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Observation of Cosmic Gamma Ray Bursts in the Experiments Onboard Lomonosov and Vernov Satellites

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Abstract—The study of cosmic gamma ray bursts (GRBs) is one of the main goals of the *Lomonosov* space mission. The main advantage of this mission is simultaneous multiwavelength observations of GRBs covering the optical, X-ray and gamma-ray ranges. The mission payload includes the GRB monitor BDRG, wide-field optical cameras SHOK, and the UFFO instrument. Data are recorded mainly by the event trigger provided by the BDRG instrument, which measures the spectral and temporal properties of the burst in the energy range 10–3000 keV. The BDRG instrument also provides estimation of the source coordinates by comparing the readings of three differently directed detectors with an accuracy of several degrees. Wide-field SHOK optical cameras have a field of view of ~20° × 40°. They fix a set of images with a frequency of about five frames per second prior to the trigger and another set immediately after the trigger. The UFFO instrument includes the UBAT telescope with a coded mask for measurements in hard X-ray and soft gamma-ray ranges and an optical telescope with a slewing mirror (SMT) that can be directed on the GRB source for a time ~1 s for measuring GRB prompt emission in the early stages. In response to an BDRG trigger signal, the real-time data on a detected GRB are transmitted to the Earth via *Globalstar* network to the *Gamma-ray Coordinates Network* (GCN) and ground-based observatories. During observations on the *Lomonosov* satellite, 20 gamma-ray bursts were detected and catalogued. Several gamma-ray bursts were also detected in the *Vernov* satellite experiment. An example of such an event is given.

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1. INTRODUCTION

Despite numerous theoretical models regarding gamma-ray bursts (GRBs), the nature of the cosmic GRB phenomenon has not yet been completely clarified. The principal factor in the further progress of understanding this phenomenon is simultaneous multiwavelength observations of GRBs. Such observations were realized with the *Lomonosov* satellite [1] launched on April 28, 2016, from *Vostochny* cosmodrome on a circular Sun-synchronous orbit with an altitude of about 500 km. The mission payload includes the TUS detector developed for detecting extensive air shower (EAS) tracks from ultra-high energy cosmic ray (UHECR) particles by ionizing radiation, as well as the instruments for studying GRBs, which includes GRB monitor BDRG, SHOK wide-field optical cameras, and ultraviolet (UV) and X-ray UFFO instruments. All detectors operate in the continuous measurement mode, thereby providing simultaneous event recording in X-ray, UV, and optical ranges. The real-time data transfer into the GCN system of detected GRBs, as well as operative control of BDRG data on triggers from ground-based facilities, detected UHERCH (Auger, TA), high-energy neutrino (IceCube, ANTARES), and gravitational waves (LIGO), are provided. The *Lomonosov* satellite is the first space mission in which the observations of GRBs are realized in optical and gamma ranges in real time without the necessity of reorientation of optical instruments. This is achieved by the optical wide-field cameras, which are coaligned with gamma-ray detectors and are continuously recording the sequence of images. So, this allows us to fix the optical light curves of prompt emission as well as of precursors.

Study of GRBs is also one of the main goals of the *Vernov* space mission [2], which operated from July to December 2014 on a Sun-synchronous orbit with an altitude of 640 to 830 km. Its detectors were mostly used to detect gamma-ray bursts in the Earth's atmosphere and the variability of magnetospheric relativistic electrons fluxes. The main advantage of *Vernov* experiment is the possibility to investigate the rapid variability of GRBs, which is achieved by recording individual photons (the so-called photon-by-photon detection) [2].

1. INSTRUMENTATION FOR GRB STUDYING ONBOARD LOMONOSOV AND VERNOV SATELLITES

GRB Monitor BDRG Onboard the Lomonosov Satellite

The BDRG [3] instrument consists of three identical detector units, BDRG-1 through BDRG-3, and the electronics unit, BA-BDRG. The BA-BDRG provides an interface with the BI electronics unit, including the power supply and control signals for detector units, the output data generation and its transmission to the BE.

Each BDRG box consists of a detector unit, electronics boards, and mechanical construction elements. The detector units consists of an assembly of NaI(Tl)/CsI(Tl) scintillator detectors with a diameter of 13 cm and thickness of 2 cm (the thickness of the NaI(Tl) crystal is 0.3 cm, while that of the CsI(Tl) crystal is 1.7 cm). Both scintillators are in optical contact and viewed from the CsI(Tl) side by one photomultiplier tube (PMT, *Hammamatsu R877*). The difference in decay times for the NaI(Tl) (~0.25 ms) and for CsI(Tl) (~2.0 ms) crystals provides an opportunity to separate events in both scintillators. This considerably reduces the gamma-ray background detection in a thin NaI(Tl) crystal and expands the energy range due to a thick CsI(Tl) crystal performance. Configured in this way, the NaI(Tl)/CsI(Tl) assembly enables us to distinguish events related to the GRB from magnetospheric electron precipitations. The BDRG instrument is designed to detect gamma-rays in the energy range 10–3000 keV with an effective area of each detector of ~130 cm^2. This effective area provides the detection sensitivity of ~10^{-7} erg/cm^2 estimated from background counts near the geomagnetic equator.

The axes of the three detectors are oriented 90° from each other, forming a Cartesian coordinate system. This allows us to determine the direction of the GRB source by correlating the values from different detectors.

The BDRG instrument operates in two main observational modes: monitor and burst modes. In the monitor mode, the continuous recording of the counting rates averaged over 0.1 s in corresponding energy channels are performed for events in each crystal. Furthermore, the energy spectra (averaged over 15 s) are measured with the multichannel ADCs for both crystals. In the burst mode, there are three types of trigger, distinguished by different exposure-time scales, during which the events are collected to define an excess in the background counting rate: 10 ms ("fast"), 1 s ("slow") and 20 s ("super-slow"). When the trigger occurs, the counting rate (up to 1 ms) and average energy spectra (up to 1 s) are recorded with more details, the amplitude of the energy release for each detected event (quantum or particle) being measured for both crystals. Furthermore, the trigger signals are sent to wide-field optical cameras SHOK and the UFFO instrument. The BDRG triggers also provide the telegrams with operative information on the GRB event for transfer to the GCN system.

Wide-Field Optical Cameras SHOK Onboard the Lomonosov Satellite

The *Lomonosov* spacecraft (SC) is equipped with two identical wide-field optical cameras, SHOK 1 and SHOK 2. Both devices are directly connected to the central electronic unit BI, which provides an interface with the satellite onboard systems and another units of the facility. The main parameters of SHOK cameras are given in Table 2. These cameras are of the same type as those of the ground-based global network of robotic telescopes, MASTER, used for search the for optical transients including cosmic GRBs [4]. Each unit is based on a recording camera with a Nikkor optical lens and a CCD-matrix Kodak KAI-11002. The camera sensitivity allows optical emissions with a magnitude of 9–10^m to be recorded. Each optical camera is oriented such a way that its field of view (FOV) is inside of one of the BDRG FOV. The cameras continuously record the images with a time resolution of 0.2 s. After the trigger produced by the BDRG units or the X-ray telescope UBAT/UFFO, the data are fixed in the one minute prior to the trigger and two minutes after the trigger. The alignment of SHOCK axes with the BDRG axes allows us to detect a cosmic GRB simultaneously with both detectors and produce the optical images at the burst moment as well as before the burst. Preselected time intervals for the data-fixing cover typical time intervals between a precursor and burst. It is possible to fix the SHOK images by the trigger sent from the Earth, i.e., by bursts registered by GCN. The cameras can also perform observations in the optical transient search mode, under internal trigger. In this mode, the comparison between the following and preceding images is performed automatically and, in this way, the new object occurrence or source brightness variation in the camera FOV is fixed. This mode can be used not only for the observations of astrophysical phenomenon such as supernovas and novas, but also for investigation of space debris, meteorite hazards etc.

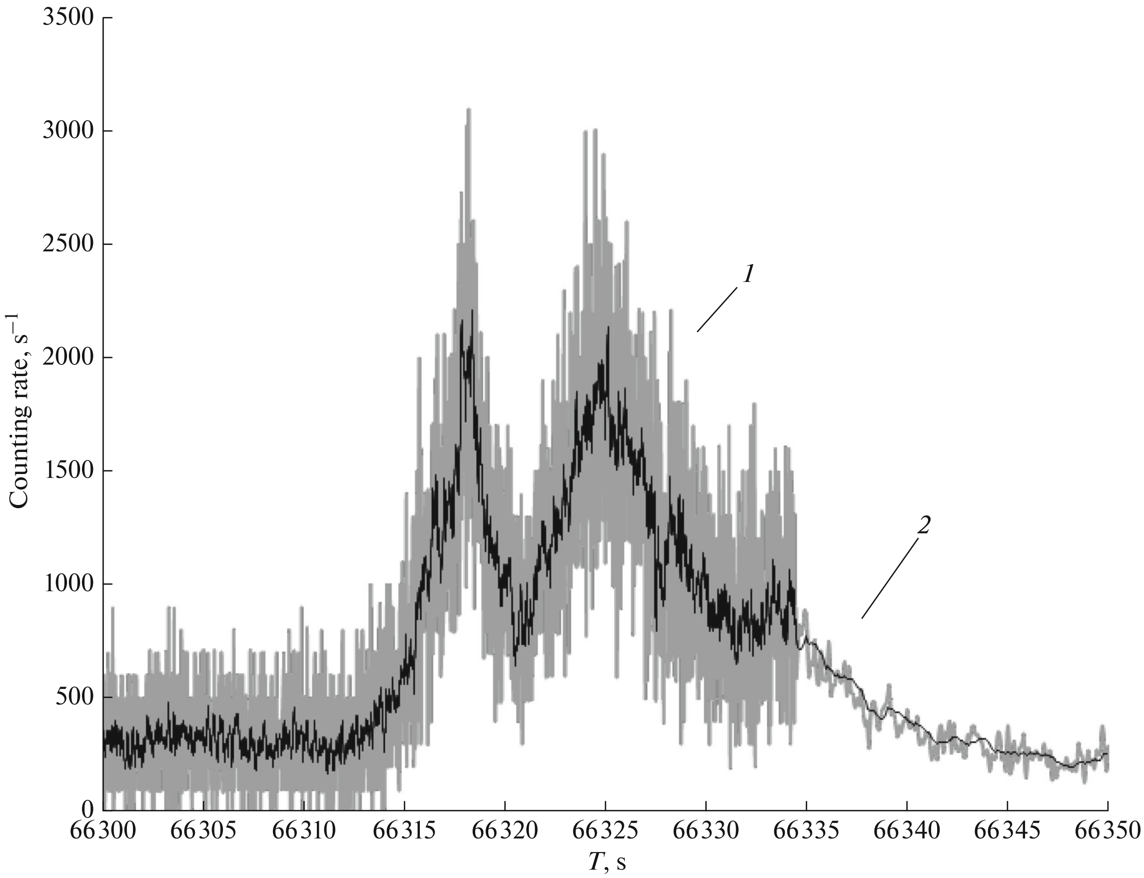

Fig. 1. Integrated counting rate of GRB 160720 versus time T measured in the NaI(Tl) 20–170 keV range of the BDRG-3 detector. Here, gray and black curves stand for primary data and 10-point moving average data, respectively. The X-axis shows the time since 20.07.2016, 00:00 UTC. The data points on the source light curve are shown with the time interval of 10 ms up to the point $T = 66335$ s (fragment *1*) and with the time interval of 100 ms after that point (fragment *2*).

The UFFO Instrument Onboard the Lomonosov Satellite

The UFFO instrument includes the X-ray telescope UBAT and a rapid slewing UV and optical telescope SMT [5]. The telescope UBAT is designed as a combination of a position-sensitive detector (PSD) and a coded mask. The PSD along with a coded mask have planar configuration and is made of YSO scintillation crystal array containing 48 × 48 pixels viewed by multianode PMTs. The PSD size and pixel area are 2.8 × 2.8 mm^2 and 191 cm^2, respectively. The FOV of UBAT is 70.4° × 70.4°. It provides GRB detection in the hard X-ray band (5–150 keV) and determination of the source position with high accuracy (~10'), the data collection time for determination of GRB coordinates being 0.1 s. In response to the UBAT trigger, the SMT, which is sensitive to photons of 200–650 nm in wavelength, is rapidly slewed to the location of the GRB (GRB destination). The currently-best value for the optical telescope slewing time (~1 s) should be achieved in this experiment. For comparison, NASA's SWIFT mission is the extremely fast response space observatory among the currently operating orbital instruments which provides the optical telescope slewing in 27 seconds. This also allows to record the optical light curve during the gamma-ray burst itself with high time resolution.

DRGE Instrument on the Vernov Satellite

The DRGE instrument consists of three units, i.e., two identical DRGE-1 and DRGE-2 units, and the DfRGE-3 unit. Each of DRGE-1(2) consist of two identical detector assemblies (DRGE-11, DRGE-12 and DRGE-21, DRGE-22 units). Structurally, the detector assemblies of DRGE-1(2) units are completely analogous to the detector assemblies of BDRG unit onboard the *Lomonosov* satellite. The detectors of the DRGE-1 and DRGE-2 units are oriented towards the nadir. The recording format of the output data is analogous to that of BDRG unit, i.e., during the experiment the counting rates of the DRGE-1(2) detectors are continuously recorded in two modes: the monitoring and time-tagged event ones. The initialization of an internal clock at the instant the synchronizing pulse arrived from the satellite was used in each unit to ensure the synchronous operation of all detector units with a good time resolution. The clock of each unit had a period of 15.48 μs. The clock stability $\sim 10^{-5}$ provided a synchronization accuracy of ~ 15 μs.

3. RESULTS OF OBSERVATIONS FOR COSMIC GRBs ONBOARD LOMONOSOV SATELITE

Taking into account the background peculiarities at the orbit of the *Lomonosov* satellite, gamma-ray bursts can be detected with an acceptable sensitivity in equatorial and in polar (the so-called polar caps) regions where the background was more or less constant. The triggering of the data recording of the burst was realized at two levels. The threshold of the first level was chosen relatively low but only more detailed gamma-ray data than that for the monitoring mode were stored by such a trigger. A few tens of triggers of that type occurred per day. Most of them were caused by the variations of electron fluxes, including precipitations from the radiation belts. The second level, the so-called alert level, triggering has a much higher threshold and some additional conditions such as the demand for a satellite to be out of the regions of trapped radiation and precipitations. When the alert trigger occurs, the data of BDRG instrument, SHOK cameras and the UFFO instrument are fixed and a fast telegram is sent to the GCN network via the GlobalStar modem.

Twenty GRBs were detected in the period of observations onboard the *Lomonosov* satellite from June 2016 to January 2017 [6]. They were confirmed by other experiments and presented in the GCN network. The effective time of GRB detection in the *Lomonosov* experiment is ~20%, which is determined by shadowing by the Earth and by the time when the satellite is in the radiation belt and precipitation regions. Moreover, the probability of detecting a GRB not listed in GCN is less than 10%. However, there are a few GRBs in the Lomonosov/BDRG catalogue that were not observed by the main specialized missions such as Swift, Fermi and Konus-Wind. For example, GRB 160908A was observed only in CALET experiment [7].

It should be noted that several bursts detected by Lomonosov/BDRG were observed by ground robotic telescopes of the MASTER net, developed at Moscow State University. For two of them the upper limits on the brightness of optical transients were obtained: 16.5^{m} for GRB 160720A at 30794 s after the trigger [8, 9] and 18^{m} for GRB 160824B at 1165 s after the trigger [9]. In the case of GRB 161017A an optical transient was discovered.

Figure 1 shows the time profile of gamma quantum counts of GRB 160720 detected by a NaI(Tl) detector of the BGRG-3 unit in the 20–170 keV energy range. Data recording was performed in “slow” trigger mode, i.e., for 100-s time interval before the trigger and in the 800 s time interval after the trigger data were recorded with 10- and 100-ms time resolution, respectively. In this Figure the fine structure variations are seen at a time scale of 10 ms.

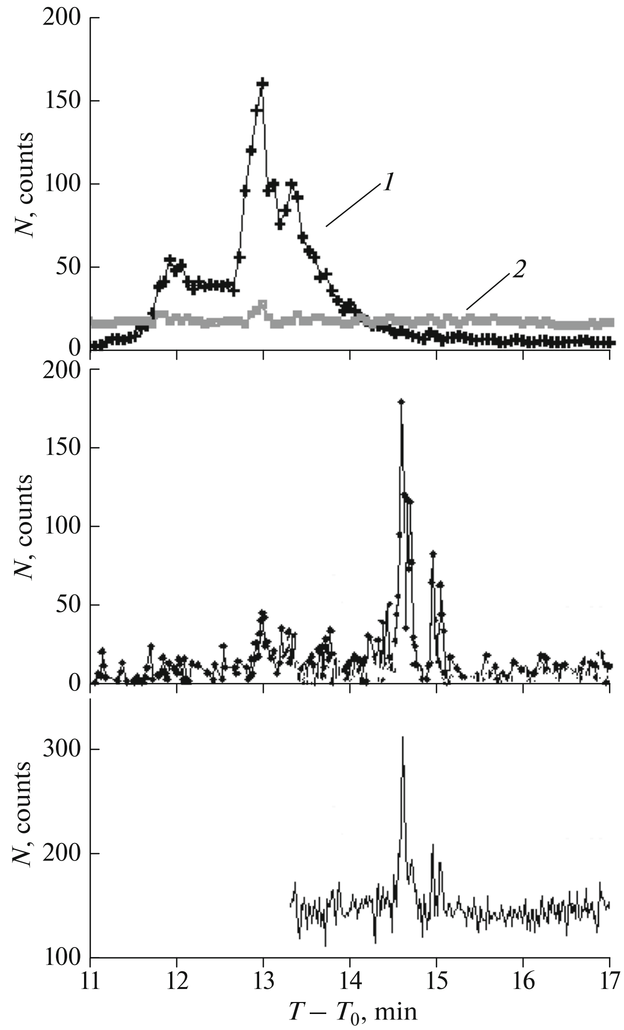

Fig. 2. Time profiles of the X-ray and gamma-ray radiation from GRB 141029 obtained onboard the Vernov satellite with the DRGE-12 unit (30–300 keV, middle panel), with GBM Fermi (52.2–97.8 keV, bottom panel) and for the solar flare on 2014 October 29, detected with RHESSI (top panel) in the 12–25/25–60 keV energy range (curve *1*/curve *2*). X-axis shows the time since the time instant T_0 = 29.10.2014, 13:00 UTC.

4. OBSERVATIONS OF COSMIC GRBs ONBOARD THE VERNOV SATELLITE

An example of a GRB detected with the *Vernov* satellite on October 29, 2014, is presented in Figure 2. Here, one can see that the hard X- and gamma-ray burst from the Sun occurred just before a cosmic GRB. However, in contrast to the solar flare, the GRB is characterized by considerably harder emission and a complicated temporal structure.

5. CONCLUSIONS

The *Vernov* and *Lomonosov* satellites have detected cosmic and solar gamma-ray bursts. The mission payloads recorded the light curves with very high (less than 1 ms) time resolution. The *Lomonosov* satellite is the first space mission in which the multiwavelength observations of prompt emission of cosmic GRBs are realized in real time.

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REFERENCES

1. V. A. Sadovnichiy, A. M. Amelyushkin, V. Angelopoulos, V. V. Bengin, V. V. Bogomolov, G. K. Garipov, P. A. Klimov, B. A. Khrenov, M. I. Panasyuk, V. L. Petrov, S. I. Svertilov, E. A. Sigaeva, N. N. Vedenkin, I. V. Yashin, E. S. Gorbovskoy, V. M. Lipunov, B. Grossan, G. F. Smoot, J. Lee, G. W. Na, I. H. Park, V. Angelopoulos, C. T. Russell, and Y. Shprits, "Space experiments aboard the Lomonosov MSU satellite," Cosmic Res. **51**, 427–433 (2013).
2. M. I. Panasyuk, S. I. Svertilov, V. V. Bogomolov, G. K. Garipov, V. O. Barinova, A. V. Bogomolov, N. N. Veden'kin, I. A. Golovanov, A. F. Iyudin, V. V. Kalegaev, P. A. Klimov, A. S. Kovtyukh, E. A. Kuznetsova, V. S. Morozenko, O. V. Morozov, I. N. Myagkova, V. L. Petrov, A. V. Prokhorov, G. V. Rozhkov, E. A. Sigaeva, B. A. Khrenov, I. V. Yashin, S. I. Klimov, D. I. Vavilov, V. A. Grushin, T. V. Grechko, V. V. Khartov, V. A. Kudryashov, S. V. Bortnikov, P. V. Mzhel'skiy, A. P. Papkov, S. V. Krasnopeev, V. V. Krug, V. E. Korepanov, S. Belyaev, A. Demidov, Ch. Ferenz, L. Bodnar, P. Szegedi, H. Rotkel, M. Moravskiy, I. Park, J. A. Jeon, J. I. Kim, and J. Lee, "Experiment on the *Vernov* satellite: Transient energetic processes in the Earth's atmosphere and magnetosphere. Part I: Description of the experiment," Cosmic Res. **54**, 261–269 (2016).
3. A. M. Amelyushkin, V. I. Galkin, B. V. Goncharov, E. S. Gorbovskoi, V. G. Kornilov, V. M. Lipunov, M. I. Panasyuk, V. L. Petrov, J. F. Smut, S. I. Svertilov, N. N. Veden'kin, I. V. Yashin "The BDRG and SHOK devices for studying gamma ray burst prompt emission on board the Lomonosov spacecraft," Cosmic Res. **51**, 434–438 (2013).
4. V. M. Lipunov, V. G. Kornilov, E. Gorbovskoy, N. Shatskij, D. Kuvshinov, N. Tyurina, A. Belinski, A. Krylov, P. Balanutsa, V. Chazov, A. Kuznetsov, P. Kortunov, A. Sankovich, A. Tlatov, A. Parkhomenko, V. Krushinsky, and I. Zalozhnyh, "Master robotic net," Adv. Astron., **349171** (2010). doi 10.1155/2010/349171
5. J. W. Nam, S. Ahmad, K. B. Ahn, P. Barrillon, S. Brandt, C. Budtz-Jrgensen, A. J. Castro-Tirado, C.-H. Chang, C. -Y. Chang, Y. Y. Chang, C. R. Chen, P. Chen, M. Cho, H. S. Choi, Y. J. Choi, P. Connel, S. Dagoret-Campagne, C. Eyles, B. Grossan, J. J. Huang, M. H. A. Huang, S. Jeong, A. Jung, J. E. Kim, M. B. Kim, S.-W. Kim, Y. W. Kim, A. S. Krasnov, J. Lee, H. Lim, E. V. Linder, T. C. Liu, N. Lund, K. W. Min, G. W. Na, M. I. Panasyuk, I. H. Park, V. Reglero, J. Ripa, J. M. Rodrigo, G. F. Smoot, J. E. Suh, S. Svertilov, N. Vedenkin, M. Z. Wang, and I. Yashin, "The status of the Ultra Fast Flash Observatory – Pathfinder," Nucl. Phys. B, Proc. Suppl., **246–247**, 29—33 (2014).
6. GRB catalogue on the site of Lomonosov space mission, http://downloader.sinp.msu.ru/grb_catalog/ (2017).
7. T. Sakamoto, A. Yoshida, Y. Kawakubo, M. Moriyama, Y. Yamada, K. Yamaoka, S. Nakahira, I. Takahashi, Y. Asaoka, S. Ozawa, S. Torii, Y. Shimizu, T. Tamura, W. Ishizaki, M. L. Cherry, S. Ricciarini, P. S. Marrocchesi, and the CALET collaboration, "GRB 160908A: CALET Gamma-Ray Burst Monitor detection," GRB Coordinates Network, No. 19903, 1 (2016).
8. A. M. Amelushkin, V. O. Barinova, A. V. Bogomolov, V. V. Bogomolov, A. F. Iyudin, V. V. Kalegaev, M. I. Panasyuk, V. L. Petrov, S. I. Svertilov, I. V. Yashin, I. Park, J. Lee, S. Jeong, V. Lipunov, E. S. Gorbovskoy, N. Tyurina, V. Kornilov, P. Balanutsa, A. Kuznetsov, D. Kuvshinov, R. Rebolo, M. Serra Ricart, N. Lodieu, and G. Israelian, "GRB 160720A: Lomonosov BDRG gamma ray detection and MASTER limit," GRB Coordinates Network, No. **19728**, 1 (2016).
9. N. L. Dzhioeva, A. M. Amelushkin, V. O. Barinova, A. V. Bogomolov, V. V. Bogomolov, A. F. Iyudin, V. V. Kalegaev, M. I. Panasyuk, V. L. Petrov, S. I. Svertilov, I. V. Yashin, I. Park, J. Lee, S. Jeong, V. Lipunov, E. S. Gorbovskoy, N. Tyurina, P. Balanutsa, A. Kuznetsov, D. Kuvshinov, K. Ivanov, S. Yazev, N. M. Budnev, O. Gres, O. Chuvalaev, V. A. Poleshchuk, V. Yurkov, Yu. Sergienko, and A. Gabovich, "GRB 160824B: Lomonosov BDRG gamma ray detection and MASTER limit," GRB Coordinates Network, No. 19884, 1, (2016).

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