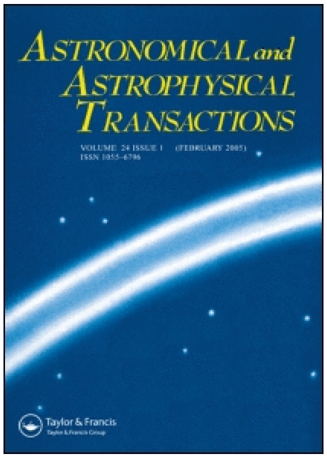

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 February 2007
To cite this Article: Lipunov, V. M., Kornilov, V. G., Krylov, A. V., Kuvshinov, D. A., Gorbovskoy, E. S., Tyurina, N. V., Belinsky, A. A., Borisov, G. V. and Sankovich, A. V. (2007) 'Observations of gamma-ray bursts and a supernovae search at the robotic telescope MASTER', Astronomical & Astrophysical Transactions, 26:1, 79 - 86
To link to this article: DOI: 10.1080/10556790701300462
URL: http://dx.doi.org/10.1080/10556790701300462

Astronomical and Astrophysical Transactions
Vol. 26, Nos. 1–3, February–June 2007, 79–86

Observations of gamma-ray bursts and a supernovae search at the robotic telescope MASTER

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(Received 26 January 2007)

We present here the results of observations made during 2005–2006 using the robotic telescope MASTER. The world's first observations of the optical emission of gamma-ray bursts GRB050824 and GRB060926 are shown. Our data combined with later observations give the law of brightness as proportional to $t^{0.55\pm0.05}$ for GRB050824. We discovered an optical flare for GRB060926 at about 500–700 s. The power law spectral index ($F \propto E^{-\beta}$) is equal to $\beta = 0.7 \pm 0.2$. During the sky survey we have imaged more than 90% of the observable sky. Also we discovered three supernovae (SNs): SN2005bv of type Ia (this is the first SN discovered in Russia), SN2005ee (which is one of the brightest type II SN stars) and SN2006ak (type Ia).

Keywords: Gamma-ray bursts; Telescope robot; Supernovae; Dark energy

1. Introduction

Telescope robots are telescopes that automatically observe the sky, process images and choose a subsequent strategy for observations. Such telescopes are rapidly developing current technology tools. MASTER [1, 2] is the first and unique robotic telescope in Russia. It was designed at the Sternberg Astronomical Institute and Moscow Union 'Optics' in 2002. The modern version of the MASTER system consists of four parallel telescopes on an automatic parallax mount, which points at the source with a speed of up to 6° s^{-1}, and two wide-field cameras on their own mounts with their own covers. One of the wide-field cameras is located at the Mountain Astronomical Station of the Pulkovo Observatory (Kislovodsk). The parameters of the telescopes and the charge-coupled device (CCD) cameras are presented in table 1.

Another system that has very similar characteristics to the MASTER telescope (http://observ.pereplet.ru) is the American ROTSE-III system [3] (http://www.rotse.net). There are some differences between them; the field of view of MASTER is larger, and it has several tubes mounted on the same axis (this design enables us to observe the source at different

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790701300462

Table 1. Equipment for the MASTER system.

	Optical system	Diameter (mm)	F/D	CCD camera	Field of view (deg × deg)	Number of megapixels
1	Modified Richter–Slevogt	355	2.6	Apogee U16E	2.4 × 2.4	16
2	Modified Richter–Slevogt	200	2.6	Sony LCL902K	1 × 0.7	0.4
3	Flugge	280	2.5	Pictor-416	1 × 0.7	0.4
4	Write	200	4	SBIG ST-10XME	1 × 0.7	3.2
5	Very-wide-field camera (Domodedovo)	25	1.2	Foreman Electronics FE-85, Sony ICX285AL chip	30 × 40	1.4
6	Very-wide-field camera (Kislovodsk): MASTER WFC Kislovodsk	60	1.4	Lynx IPX-11M5-G	16 × 24	11

wavelengths simultaneously). The main telescope ($D = 355$ mm; modified Richter–Slevogt system designed by V.Yu. Terebizh and made by G. Borisov) produces unfiltered images. It is equipped with the Apogee Alta U16 CCD camera, which enables us to obtain 6 deg^2 images. The second telescope ($D = 200$ mm; of the same type and made by the same researcher) has a Sony video camera, which images up to 14 m with 0.05 s time resolution. The third telescope ($D = 280$ mm; Flugge system; Pictor-416 CCD camera) has a grism that images the spectra of objects up to 13 m in a $30' \times 40'$ field with 50Å resolution. The fourth telescope ($D = 200$ mm; Write system, made by A. Sankovich) has *UBVR* filters and an SBIG ST-10XME CCD camera. There is a very-wide-field camera (50° × 60°), which covers the HETE (a space gamma telescope) field of view. It can take synchronous observations up to 9 m. This camera has its own automatic cover. The wide-field camera lets us search for short-lived bright objects.

We employed another very-wide-field camera MASTER WFC Kislovodsk on its own mount at the Mountain Astronomical Station of the Pulkovo Observatory (Kislovodsk). This camera gives us continuous wide-field sky monitoring up to 13 m at 5 s exposure.

So at present we have three mini-observatories with the following instruments:

(i) telescopes and CCD cameras, six;
(ii) automatic equator mounts, three;
(iii) automatic covers, three;
(iv) weather stations, two;
(v) Global Positioning System points, one;
(vi) control and reducing computers, six.

The Kislovodsk and Domodedovo systems are connected through the Internet and can respond to new transient objects (not included in the catalogues) during several tens of seconds. MASTER works in a fully automatic regime, which can be described in the following way. By ephemeris (at sunset) and under satisfactory weather conditions (using data from our weather station) the roofs automatically open (both above the main mount and the wide-field camera mount), and the telescope points to bright stars, makes a correction and, depending on image quality, stays in a waiting state or begins a survey using a special automatic program of observations.

So, we have two observation modes: survey mode and alert mode (observations of gamma-ray bursts (GRBs) using position data from orbital gamma observatories). In the first mode our telescope automatically produces three images of a given field with 30–60 s exposure and then points to the next square with 2° steps and repeats all steps after 40–50 min. So, we can mark artefacts and find moving objects. The alert mode is supported by permanent connection of our control computer to The Gamma Ray Bursts Coordinates Network (GCN) (http://gcn.gsfc.nasa.gov [4]). After the GRB registration by the space observatory (e.g. Swift, HETE, Konus-Wind or INTEGRAL) our telescope receives an error box of the burst, then points automatically to this direction, observes it, processes images and marks all objects that are not in the catalogues.

Unique programs for real-time image reduction were written; they allow both astrometry and photometry of each image and recognition of the object (which are not described in the catalogues, i.e. supernovae (SNs), new asteroids, optical transients, etc.).

During all the observational time (2002–2006) we have imaged 52 GRB error boxes at MASTER, 23 of which were recoded for the fist time in the world. We were the first in Europe to fix the optical emission from GRB030329 and the first in the world to fix the optical emission from GRB050824 and GRB060926.

We should remark that for about half of 2006 our main CCD camera was under repair and we did not carry out surveys at that time.

2. Observations of gamma-ray bursts in 2005–2006

During the period from the beginning of 2005 to October 2006 our system MASTER (Domodedovo) had observed 31 GRBs, 16 of which were are the world's first observations within the GRB optical emission limits. We should note that only a few GRBs were detected by Swift in 2006 during night-time in Moscow. In 2005 it gave us 90% of all bursts. In spite of this, we made the world's first observations of optical emission of two GRBs.

We carry out photometry in the automatic mode, using USNO-A2.0 [5] for all stars in the image (up to 10 000 stars) with combined stellar magnitude $m = 0.89R + 0.11B$, which is the optimum for our instrumental magnitude. The image reduction takes less than 1 min. As a result the robot finds the objects that are not included in the catalogues within the error box of the GRB and writes a telegram to GCN using the magnitude of the suspected new source and limiting magnitude of the image. At that time the full image with marked error box and DSS-II-Red image and our old image of this field appear in our database (the base is accessible through the Internet). If the object could not be found in separate images, the limit can be raised to 20 m in summing 10–15 images on a clear moonless night. The results of our observations will shortly be published.

3. GRB050824

MASTER responded [6, 7] to GRB050824 (Swift trigger 151905). The first image was obtained 764 s after Swift GRB050824 detection under the moonlight.

We detected the optical transient (OT) candidate proposed in [8]. Our combined stellar magnitude is $m = 0.89R + 0.11B$ (R and B from USNO-A2). In table 2 we present some results of OT photometry.

We have analysed all photometric points obtained during the first 2 h (see the image that is available at http://observ.pereplet.ru/images/GRB050824/2.jpg) from ROTSE [9], MASTER [7], Gorosabel *et al.* [8] and Swift UVOT [10] in similar colours.

Table 2. OT photometry results.

Universal time (UT)	Time after GRB	Stellar magnitude	Exposure time (s)	Comments
23:25:00	788 s	>17.8	45	Upper limit
23:25:00–23:47:55	24 min	18.6 ± 0.3	15×30	
23:49:00–00:09:30	47 min	19.4 ± 0.3	15×30	

The upper limits of ROTSE and MASTER for 500–750 s (GRB time) are in agreement. Both instrumental systems are more or less similar. There is some contradiction between [8] and MASTER data for the phase 24–47 min, but there is no error bar in [8]. The Swift UVOT V band is most similar to that obtained with MASTER in colour sense. If we include only two MASTER points and the Swift UVOT V point we can obtain the power law $m = (2.1 \pm 0.2) \log t + 19.5$, where t is the time in hours. This corresponds to the usual flux power law $F \propto t^{-0.9}$. The images are available at http://observ.pereplet.ru/images/GRB050824/1.jpg.

4. GRB051103

The MASTER robotic system responded [11, 12] to GRB051103.4 (GRB time, 09:25:43.785 UT on 3 November 2005 [13]). The first image (6 deg^2) was made on 5 November 2005 at 19:55:47 UT, 2 days (10:30:03.215 UT) after the GRB time. We have 36 images with total exposure 1080 s between 19:55:47 and 21:45:17 UT on a 6 deg^2 area. The robot did not find an OT candidate within the Interplanetary Network (IPN) error box. Our upper limit of the sum is about 18.5 m (the weather was not very good). The unfiltered images are calibrated relative to USNO-A2.0 ($0.8R + 0.2$B).

There are four galaxy overlaps inside the IPN error box (see image), as listed in table 3.

M81 as a candidate [13] for a soft gamma-ray host galaxy is very probable, but we note that the error box is placed outside the spiral arms region, where the progenitor of a highly magnetized neutron star formed. However, the structure of the galaxy is distorted by tidal interaction. For example, there is ultraluminous X-ray source M81 X-9 [14] at the same distance from the centre of M81 (this source is not within the error box and belongs to a high-mass binary population). There are no known SN remnants inside the error box. We would like to emphasize the elliptical galaxy from the Principal Galaxy Catalogue (PGC) named PGC028505. This galaxy is close to the centre of the IPN error box. The distance to PGC028505 can be estimated as about 80 Mpc. Assuming that the burst originates from a source in PGC028505, the isotropic energy release of this GRB is about 2×10^{49} erg. This energy is about one order of magnitude higher than the GRB050509b energy associated with an elliptical galaxy [15]. Whatever the case, X-ray and optical observations are urgently needed in the search for SN remnants.

The sum JPG image is available at the following website: http://observ.pereplet.ru/images/GRB051103.4/sum36.jpg. The IPN error box and galaxies are presented.

5. GRB060926

The MASTER robotic system responded to GRB060926 [16] under good conditions. The first image was started on 26 September 2006 at 16:49:57 UT, 76 s after the GRB time. The

Table 3. Galaxy overlaps.

			Stellar magnitude			
Galaxy name	Type	Coordinates (J2000)	*B*	MASTER	Red shift	D_{25}
M81	Sab	095 533.2 + 690 355	7.8	–	0.000 376	26′.9
M82	Sb	095 552.2 + 694 047	9.3		0.000 677	11′.2
PGC2719634	–	095 132.3 + 683 124	17.8	16.7	–	16′.9
PGC028505	E	095 310.22 + 690 002.0	17	14.8	–	6′.0

Table 4. Optical flare.

Beginning of exposure (s)	Mean time (s)	Exposure time (s)	Stellar magnitude	Flux (erg cm^{-2} s^{-1} eV^{-1})	Flux using absorption (erg cm^{-2} s^{-1} eV^{-1})
76	91	30	17.3 ± 0.3	$(1.4 \pm 0.3) \times 10^{-13}$	$(4.3 \pm 1.0) \times 10^{-12}$
150	165	30	18.5 ± 0.3	$(4.6 \pm 1.1) \times 10^{-14}$	$(1.4 \pm 0.4) \times 10^{-12}$
165	343	5×30	19.3 ± 0.3	$(2.2 \pm 0.5) \times 10^{-14}$	$(6.9 \pm 1.7) \times 10^{-13}$
255	432	5×30	18.9 ± 0.3	$(3.2 \pm 0.8) \times 10^{-14}$	$(9.9 \pm 2.4) \times 10^{-13}$
343	519	5×30	18.5 ± 0.3	$(4.6 \pm 1.1) \times 10^{-14}$	$(1.4 \pm 0.3) \times 10^{-12}$
432	608	5×30	18.3 ± 0.3	$(5.8 \pm 1.3) \times 10^{-14}$	$(1.7 \pm 0.4) \times 10^{-12}$
519	707	5×30	18.4 ± 0.3	$(5.1 \pm 1.2) \times 10^{-14}$	$(1.6 \pm 0.4) \times 10^{-12}$
608	804	5×30	18.7 ± 0.3	$(3.9 \pm 0.9) \times 10^{-14}$	$(1.2 \pm 0.3) \times 10^{-12}$
707	1001	5×30	20.0 ± 0.3	$(1.2 \pm 0.3) \times 10^{-14}$	$(3.6 \pm 0.9) \times 10^{-13}$
804	1200	5×30	20.1 ± 0.3	$(1.1 \pm 0.3) \times 10^{-14}$	$(3.3 \pm 0.8) \times 10^{-13}$
901	1298	5×30	$>20.1 \pm 0.3$	$>(1.1 \pm 0.3) \times 10^{-14}$	$>(3.3 \pm 0.8) \times 10^{-12}$

unfiltered image is calibrated relative to USNO-A2.0 ($0.8R + 0.2$B). We find a faint OT on the first and on the co-added images at the following position:

$$\text{RA(2000)} = \text{17h 35m 43.66s} \pm \text{-0.05s},$$

$$\text{Dec(2000)} = \text{13d 02'18}''.3 \pm \text{-0}''.7,$$

which coincided with the OT position [17]. We discovered an optical flare around 500–700 s after the GRB time (note that optical flares are a very rare phenomenon, which consists of a sharp rise in the luminosity during GRB fading) (table 4).

The light curve is available at the following website: http://observ.pereplet.ru/images/GRB060926/light_curve_new.jpg.

Between 91 and 255 s the power law has a temporal index which is estimated to be equal to -1.40 ± 0.24. Between 707 and 1200 s the power law has a temporal index which is estimated

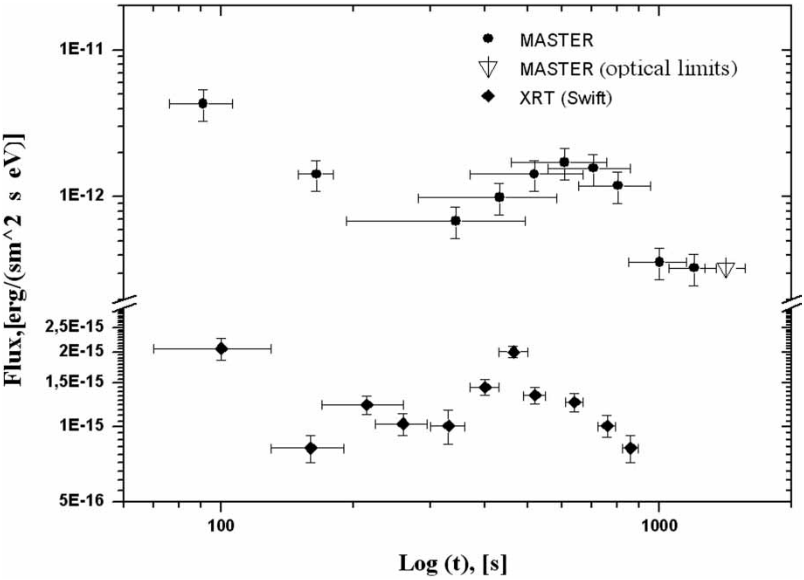

Figure 1. Optical light curves of GRB060926 obtained using the MASTER system [16] and the OPTIMA-Burst [18], and the X-ray light curve obtained by XRT Swift [19].

to be equal to -3.30 ± 0.70. After 1000 s a power law with a temporal index of 0.73 ± 0.1 was obtained [18].

We recall that the X-ray flare in GRB060926 was discovered by the XRT team [19]. The X-ray spectrum covering the time period from $T + 67$ s to $T + 878$ s is well fitted by an absorbed power law with a photon index of 2.1 ± 0.3 and a column density of $(2.2 \pm 0.9) \times 10^{21} \mathrm{cm}^{-2}$ [19] (figure 1). They noted that the Galactic column density in the direction of the source was 7.3×10^{20} cm^{-2}. This means that the absorption magnitude is about 1 in our band. The optical and X-ray data are well fitted by a power law with a photon index of 1.7 ± 0.2 during all our time observations.

6. Supernovae search

The formation rate of cosmological SNs was calculated in [20] using the population synthesis method. It was shown that the discovery of distant SNs and their formation rate depend on the ratio of baryonic matter in the Universe, which is included in stars, to the dark-energy contribution to the density of the Universe. Using the results of these calculations, we can show that, on average, in a field of 6 deg^2 the number of SNs at any time is equal to $N = 2 \times 10^{3(m-20)/5}$, where m is the image limit.

It should be noted that this is true for the isotropic galaxy distribution and therefore can be applied to SNs, which are farther than 100 Mpc, i.e. for SNs that have stellar magnitudes $m > 15 - 16$ maximum ($m = 20$ corresponds to type Ia SNs at a red shift $z \approx 1$ without absorption). So, it can be seen that even a chance sky survey by a wide-field telescope such as MASTER can result in the mass discovery of SNs. This is very important for a type Ia SN study (especially if the type Ia SN is brighter than our 20 m), which can help us to calculate the acceleration of expansion of the Universe [21].

The search scheme for SNs using MASTER is as follows.

(i) The robot marks the signal above the galaxy phone.
(ii) The coordinates and stellar magnitudes of the stars found are compared with objects in this field from the catalogues and so we find new objects.
(iii) If this field was observed by MASTER previously, new objects are compared with marked objects during previous observations; if there was no marked object, then this object can be considered as an SN.

This process is fully automatic. The last fact makes our software unique in the world.

We now present the SNs discovered by MASTER.

6.1 *SN2005bv*

This is the first SN discovered in Russia. It was discovered on 28 April 2005 [22] during the first MASTER survey. SN2005bv is type Ia and has a right ascension (RA) (2000) of 14 h 24 m 07.44 s, a declination (2000) of $+26^\circ\ 17'\ 50''.3$ and a magnitude of 16.8 at the discovery time (close to R). It is located near PGC1770866.

6.2 *SN2005ee*

This was discovered on 26 September 2005, at magnitude 16.0 on the discovery day [23]. This is a type II SN; it belongs to PGC73054 with the coordinates RA = 23 h 57 m 55.83 s and declination $= +32^\circ\ 38'\ 08''.9$ (equinox 2000.0). This is an anomalously luminous SN. The absolute stellar magnitude on the plateau is about -18.6 (without absorption).

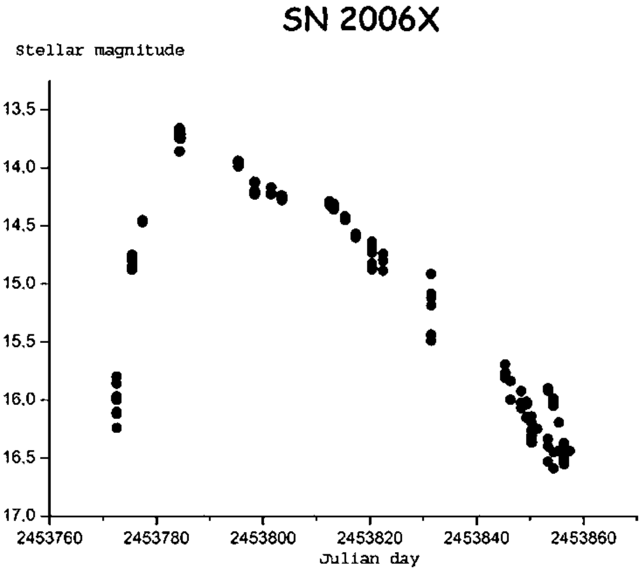

Figure 2. The light curve of SN2006X.

6.3 *SN2006ak*

This was discovered on 17 February 2006 [24], during the second day after its maximum. This is a type Ia SN; its coordinates are RA = 11 h 09 m 32.83 s and declination = +28°37″50′.3 in PGC083454.

6.4 *SN2006X*

We imaged one of the brightest (and nearest) SNs in the M100 galaxy, namely SN2006X. Its stellar magnitude was $m = 16.2 \pm 0.3$ (06:16:2 UT on 6 February 2006). Our point was the second in the world at the ascending part of the light curve of SN2006X (type Ia SN) [25]. Its light curve is given in figure 2.

The discovery of an SN by MASTER allows us to estimate the efficiency of a random search for SNs at wide-field telescopes. We calculated that, using a telescope of 40–50 cm diameter with a 6 deg^2 field of view and in good climatic zones, it is possible to discover up to 100 SNs per year. MASTER-IV will be able to discover up to 500 SNs per year and can help to detect the contribution of dark energy to the total density of the Universe during observations over 2–3 years.

7. Conclusions

We present here the results of observations made during 2005–2006 using the robotic telescope MASTER. The world's first observations of the optical emission of GRB050824 and GRB060926 are introduced. Our data combined with later observations give the law of brightness as proportional to $t^{0.55\pm0.50}$ for GRB050824. We discovered an optical flare for GRB060926 at about 500–700 s. The power law spectral index ($F \propto E^{-\beta}$) is equal to $\beta = 1.0 \pm 0.2$. During the sky survey we have imaged more than 90% of the observable sky. A virtual database and pipeline were created. The limit to the orphan optical bursts rate is presented. We discovered three SN stars, and they are the following: SN2005bv (type Ia), which is the first discovered from Russian territory, SN2005ee, which is one of the nearest and brightest SNs among type II SNs, and SN2006ak (type Ia). The light curve for SN2006X is presented. A new method of OT search after IPN triangulation of the gamma-ray observation is proposed and tested.

Acknowledgements

The authors are deeply indebted to S.M. Bodrov and Moscow Union 'OPTICS' for financial support of all project instruments, to V.L. Afanas'ev for the grism, to V.D. Pallshin and the Konus-Wind team for collaboration and to the INET internet provider.

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