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A GRB Follow-up System at the Xinglong Observatory and Detection of the High-Redshift GRB 060927 *

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Abstract A gamma-ray burst (GRB) optical photometric follow-up system at the Xinglong Observatory of National Astronomical Observatories of China (NAOC) has been constructed. It uses the 0.8-m Tsinghua-NAOC Telescope (TNT) and the 1-m EST telescope, and can automatically respond to GRB Coordinates Network (GCN) alerts. Both telescopes slew relatively fast, being able to point to a new target field within ~ 1 min upon a request. Whenever available, the 2.16-m NAOC telescope is also used. In 2006 the system responded to 15 GRBs and detected seven early afterglows. In 2007 six GRBs have been detected among 18 follow-up observations. TNT observations of the second most distant GRB 060927 ($z = 5.5$) are shown, which started as early as 91 s after the GRB trigger. The afterglow was detected in the combined image of the first 19×20 s unfiltered exposures. This GRB follow-up system has joined the East-Asia GRB Follow-up Observation Network (EAFON).

Key words: gamma–rays: bursts — gamma–rays: observations — telescopes

1 INTRODUCTION

Gamma-Ray bursts (GRBs) are short-lived, intense flashes of gamma-rays from space, lasting from a few milliseconds to many minutes (see Zhang & Mészáros 2004 for a review). They were first discovered by accident by the US military VELA satellites in the late 1960s (Klebesadel et al. 1973), but their origin was an enigma to astronomers for nearly 30 years. The breakthrough came in 1997 when for the first time the X-ray and optical counterparts (i.e. afterglows and host galaxies) of a GRB were found (van Paradijs et al. 1997). This in turn enabled the distance to be established as "cosmological", with a typical redshift of $z \sim 1 - 3$ (Jakobsson et al. 2006). The observations of the *Swift* satellite since its launch in the late 2004 (Gehrels et al. 2004), in particular in the soft X-ray band, have provided considerable new insight into the nature of GRBs (e.g., Yu & Huang 2007; Gao & Fan 2006), as well as raising many new problems. A comprehensive review of new progress in the *Swift* era can be found in Zhang (2007).

Fast follow-up observations in the optical are still of paramount importance for the understanding of GRBs. Now, optical afterglows in early phase contain fruitful information on GRB physics (e.g., Fan et al. 2002; Zhang et al. 2003; Yan et al. 2007), compared with the later self-similar Sedov stage. On the other hand, GRB afterglows are optical transients, whose brightness declines roughly as a power law with a typical index of ~ 1 (Wu et al. 2004; Liang & Zhang 2006). For example, a "bright" afterglow of ~ 15 mag in 100 s may already become as faint as ~ 19 mag just 1 hour later.

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Since the late 1990's, many fast-responding GRB optical follow-up systems have been in operation around the world attached to small or middle-size telescopes (ROTSE-III, TAROT, RAPTOR, PROMPT, KAIT, REM, Liverpool & Faulkes, etc., just to name a few). However, by 2004 such a facility was still conspicuously absent in China despite the vast longitudinal and latitudinal range the country spans. Then for a GRB that happens to occur in the night sky, the golden chance to catch its early afterglow could be missed.

In this paper, we report on the GRB optical photometric follow-up system at the Xinglong Observatory of National Astronomical Observatories of China (NAOC) that we have constructed since 2004, concentrating mainly on the second routine run that started in early 2006, although the first observation was made as early as in 2004 April (Qiu & Hu 2004). Our telescope system, observing program and strategy are described in Sections 2 and 3, respectively. The performance of our system in 2006 and 2007 is summarized in Section 4. The detection of the optical afterglow of the very high-redshift GRB 060927 ($z = 5.5$) is presented in Section 5, which demonstrates a good capability for GRB investigations.

2 THE TELESCOPE SYSTEM

Our telescopes are located at one of the major optical astronomy sites in East Asia, the Xinglong Observatory of NAOC. The site is about 170 km to the northeast of Beijing and about 900 m above sea level, at longitude $7^{\rm h}50^{\rm m}18^{\rm s}$ east and latitude $40°23'36''$ north. On average there are $\sim 240 - 260$ spectroscopic nights and $\sim 100 - 120$ photometric nights every year.

The development of the system started with the 80-cm Tsinghua-NAOC Telescope (TNT) in early 2004. This is an equatorial-mounted Cassegrain system with a focal ratio of $f/10$, made by AstroOptik, founded by Tsinghua University in 2002 and jointly operated with NAOC. TNT is our primary instrument for GRB photometric follow-up observations, although it also serves more general purposes like the monitoring of supernovae, blazars and variable stars (e.g. Wu et al. 2005).

Since 2006 our system has been enlarged to include the 1-m EST telescope after its installation was completed in 2005. This telescope, manufactured by the EOS Technologies, is a Ritchey-Chrétien system and is alt-azimuth mounted. It features dual Nasmyth focal positions at a focal ratio of $f/8$ with two field de-rotators.

The two telescopes are equipped with the same type Princeton Instrument 1340×1300 thin back-illuminated CCDs, with pixel size $\sim 20\ \mu$m and is liquid-nitrogen cooled. The resulting field of view, i.e. $\sim 11' \times 11'$ at the aforementioned focal ratios, well covers the typical $\sim 1' - 4'$ location error circle of the *Swift* Burst Alert Telescope (BAT), the main provider of real-time GRB alerts since 2004. Both CCD cameras are covered with standard Johnson-Cousin $UBVRI$ filters made by Custom Scientific, but we also took unfiltered exposures.

The telescopes can respond quickly to a request for GRB observations. The TNT slews at a speed of $\sim 2°$ per second, while the EST is about two times faster. The traditional rotating domes that house them also move fast. A software system had been developed that can automatically take control of the telescope and CCD camera immediately upon receiving a GRB Coordinates Network (GCN) alert via a socket connection.

The 2.16-m NAOC optical telescope may also be used if the Beijing Faint Object Spectrograph and Camera (BFOSC) is mounted at the time. The camera uses a Loral Lick 3 thin 2048×2048 15-μm CCD that provides a field of view of $\sim 10' \times 10'$ for direct imaging. Standard Johnson-Cousin $UBVRI$ filters are also fitted. However, this relatively old telescope cannot be used in fast response: it was only used for later time faint GRB afterglows.

3 THE OBSERVING PROGRAM AND STRATEGY

Our GRB follow-up system and observing program, to a large extent automatic, are outlined in Figure 1. Automation is required in order to catch the fast-fading GRB afterglows early on. It has been implemented in most systems dedicated to GRB follow-up projects, pioneered by the French TAROT (Böer et al. 1999).

In our system, a daemon program receives and reduces the GRB alert messages that are distributed by GCN through the internet. It continuously communicates with GCN through a socket interface. Although GRB triggers of various satellites are available, currently the program only lets through those of the *Swift*, whose BAT detects the most of the GRBs with locations and provides on-board location error circles as

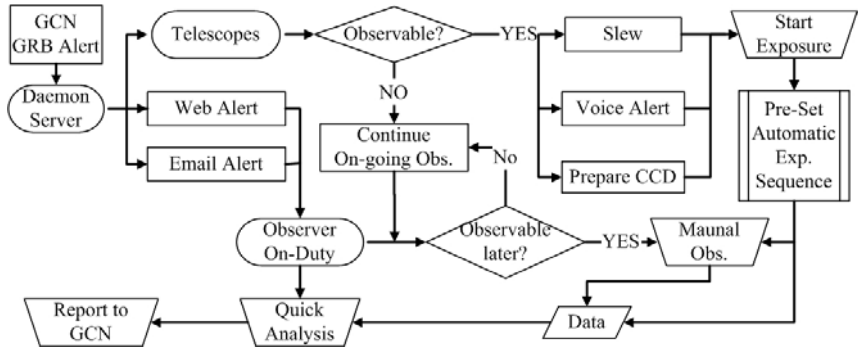

Fig. 1 Flow chart of the GRB follow-up system. *Trapeziums* mark manual operations, *rectangles* mark automatic ones.

small as $\sim 1' - 4'$ to the ground within just 20 s (Barthelmy et al. 2005). The trigger is then broadcast to our system connected in the local network, which is sent to the team members via email and recorded in a dedicated web site.

Once the system obtains the alert, a software will check the GRB coordinates. If the GRB is observable at that time, the software will immediately point the telescope at it and prepare the CCD camera for GRB imaging, overriding any on-going observation. A voice alert is also generated to inform the night assistant to start the pre-set sequence of automatic CCD exposures. This human intervention means no more than a hit of the keyboard in most cases and can be avoided with further automation.

An observer on-duty is activated after receiving the alert email or checking the web site, and he/she shall make a quick analysis of the observed data to look for an optical counterpart, and circulate the results to GCN. It is also his/her responsibility to plan any manual observation, if the GRB is to rise above the horizon later that night, or after the pre-set exposure sequence is completed.

The pre-set sequence starts with 20×20 s unfiltered automatic exposures, within a total of $450 - 500$ s. The unfiltered, i.e. the white band, is used in order to have the best sensitivity, since it is all-important to have an early detection of an optical counterpart. With a 20 s white-band exposure, the TNT can reach a limiting magnitude of $\sim 18 - 19$, thus sensitive to a large fraction of afterglows within ~ 1000 s after GRB (Guidorzi et al. 2006). The CCD operates in high-speed mode to minimize the read-out time to only ~ 1.8 s per image, in an effort to keep the details of temporal variability of the afterglow.

Then 20×60 s R-band automatic exposures are carried out. The CCD is switched to low-speed mode to reduce the noise, with a read-out time of ~ 18 s per image. The increased exposure time matches the fast-decaying brightness of GRB afterglows. After the pre-set sequence, only exposures of 300 s are taken and the observer on-duty will decide when to change the filter and when to terminate the observation.

The above program and strategy are for the TNT. For the EST, the GRB alert with coordinates is displayed on the telescope-control computer in real time. The observer on-duty will start an on-going observation to let the EST follow up a GRB trigger. Nevertheless, we continue to update the control software of the EST to make its GRB observations automatic and simultaneous with the TNT but in a different photometric band.

Flat-field and bias frames are routinely obtained by the night assistant during dusk or dawn. No dark frame is needed since our CCDs are sufficiently cooled. For any GRB afterglow detected, the data reduction will be done after the reference stars in the GRB field have been calibrated in a good photometric night.

4 THE OBSERVATION PERFORMANCE

The first routine run of the system was mainly in 2004, mainly for GRBs localized by HETE-2. However, only one afterglow, that of GRB 041006, about 0.1 day after the trigger, was detected (Urata et al. 2007a), owing to the relatively low event rate and relatively large error circle ($\sim 30'$ by the HETE-2 Wide-Field X-ray Monitor, Shirasaki et al. 2003). The system was unfortunately disabled from running automatically in the first year of the *Swift* era by an accidental loss of socket connection to GCN.

The second routine run[1] began in 2006 February after the socket connection had been recovered and the system refurbished. In 2006 and 2007, 13 afterglows were detected among the 33 bursts observed [2]. All the bursts were localized by *Swift*, except GRB 060930 and GRB 070125.

For 17 of the *Swift* GRBs, our observations were automatically triggered, and started within ~ 1000 s of their first BAT detections, which largely matches the expectations. Simple statistics show that $\sim 20\%$ of the ~ 100 *Swift* GRBs each year were discovered by BAT during nighttime hours with altitudes $> 20^\circ$ at our observatory [3]. The expected number would be ~ 25, allowing for the $\sim 65\%$ of observable nights. The small residual difference may be accounted for by a few non-operational days of our telescopes caused by hardware failures.

The detection rate is the highest for the six GRBs whose observation start-time was less than 2 min after the space γ-ray instruments were triggered, which is $\sim 70\%$. It deteriorates to $\sim 50\%$ for the whole automatic sample and further to $\sim 25\%$ for those of only relatively-late manual observations (i.e. > 1 hr). Note that $\sim 65\%$ of our undetected GRBs have no afterglows identified by other optical telescopes either.

Among the detected afterglows, we have the earliest photometry for GRB 060912A and GRB 061110A, even before the onboard Ultra-Violet/Optical Telescope (UVOT) of *Swift*. In the cases of GRB 060323 and GRB 070518, our detection seems to precede any other ground telescopes. We have detected the very high-redshift GRB 060927, as shown in the next section. We also note that had it not been our automatic observations taken between UVOT and other ground telescopes, that of GRB 060323 would have been accepted as "one of the faintest afterglows ever discovered" (Kann et al. 2006). Detailed analysis of the afterglows will be presented elsewhere, although preliminary results of GRB 060124, GRB 060218 and GRB 060323 have been shown in Deng et al. (2006).

5 THE VERY HIGH-REDSHIFT GRB 060927

GRBs have long been believed to be promising powerful probes of the early universe thanks to their extreme brightness (e.g. Lamb & Reichart 2000). In fact, the most distant GRB 050904 has already been used to explore the universe's reionization epoch (Totani et al. 2006). However, so far there are still only four GRBs with measured redshift of $z > 5$, which are GRB 050814 ($z \sim 5.3$), GRB 050904 ($z = 6.3$), GRB 060522 ($z = 5.1$) and GRB 060927 ($z = 5.5$), all detected by *Swift* [4]. GRB 060927 triggered the *Swift* BAT at 14:07:35 UT on 2006 September 27. An optical counterpart was detected by ROTSE-III in < 20 s (Schaefer et al. 2006), and was soon confirmed by other telescopes including the TNT (Zhai et al. 2006). A redshift of $z = 5.6$ was found by Fynbo et al. (2006) through VLT spectroscopy, making it the second most distant GRB. The value was later updated to 5.47 (Ruiz-Velasco et al. 2007).

The TNT responded to this burst as early as 91 s after the BAT trigger, or within 80 s of the receipt of the GCN alert. This was only second to ROTSE-III. The exposure sequence was slightly different from the routine one described in Section 3; it produced 19×20 s white-band images followed by seven 60 s and three 600 s R-band images. The observation was ended when the observer on-duty judged that the afterglow had become too faint to be detected.

The afterglow is identified as a 3.2σ source in the combined image of first 19×20 s exposures, as shown in Figure 2. It can not be seen in any single-exposure image, nor in the combined later R-band images. The image reduction (including bias subtraction and flat-field correction) was performed using standard IRAF [5]. Differential aperture photometry was performed using the APPHOT package in IRAF and using the R-band magnitudes of reference stars, which were calibrated by observing the Landolt standards on 2006 December 21. The afterglow magnitudes so obtained are listed in Table 1.

Caution must be exercised while comparing our white-band results with those of ROTSE-III as published in Ruiz-Velasco et al. (2007). Although the spectral response of an unfiltered CCD typically peaks in the R band, for such a high-z object the Lyα blanketing absorption at < 8000 Å makes the white band

[1] Real-time updated log can be found at: *http://www.xinglong-naoc.org/grb/index.html*.

[2] GRB 060124 was observed under the request of our collaborators in the East-Asia GRB Follow-up Observation Network (EAFON): *http://cosmic.riken.go.jp/grb/eafon/index.html*

[3] *http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table/*

[4] *http://www.mpe.mpg.de/~jcg/grbgen.html*

[5] IRAF is distributed by NOAO, which is operated by AURA, Inc., under cooperative agreement with NSF.

Table 1 Observation Log of 2006 and 2007

GRB	Time start	Filters	Telescopes	Detection?	GCN Circ.
071112C	113s	W,R,V	TNT,EST	YES	7063
071101	94s	W,R	TNT	NO	7036
071028A	203s	W,R,V	TNT,EST	NO	7015
071025	6.3h	I	TNT	NO	6999
071021	814s	W,R	TNT	NO	6962
071020	10.1h	R	TNT	YES	6956
071018	10.44h	R	TNT	NO	6936,6965
071013	289s	W,R	TNT	NO	6908
071011	353s	W,R,V	TNT,EST	YES	6904
071010B	23.31h	V	EST	YES	6924
070810B	300s	W,R	TNT	NO	6747
070808	115s	W,R	TNT	NO	6722
070529	2.03h	R,V	TNT	NO	6467
070520A	579s	R	EST	NO	6424
070518	512s	W,R,V,I	TNT,EST	YES	6416
070406	19.86h	W	TNT	NO	6250
070129	11.98h	R	TNT	NO	6057
070125	27.6h	R,V	TNT,EST	YES	6035
061222A	9.97h	R	2.16m	NO	5976
061110A	76s	W,R	TNT	YES	5798
060930	2.74h	R	TNT	NO	5669
060927	91s	W,R	TNT	YES	5638
060923C	215s	W,R	TNT	NO	5596
060912A	89s	W,R	TNT	YES	5560
060605	231s	W,R	TNT	YES	5230
060502B	305s	W,R	TNT	NO	5057
060428B	3.54h	I	TNT	NO	5028
060427A	4.79h	R	TNT	NO	5015
060403	6.07h	R	TNT	NO	4955
060323	540s	W	TNT	YES	4930
060223A	5.42h	W	TNT	NO	4827
060218	7.20h	W,R,V,I,B	TNT,EST,2.16m	YES	4802
060124	0.45h	R,I	TNT	YES	4588

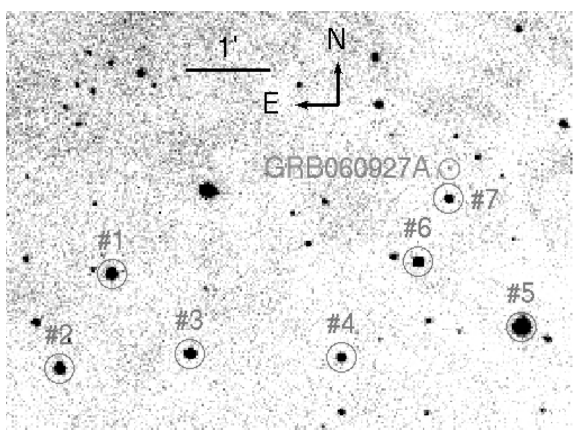

Fig. 2 A combined TNT white-band image of GRB 060927. The GRB afterglow is indicated by the *small circle*, while the photometric reference stars, by the *large circles* labelled #1 to #7.

Table 2 Data of GRB 060927 with the TNT

Time Start	Time End	Mean Time	Exp Time	Filter	Mag	Upper Limit
91 s	572 s	331.5 s	19×20 s	White	19.67±0.33	NO
626 s	1214 s	920 s	7×60 s	R	>19.25	YES
1434 s	2430 s	1932 s	3×300 s	R	>20.02	YES

an effective I band. For the first two ROTSE-III white-band measurements, both preliminary R-band calibrated results (Schaefer et al. 2006) and final I-band calibrated results (Ruiz-Velasco et al. 2007) were reported. The difference between them is as large as ~ 2 mag. Assuming that this value is also applicable to our data, the ~ 19.7 mag at ~ 5.5 min in Table 2 would correspond to ~ 17.7 mag, consistent with the I-band calibrated ROTSE-III result of ~ 17.9 mag at ~ 4.6 min (Ruiz-Velasco et al. 2007).

6 CONCLUSIONS AND FUTURE PLANS

Our GRB optical follow-up system ran efficiently in 2006 and 2007, resulting in the automatic detection of eight very early afterglows including that of the second most distant GRB. Our system has advantage in terms of limiting magnitude over the dedicated, ultra-fast, small-size telescopes that can slew at several tens of degrees per second, similar to the 25-cm TAROT and 45-cm ROTSE-III (Akerlof et al. 2003). Within the East-Asia GRB Follow-up Observation Network (EAFON, Urata et al. 2005), our observations of early-phase afterglows and the later but deeper detections made by the Kiso 1.05 m and Lulin 1-m telescopes, are complementary to each other (e.g., Huang et al. 2005, 2007; Urata et al. 2007b), since a long time coverage of optical afterglows is very important for understanding the nature of GRBs (e.g., Huang & Cheng 2003; Urata et al. 2007c).

Further automation is planned in order to fully exploit the capacity of the system, e.g. the fast slewing speed of the EST. A three-channel camera based on CCD detectors is under development, which will allow our telescope to perform simultaneous multi-color photometry without loss of sensitivity and time resolution. We are also developing a pipeline for real-time data analysis. In addition, the CCD exposure sequence will be optimized regarding the use of the white band, which was both a blessing (i.e. good sensitivity) and a pain (i.e. no reliable calibration at all).

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