaction of the fireball with moderate density enhancements in the ambient medium, with a density contrast of the order of 10 (Lazzati et al. 2002), and later by additional energy injection episodes (Björnsson et al. 2004).

The optical variability due to the interaction with the ISM is expected to be not faster than $10^7$ s, because the blast wave, once it has swept up enough ISM to produce the canonical afterglow emission, is thought to be only mildly relativistic. This is different with optical emission possibly related to the forward or reverse shock: here the emission is relativistic, and the timescales in the observer frame are shortened by $\Gamma^{-2}$, with $\Gamma$ being the bulk Lorentz factor which typically is assumed to be $300$–$500$. The reverse shock is predicted to happen with little delay with respect to the gamma-ray emission unless the Lorentz factor is very small, and the corresponding optical emission has a decay-time power-law index of $-2$ for a constant density environment, or up to $-2.8$ for a wind density profile (Kobayashi 2000).

Swift/BAT triggered on GRB 080129 (trigger 301981) at 06:06:46 UT (Immler et al. 2008) which had an observed duration of $T_90 = 48$ s. BAT measured a fluence (over $T_{90}$, the time during which 90% of the fluence is emitted) of $8.9 \times 10^{-7}$ erg cm$^{-2}$ in the 15–150 keV band. The spectral slope is 1.3 with no spectral turnover up to 150 keV. If we assume the expected spectral turnover according to a canonical GRB spectrum to be at $E_{\text{peak}} = 300$ (500) keV, the total isotropic gamma-ray energy equivalent is $E_{\gamma(\text{iso})} = 6.5(7.7) \times 10^{52}$ erg (15–1000 keV). At 320 s after the trigger, Swift slewed to a different location on the sky, placing the line of sight (LOS) toward the GRB nearly in the BAT detector plane, therefore being blind to any late emission. Pointed observations of the GRB with the X-ray telescope (XRT) and the UV optical telescope (UVOT) started only at 07:00:08 UT. 3.2 ks after the GRB trigger. A clearly fading X-ray source was discovered, but no emission seen with UVOT (Holland 2008).

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We started optical/near-infrared (NIR) imaging with GROND immediately after the trigger, and had independently identified the optical/NIR afterglow (Kührer et al. 2008) though we reported it after Bloom (2008). Here, we report the full results.

2. OBSERVATIONS AND RESULTS

2.1. Optical/NIR Photometry

GROND, a simultaneous seven-channel imager (Greiner et al. 2008) mounted at the 2.2 m MPI/ESO telescope at La Silla (Chile), started observing the field at 06:10:18 UT, about 4 minutes after the GRB. Our imaging sequence began with 46 s integrations in the $g'r'i'z'$ channels, spaced at about 50 s due to detector readout and preset to a new telescope dither position. After about 10 minutes, the exposure time was increased to 137 s, and after another 28 minutes to 408 s. Since the afterglow brightness was rising, the exposure time was reduced back to 137 s at 07:21 for the rest of the night. In parallel, the three NIR channels $JHK$ were operated with 10 s integrations, separated by 5 s due to readout, data transfer, and K-band mirror movement.

The first images immediately revealed a strongly flaring source. The light curve of the afterglow (Figure 1) shows this unique pattern in more detail: there is a $\approx 3$ mag amplitude flare.
flare of 80 s (full width at half-maximum (FWHM)) duration, peaking at ≈540 s postburst.

Thereafter, the afterglow brightness is continuously rising until 6000 s after the GRB. At the beginning of the next night, at 65 ks after the GRB, the afterglow intensity is still at the same level, despite declining by a factor of 25 at X-rays. In contrast, in the 65–500 ks interval the emission in the optical/NIR and X-rays is correlated, with a slow rise ($t^{0.15}$) over another day, and a subsequent rapid decay ($t^{-2.0}$).

2.2. Optical Spectroscopy

We obtained an optical spectrum of the afterglow of GRB 080129 in the 500–800 nm region with FORS1/Very Large Telescope (VLT; Figure 2) on 2008 January 30, 06:16 (midtime) consisting of four exposures of 1800 s each. The strong fringing of the blue-sensitive detector longward of 7500 Å and the strong foreground extinction of $A_V = 3.4$ mag result in a limited range of the spectrum being useful for analysis; but luckily Ly$\alpha$ and some metal absorption lines such as Si ii (1260 Å) and Si iv (1402 Å) happen to fall in this usable range, so that a redshift of $z = 4.349 \pm 0.002$ (luminosity distance of 40 Gpc in concordance cosmology) could be derived.

2.3. NIR High Time Resolution Photometry

Observations with VLT/ISAAC (ESO Paranal, Chile) and New Technology Telescope (NTT)/SOFI (ESO La Silla, Chile) were triggered to monitor GRB 080129 in the NIR with high time resolution photometry. ISAAC was used in FastPhot mode in the $J$ band. After bias and flat-field correction and background subtraction, the frames were stacked to achieve longer total integration times (4000 frames combined give 57.2 s integration time in ISAAC, 1000 frames combined give 40 s integration time in SOFI). The light curves do not show any flaring activity above 0.3 mag amplitude.

2.4. Submillimeter Observations

For the photometric observations at 1.2 mm (250 GHz) we used the 117 channel Max-Planck Bolometer array MAMBO-2 (Kreysa et al. 1998) at the IRAM 30 m telescope on Pico Veleta, Spain. MAMBO-2 has a half-power spectral bandwidth from 210 to 290 GHz, with an effective bandwidth center for flat spectra of $249 \pm 1$ GHz (1.2 mm, $2 \pm 2$ mm precipitable water vapor). The effective beam FWHM is 10.5mas, and the undersampled FOV is 4'. Atmospheric conditions were generally good during the observations, with typical LOS opacities between 0.2 and 0.3 and low sky noise. The on sky integration times varied between 1200 and 5000 s on the five epochs. Observations were performed using the standard on–off technique, with the subreflector switching every 0.25 s between the two sky positions (on and off sources) separated by 32 mas. The telescope pointing was frequently checked on a nearby quasar and was found to be stable within 2". The data were analyzed using the MOPSIC software package. Correlated noise was subtracted from each channel using the weighted average signals from the surrounding channels. Absolute flux calibration was done through observations of planets, resulting in a flux calibration uncertainty of about 20%. The third–fifth epochs on February 3, 6, and 10 yielded only upper limits of less than 0.5 mJy (3σ; see Table 1).
3. DISCUSSION

3.1. The Rising Afterglow

The rising light curve between 1000 and 6000 s after the GRB is likely the emerging afterglow. The rather steep power-law photon index of $\alpha = -1.35 \pm 0.15$ and the flux rise ($F \sim t^\beta$) with $\beta \sim 1$ (Figure 3) indicate that the characteristic synchrotron frequency has already crossed the optical band at $t = 1000$ s. Our interpretation for the rising part is that the ejecta have not entered the deceleration phase at $t = 6000$ s. In this case, one can use the peak time of the light curve at $t \gtrsim 6000$ s, to estimate the fireball Lorentz factor at the time of the deceleration which is expected to be half of the initial Lorentz factor $\Gamma_0$ (Sari & Piran 1999b; Panaitescu & Kumar 2000; Molinari et al. 2007). Using the formulation of (Molinari et al. 2007), we obtain for the ISM case $\Gamma_0 \approx 130 \left(\frac{E_{53}}{0.1}\right)^{1/8}$, where $\eta = 0.2\eta_0$ is the radiative efficiency (Bloom et al. 2003).

Ignoring the weak dependence on $\eta$ and the external density $n$, and using our above derived $E_{53} = 0.7$, we get $\Gamma_0 \approx 120$ (with allowed values down to 85 if the peak emission was at 15,000 s instead of 6000 s).

3.2. The Late Decay Light Curve

At very late times, starting at 180 ks after the GRB, the X-ray and optical/NIR emission vary achromatically. Again, this is in contrast to the behavior in most Swift GRBs (Panaitescu 2007), but the steepening of the decay to $\alpha \sim -2$ and the spectrum by $\delta \alpha \sim 0.5$ (Table 2) is consistent with a jet break. The jet angle $\Theta$ was calculated following Sari et al. (1999) for the ISM model and Bloom et al. (2003) for the wind model, where in the former case the redshift factor was added

$$\Theta_{\text{ISM}} = \frac{1}{6} \left(\frac{t_b}{1+z}\right)^{3/8} \left(\frac{n \eta_0 \times 10^{21} \text{cm}^{-2}}{E_{52}}\right)^{1/8}$$

(1)

$$\Theta_{\text{wind}} = 0.169 \left(\frac{2 t_b}{1+z}\right)^{1/4} \left(\frac{\eta_0 A_*}{E_{52}}\right)^{1/4}$$

(2)

Using $E_{iso} = 6.5(7.7) \times 10^{52}$ erg s$^{-1}$ (see Section 1), our derived redshift, a circumburst density $n = 1$ cm$^{-3}$, and a break time of $t_b = 180,000$ s = 2.08 days, as well as the canonical values $A_* = 1$ and $\eta_0 = 1$, we derive a jet opening angle of 4$^\circ$.35(4$^\circ$.26)
for ISM and 3.82(3.66) for a wind medium (where the density follows \( A^{-2} \), with \( A = M/4\pi v = 5 \times 10^{13} M_\odot \) g cm\(^{-3} \) derived for the reference values \( M = 1 \times 10^{-5} M_\odot \) yr\(^{-1} \) and \( v = 1000 \) km s\(^{-1} \)). The beaming factor is \( b \approx \Theta^2/2 \). The corresponding jet angle-corrected energy is 1.88(2.13) \( \times 10^{50} \) erg s\(^{-1} \) for ISM, and 1.44(1.57) \( \times 10^{50} \) erg s\(^{-1} \) for wind medium.

### 3.3. The Plateau

This GRB is remarkable for a second reason: it showed a prolonged plateau phase in its afterglow emission, most pronounced in the X-ray band. Flat, or shallow-decay parts of the light curve are now commonly detected in the Swift era (Liang et al. 2007), and occur between 100 s until \( 10^{3}–10^{5} \) s after the burst. In GRB 080129, we observe the plateau to last from 9000 to 56,000 s in the rest frame (50,000–300,000 s observers frame), so starting substantially later, but with a duration (in the rest frame) which is not extraordinary. However, the stunning fact is that this same plateau is also seen in the optical/ NIR data of GROND. Using also the MAMBO detection at 1.2 mm (Figure 4), the overall spectrum during the plateau cannot be fit by a single power law, but requires a second component (Tables 3 and 4). Adopting a broken power law, at least one break is required, with the break energy between the optical (400 nm) and X-rays (0.5 keV). The best-fit power-law indices are 1.57 \( \pm \) 0.06 for the MAMBO-GROND spectrum, and 2.36 \( \pm \) 0.58 for the high-frequency part of the spectrum. Integrating this spectrum over the duration of the plateau phase (69 hr) results in a total emitted energy of \( 3.4 \times 10^{52} \) erg, about 50% of the total energy emitted during \( T_{90} \) in the 15–150 keV band.

#### 3.4. The Flare

##### 3.4.1. Nonfavored Explanations

The optical flare is more difficult to explain due to primarily two facts: it is not correlated to the gamma-ray emission, but delayed by \( 12 \times T_{90} \), and it occurs well before the peak of the optical afterglow. One possibility is to assume that it is the prompt emission of the GRB while BAT triggered on the precursor. The typical ratio of at least 30 for the gamma-ray fluence of proper burst to precursor (Lazzati 2005) implies \( E_{\gamma,\text{burst}} = 2.0(2.3) \times 10^{52} \) erg, similar to the brightest previously known burst GRB 990123 (Akerlof et al. 1999), therefore making the precursor hypothesis unlikely.

Another possibility to explain the optical flare is as the reverse shock emission. In a constant density environment, a reverse shock (Kobayashi 2000) is expected to rise rapidly (\( \beta_{\text{rise}} = 3.0 – 3.2 \), where \( \beta \) is the power-law index of the electron distribution), and decline, in the thin shell case, with \( \beta_{\text{decline}} = -(27 + 7)/35 \). With the canonical range of \( p = 2.2–2.5 \), this implies \( \beta_{\text{rise}} = 5.1–6.0 \), and \( \beta_{\text{decline}} = -1.9 \) to \(-2.1 \), in contrast to our observed values of \( \beta_{\text{rise}} = 12.1 \pm 1.5 \) and \( \beta_{\text{decline}} = 8.3 \pm 1.8 \) while this is true only for the simplest model, and the actual rise and decline values depend on the
density profile and the $p$ values of the electron distribution, we are not aware of any reverse-shock model that gives so steep flux density variations. Note also that a wind profile, while helping in steepening the decline time, would not give a rising forward shock optical emission as we observe.

Yet another option is to interpret the flare as the simultaneous optical emission from an unobserved (because Swift/XRT did not point to the GRB at that time) X-ray flare. X-ray flares are commonly seen in GRB afterglows, at times typically 1000–10,000 s (rest frame) after the GRB (Chincarini et al. 2007). In our case, the early occurrence would be on the short side of this distribution, still consistent with this distribution. The presently generally accepted explanation for the X-ray flares is that they are due to late-time internal shocks (Kocevski et al. 2007), in particular either with a low $\Gamma$ difference (so they collide late), or ejected with a large time difference (late-time activity of the engine). For both cases, one expects that the rise time is (much) shorter than the decay time. The rise time is basically the time it takes for the reverse shock of that collision to travel through the thickness of the shell. The decay time is due to the curvature effect, becoming important whenever the radius of the shell exceeds the shell thickness. Thus, if we require that the decay time is not larger than the rise time (as we observe), then the shell radius must be of the order of the shell thickness—and this is valid only very early after the GRB, thus incompatible with our late-time occurrence. Also, simultaneous Swift/UVOT observations of the many X-ray flares have not revealed such flaring activity in the UV/optical domain. Thus, we consider it unlikely that the optical flare in GRB 080129 is the optical counterpart of an unseen X-ray flare.

Invoking a late internal shock between shells which have not produced gamma-ray emission, and collide at large radii, is another option. While this scenario has been already proposed to explain the early optical emission of GRBs 990123, 041219, and 060111B (Wei 2007), it requires that the late ejections have, for some reason, very high $\Gamma$ of the order of 800–1000, without producing gamma-ray emission. This $\Gamma$ value is well above the measured $\Gamma \lesssim 120$ of the main burst.

Finally, our light curve has, at first glance, some resemblance to that of GRB 041219A, a long-duration ($T_{90} = 520$ s) burst for which PAIRITEL obtained infrared photometry starting before the end of the burst (Blake et al. 2005). In that case, the first flare, occurring before the end of the burst emission, was associated with the internal shock that produced the GRB; however, the note added in proof implies that a reanalysis of the data showed less evidence for the rising part. Thus, it remains open whether this emission was indeed a flare, or some slower decaying prompt emission. The second flare at $3 \times T_{90}$ was associated with the
The observed optical even with the simplest model of a reverse shock, while our \( \beta \) reverse shock. The rise and decline times of this second flare, Figure 5. Swift/BAT light curve of GRB 080129, rebinned with S/N = 5. Overplotted are the two peaks, modeled with two Gaussians of 11 s and 6 s FWHM, respectively. (A color version of this figure is available in the online journal.)

reverse shock. The rise and decline times of this second flare, \( \beta_{\text{rise}} = 6.1 \pm 2.9 \) and \( \beta_{\text{decline}} = -3.4 \pm 2.8 \) are fully consistent even with the simplest model of a reverse shock, while our values for GRB080129 are not. Thus, the similarity between the observed optical/infrared light curves of GRB 041219 and 080129 ends with the global structure of multiple peaks in the light curves, but does not provide clues to solve the discrepancies in the case of GRB 080129.

3.4.2. The Likely Cause of the Flare

The best match of the observed properties of the flare in GRB 080129 with theoretical predictions is with residual collisions in GRB outflows (Li & Waxman 2008). Internal collisions at small radii, which produce the gamma-ray emission, have been proposed to lead to residual collisions at much larger radii where the optical depth to long-wavelength photons is much lower. If the bulk Lorentz factor is large, the optical emission is delayed by only fractions of a second with respect to the gamma rays, and thus can explain the prompt optical emission which has been seen so far in a few GRBs such as GRB 041219A, 050820A, or 080319B. In the case of GRB 080129, \( \Gamma \lesssim 120 \), and the delay time can be longer than the duration of the burst (in such case, the electrons that radiate in the optically emitting region do not cool because of the upscattering of the GRB photons). Li & Waxman (2008) showed that the radius at which the (observer-frame) NIR \( \sim 10^{14} \) Hz radiation becomes optically thin is \( R_{\text{NIR}} \sim 7.3 \times 10^{15} L_{\text{iso}}^{1/2} \Gamma^{-1/2} \) cm, resulting in a delay \( \tau \sim R_{\text{NIR}}/2 \Gamma^2 \sim 12 L_{\text{iso}}^{1/2} \Gamma^{-3/2} \) s. Assuming that the kinetic luminosity of the flow \( L_k \sim 10 L_{\gamma} \sim 10^{53} \) erg s\(^{-1}\) (in fact the very long phase of optical emission between 1 and 3 days after the GRB with a luminosity similar to that of the burst itself implies a large kinetic energy), the delay time can be \( \tau \sim 100 \) s if \( \Gamma \sim 50 \). The predicted spectral slope above the self-absorption frequency is \( \nu F_\nu \sim \nu^{0.5} \), and \( \nu^{7/6} \) below, consistent with our measured values of 0.57 and 1.2, respectively (rising part of the flare). Also, the predicted ratio of \( F_\gamma/F_{\text{opt}} \sim 500 \) compares well with the observed ratio of 1000.

Given this tantalizing coincidences, we analyzed in more detail the shape of the optical flare light curve. It turns out that it can be well described by the superposition of two Gaussian profiles (Figure 1; note that log Gaussians or fast-rise-exponential-decay curves do not fit). We speculate that these are the direct signatures of the residual collisions. Looking at the gamma-ray light curve from Swift/BAT (Figure 5), one can recognize two pulses, the first with FWHM = 11 s, the second with FWHM = 6 s. It is interesting to note that the ratio of the FWHM of these pulses is 2, identical to the corresponding ratio of the optical pulses. Given that just the sequence of broad/narrow pulse has inverted, one could speculate even further that the shell causing the narrow, second peak in gamma rays had a slightly higher \( \Gamma \) and took over the shell causing the broader, first gamma-ray pulse, thus leading to the optical flare.

A caveat with this interpretation comes from the observed fast variability of the flare. Residual collisions are expected to result in a smooth optical light curve that varies on the delay timescale. Alternatively the flare may be powered by dissipation of pointing flux in a localized “hot spot” in strongly magnetized ejecta (Lyutikov 2006, Giannios 2006). In this picture the fast variability is the result of the small emitting volume.

The observed fluence of the flare is comparable to the energy available in the volume of the hot spot as constrained by the observed fractional duration of the flare \( \delta t_f/t_i \sim 0.15 \) (Giannios 2006). The energy contained in the “hot spot” is \( E_{\text{HS}} \sim E_{\gamma,\text{iso}}(\delta t_f/t_i)^3 \sim 3 \times 10^{50} \) erg (assuming again that the total energy in the ejecta is \( \sim 10 \) times larger than \( E_{\gamma,\text{iso}} \)). In this scenario of a “hot spot,” the radiation would also be strongly polarized—a prediction which can help to distinguish the above two models by future observations of similar phenomena.
4. CONCLUSIONS

If more detailed theoretical investigation of the properties of residual collisions and the comparison of their predictions with our data will support our interpretation of the observed flare to be correct, then the delay time between gamma ray and optical flare provides an independent way of determining the Lorentz factor $\Gamma$. Moreover, further parameters of the blast wave can be determined, which were not constrained by observations so far, such as the distance of the residual collisions, the ratio of radiation to magnetic field energy (via the ratio of inverse Compton and synchrotron emission), and the ratio of kinetic to gamma-ray energy. This offers the hope to finally measure the energetics of gamma-ray bursts beyond the rare cases of calorimetry with radio observations.

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