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EARLY EMISSION OF SHORT OPTICAL TRANSIENTS

S. Wu[1,2], V. M. Lipunov[3], A. J. Castro-Tirado[1,4], Y.-D. Hu[1,2], K. Zhirkov[3], and N. V. Tyurina[3]

RESUMEN

Este estudio presenta un análisis exhaustivo de la emisión óptica temprana de fuentes transitorias ópticas de corta duración, aprovechando los datos de los telescopios robóticos de la red GLOBAL MASTER de la Universidad Estatal de Moscú (MSU). Estos transitorios, que se han detectado relacionados con fenómenos cósmicos como estallidos de rayos gamma (GRBs), estallidos huérfanos de GRBs, precursores de supernovas, y ocasionalmente alertas de ondas gravitacionales y eventos de neutrinos de alta energía, plantean desafíos importantes debido a su naturaleza breve y a su ocurrencia impredecible en el tiempo. El núcleo de nuestra investigación se centra en la detección y caracterización de fenómenos transitorios, utilizando las capacidades únicas de los telescopios de la Red MASTER. Estos incluyen una rápida capacidad de apuntado, posibilidad de proporcionar imágenes de gran campo con polarizadores y así como un procesamiento de datos en tiempo real. Hacemos hincapié en la capacidad de esta red para capturar y estudiar estos fenómenos, contribuyendo a la comprensión de su origen y mecanismos asociados. Asímismo, discutimos en detalle la contrapartida óptica de GRB 210731A, la llamarada óptica del blázar BZQ J0526-4830, el estallido de 2022 de la nova enana AT2019axa, una nova (MASTER OT J010603.18-744715.8) en la Nube Pequeña de Magallanes (SMC), una supernova de tipo IIb (MASTER OT J091344.71762842.5 / SN2017gkk) y finalmente la fuente SWIFT J0840.7-3516.

ABSTRACT

This study presents a comprehensive analysis of early emissions of short optical transients, leveraging data from the GLOBAL MASTER MSU Network's robotic telescopes. These transients, often accompanying cosmic phenomena like gamma-ray bursts, orphan bursts, gravitational wave bursts, high-energy neutrino events, and supernova precursors, pose significant challenges due to their brief nature and unpredictable timings. The core of the research focuses on the transient phenomena's detection and characterization, utilizing the unique capabilities of the MASTER network's telescopes. These include rapid targeting, wide-field imaging in multiple polarizations, and real-time data processing. Emphasis is placed on the network's ability to capture and study these phenomena, contributing to the understanding of their origins and mechanisms. Several targets are discussed: the detected GRB 210731A optical counterpart,the BZQJ0526-4830 optical flare, the 2022 outburst of the dwarf nova AT2019axa 2022, the newly discovered Nova MASTER OT J010603.18-744715.8 in the SMC, the IIb Supernova MASTER OT J091344.71762842.5 / SN2017gkk and the SWIFT J0840.7-3516 X-ray transient

Key Words: astrophysical phenomena — telescope networks — transients GRBs, SOTs

1. INTRODUCTION

Short-term optical flashes accompany gamma-ray bursts (Akerlof et al. 1999), orphan bursts (Ho et al. 2022, Lipunov et al. 2022), gravitational-wave bursts (Abbott et al. 2017ab, Lipunov et al. 2017a), high-energy neutrino detections –blazar flare TXS 0506+056, detected by MASTER (Aartsen et al. 2014, Lipunov et al. 2020), the initial stage of supernova explosions (Matsumoto, Metzger 2022), and others. The global network of robotic telescopes MASTER of Moscow State University (Lipunov et al. 2010, 2019, 2022, Kornilov et al. 2012) regularly detects optical transients of explosive and non-explosive nature (e.g., flares on red dwarfs) during its own, inspectional, and alert surveys. The search and study of specifically short transient phenomena will help us better understand the interaction of matter and energy in the Universe, and investigate the behavior of matter in extreme physical conditions.

The complexity in studying short optical transients is related to the brevity of their availability for observation; they are recorded at unforeseen

[1]Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, E-18008, Granada, Spain.

[2]Universidad de Granada, Facultad de Ciencias Campus Fuentenueva, s/n, CP, 18071 Granada, Spain.

[3]M. V. Lomonosov Moscow State University, Leninskie Gory, GSP-1, 119991 Moscow, Russia.

[4]Unidad Asociada CSIC Departamento de Ingeniería de Sistemas y Automática, Escuela de Ingenieros Industriales, Universidad de Málaga, C. Dr. Ortiz Ramos sn, 29071 Málaga, Spain.

times and at previously unknown coordinates, therefore the physical mechanisms of the processes occurring are still not fully understood. To detect and study the optical sources of gamma-ray bursts (Figure 1), wide-field telescopes are created (historically: ROTSE, BOOTES, MASTER, TAROT). The key distinction of the robotic telescopes of the MASTER Global Network of Moscow State University lies in the distribution of identical twin telescopes around the globe, capable of quickly (30 degrees per second) aiming based on target indications, obtaining wide-field images simultaneously in two polarizing (or BVRI) filters and processing them in real-time(Figures 2 and 3). This allows for the rapid discovery (and publication) of sources and leads the research in the early optical emission of gamma-ray bursts / GRBs (Ershova et al. 2020). The BOOTES system successfully provided rapid follow-up observations for GRBs detected by BATSE on CGRO, covering 95% to 100% of GRB error boxes within 30 to 255 minutes post-detection, showcasing its efficiency in capturing transient events quickly. BOOTES-1 achieved its “first light” on 1 July 1998, marking the commencement of its operations in detecting and observing gamma-ray bursts(Castro-Tirado et al., 1999).

2. CURRENT STATUS OF RESEARCH

2.1. *Gamma-ray bursts (GRBs)*

Phenomenologically, gamma-ray bursts are classified into short and long bursts with a conventional limit on the duration of $\sim 2-4$ s. The nature of the gamma-ray spectrum is taken into account: short bursts show a tighter spectrum than long bursts. There are exceptions explained either by observational selection - short gamma-ray bursts can be mistaken for long gamma-ray bursts that are not observed completely, or the possibility of the existence of a third group of gamma-ray bursts associated with the merger of black holes and neutron stars is discussed. After 17 August 2017 (registration of gravitational waves from the merger of two neutron stars at a late stage of evolution just before the formation of a black hole as a result of the process), it can be considered proven that short bursts are the result of neutron star mergers (Blinnikov1984, Lipunov1995a, Paczynski1997). Short gamma-ray bursts can also result from the merger of pairs consisting of a neutron star and a black hole (BH+BH). Long GWs are associated with the collapse of the core of a rapidly rotating massive star (Mszros & Rees 1999, Woosley & Heger 2006, Lipunov & Gorbovskoy, 2007).

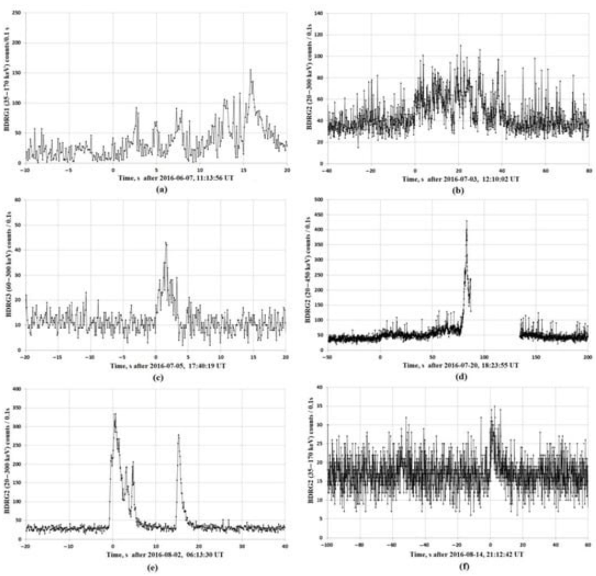

Fig. 1. Long and short (right) gamma-ray bursts registered by the Fermi-GBM detector. At the bottom are 6 bursts recorded by the Lomonosov spacecraft(Sadovnichy et al. 2021).

2.2. *Supernova explosions*

The light curve of supernovae can be traced for several months, the process of the first stage of the explosion itself takes up to 2 weeks, and supernova precursors are sometimes recorded, which can be attributed to short transient events (Tatsuya & Metzer 2022). When the core of a star runs out of nuclear fuel, it collapses into a very dense object, releasing large amounts of energy and material, leading to a supernova explosion.

2.3. *Kilonova*

Kilonova is the result of neutron star and dense star merging (Abbott et al. 2017, Lipunov et al. 2017, Figure 3a) at a late stage of evolution (Barbieri et al. 2019).In 2019, the inclusion of LIGO/VIRGO with increased sensitivity (the O3 set, which has already ended) did not lead to success in the optical localisation of grav-wave sources. Here is events at distances up to 200-300 Megaparsecs in merging neutron star binaries at a good statistical level. At 120 Megaparsecs, a Kilonova like the one detected in the galaxy NGC 4993 will have a stellar magnitude at maximum of about 20m depending on the mass shed. We are ready to inspect error-fields and detect objects on MASTER telescopes, the longitude and latitude distribution of identical MASTER telescopes with proprietary software for real-time detection of optical transients makes it possible to investigate such extreme processes in the Universe.

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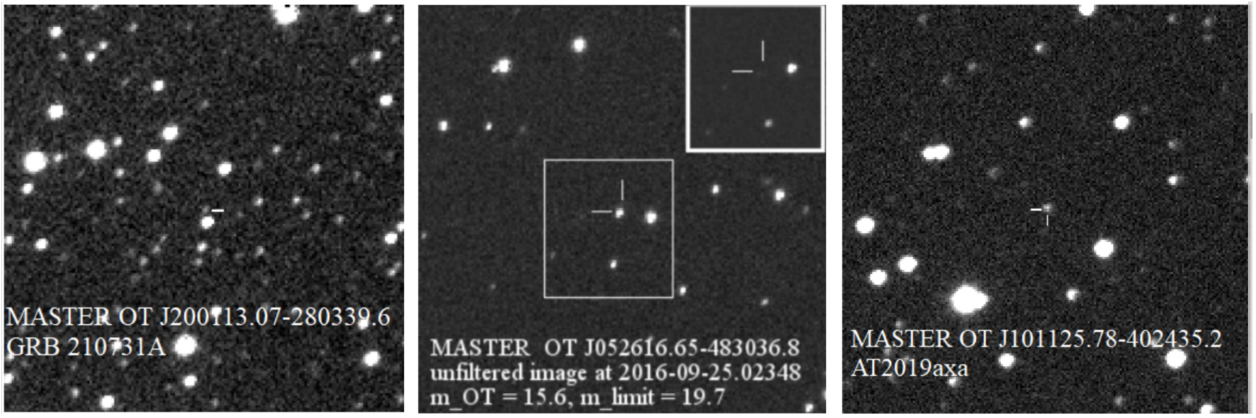

Fig. 2. On the left there is the MASTER OT J200113.07-280339.6, which is identified as the optical counterpart of GRB 210731A, as mentioned in GCN Circulars 30567, 30571, and 30578. The image in the center captures a Blazar flare (with reference image), as reported in ATel 9578. The right image shows dwarf nova (also known as AT2019axa) oturbust in 2023-04-27 00:23:12 by MASTER auto-detection system with an amplitude > 4.5. `www.wis-tns.org/object/2019axa`

3. RESEARCH METHODOLOGY

In this study, we utilized the MASTER network, a cutting-edge facility comprising robotic telescopes strategically positioned around the globe. The data collected from MASTER were subjected to rigorous analysis with the aim of advancing our understanding of the observed celestial phenomena.

3.1. *MASTER Global Robotic Net*

MASTER is very fast positioning alert, follow up and survey twin telecopes global network with own real-time auto-detection software. MASTER goal is One Sky in One Night up to 20-21m (C)(Lipunov et al. 2010). To discover optical transient there are as minimum 2 images in 2 times (there is a small shift between images to exclude any artefacts). MASTER software make initial reduction, detects all optical sources at every wide-field image (4 sq.degrees in 1 tube), compares them with catalogued ones and detected flare of known, or new outburst, or mooving object during the next exposition (30 sec). The second possibility of online auto-detection system is the difference between current and archive images and analysis of detected OT. When GCN (Barthelmy 1998) alert comeby socket, MASTER telescopes are pointing (during previous exposition is finishing) and quickly starts observation of earlier or prompt optical emission of GRB sources (Troja et al. 2017, Ershova et al. 2020, Fig. 2a with MASTER OT of GRB210731A and Fig.3a with Kilonova /short GRB 170817A optical counterpart, independently discovered by MASTER).

3.2. *Research Step*

Following telescope observations, we conduct initial screenings to identify objects for in-depth analysis, selecting appropriately sized frames for sufficient detail. These images are automatically calibrated and readied for examination. We then verify the coordinates of each object against astronomical databases and use these coordinates to extract corresponding catalog data. With Python scripts, we process this data to obtain magnitudes and errors, and subsequently plot light curves. By comparing these curves with those of known transients, we infer the nature of the observed objects.

We used the following procedure to perform the photometry. The optical transient flux is measured in a 6" aperture calibrated against several reference stars with similar colour and G values from GAIA EDR372-74. We used the following formula to estimate the errors:

$$\Delta m = \sqrt{\frac{\sum_{i=1}^{N}(m_i - m_{ij})^2}{N}},$$

where m_i is the stellar magnitude of the reference star i averaged over the observation time, m_{ij} is the stellar magnitude of the reference star i in frame j, and N is the number of reference stars.

At Figure 2 and 3 there are the examples of automatically detected optical transients: GRB optical counterpart, Blazar flare, dwarf nova outburst, SN, Nova and Kilonova outbursts.

MASTER OT J200113.07-280339.6 was found in Swift (GCN 30568) GRB 210731A error-box by MASTER-SAAO pointed 67 after trigger time (GCN 30567, started at 22:22:16UT), by MASTER-IAC (started at 2021-07-31 22:22:57UT), and by MASTER-Kislovodsk (Fig. 2a). This OT was discovered in 4 min after trigger time at 22:25:54UT

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Fig. 3. The left image features the Kilonova MASTER OT J130948.10-232253.3 is at the site of the neutron star merger GW170817 detected by the LIGO/Virgo gravitational-wave interferometers on 17 August 2017 (Abbott et al. 2017, Lipunov et al. 2017). The central image depicts a Type IIb Supernova, as detailed in the Astronomer's Telegram 10698 by Onori et al. On the right is an image of a Nova in the Small Magellanic Cloud, reported in Astronomer's Telegram 9621.

by MeerLICHT (GCN 30570) and observed also by Swift-UVOT (since 210s after trigger time), GROND 4.2h after trigger (GCN 30574), KAIT (GCN 30583), VLT (GCN 30583, z=1.2525).

MASTER OT J101125.72-402435.0 was found by MASTER auto-detection system during regular survey on 2023-04-27.02815 UT (its position coincidents with AT2019axa in TNS) with unfiltered m_{OT}=15.9. The OT is seen in 6 images during previous outburst (2018-02-14 21:48:02-23:41:31) and in 8 images in April 2023. We used reference image from 2018-02-14.98218 UT with unfiltered $m_{lim} = 20.8^m$.

MASTER OT J052616.65-483036.8, a bright blazar BZQJ0526-4830 flare, was detected on 2016-09-25.01638 UT with unfiltered $m_{OT} = 15.6^m$. Using MASTER archive reference image on 2014-12-25.95740 UT with unfiltered $m_{lim} = 20.1^m$ current flare amplitude was $> 4.5^m$.

MASTER OT J010603.18-744715.8, a Nova in SMC discovery (ATel 9621) on 2016-10-14.19341 UT with $m_{OT} = 10.9^m$ (amplitude $> 9^m$).

IIb Supernova (ATel 10698) MASTER OT J091344.71762842.5 was discovered in 3" from the center of NGC2748 galaxy by MASTER-Kislovodsk regular survey with $m_{OT} = 15.6^m$ (ATel 10667). The spectroscopic classification was made by NOT (ATel 10698), BVRI photometry made by Konkoly Observatory (ATel 10686).

4. MASTER OBSERVATIONS AND TRANSIENTS PHOTOMETRY

MASTER online reduction includes photometry, based on USNO-B1 and Gaia comparison stars, taken them a lot in 4 sq.degrees of each images (Lipunov et al. 2010, 2019, Kornilov et al. 2012).

The light curve of MASTER OT J123248.62-012924.5 (figure 4) a transient celestial phenomenon, characterized by a swift rise in magnitudedenoting a dimming of the objectbefore reaching a steady state over the course of roughly two hours. Pronounced error bars at lower brightness levels indicate a higher degree of measurement uncertainty in these observations. The pattern of the curve, marked by an abrupt decline in luminosity followed by a leveling off, is indicative of an explosive astrophysical event, potentially a supernova or nova eruption, which transitions into a phase of equilibrium after the initial outburst.

The MASTER OT J183315.33+623157.0, which corresponds to GRB 200412B, displays a characteristic dimming trend commonly seen in GRB afterglows. Over a span of approximately 8.33 hours, the brightness progressively decreases. The near-constant error bars throughout this period reflect a high level of measurement precision. Notably, when plotted on a logarithmic scale, the trend appears linear, indicative of a power-law decay. This pattern aligns well with established models of GRB afterglow behavior.

The MASTER OT J201048.64-452006.7 associated with GRB 200612A reveals a dynamic event, where the object initially brightens, then experiences a brief dimming before undergoing a rapid fade, all within a span of about 12 seconds. The consistent error bars suggest reliable measurements, though uncertainty increases as the object fades. This behav-

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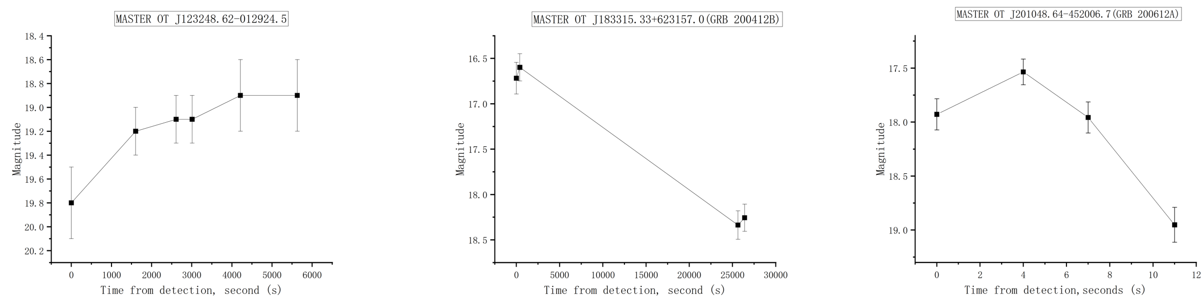

Fig. 4. Photometry of some sources discovered by MASTER.

ior is characteristic of explosive astrophysical events, such as a gamma-ray burst.

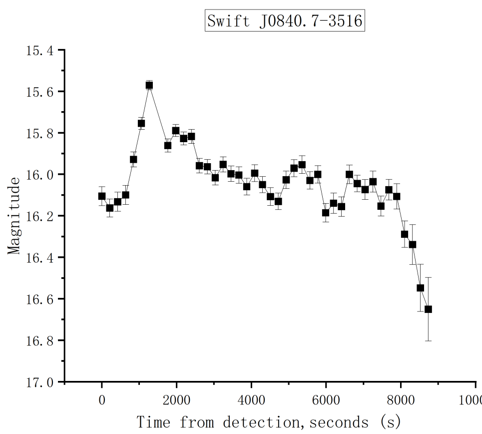

Fig. 5. Light curve of magnitude change with time for Swift J0840.7-3516

5. SWIFT J0840.7-3516

Among the sources observed by MASTER, there is a special source - Swift J0840.7-3516.An analysis of the light curve obtained with the Argentine MASTER-OAFA telescope of the MASTER Global Network shows that the brightness of the source starts to increase rapidly at $T \sim 10^3$ s, and then at $T \sim 10^4$ s it rapidly decreases to approximately the same brightness as at the beginning. During the brightness decay, an even period from $T \sim 4 \times 10^3$ s to $T \sim 7 \times 10^3$ s is maintained. The brightness remains almost constant for nine months after the decline, which also indicates a non-periodic brightness variation of this source.

The photometric profile of Swift J0840.7-3516 captures a sequence of initial brightness variations, a prolonged stable phase, and a distinct dimming towards the end, across a timespan of over two and a half hours. The error margins, relatively uniform throughout, hint at a solid measurement consistency, albeit with a slight rise in variability during transitions in luminosity. This nuanced light curve is characteristic of transient celestial events, such as eruptive stellar behavior or binary system dynamics.

This research was also conducted by a group of researchers from various institutions in Spain, Italy, and Denmark. They began by providing some reference information about ultracompact X-ray binaries (UCXBs) - a subclass of low-mass X-ray binaries (LMXBs) characterized by orbital periods shorter than 80 minutes and a donor star deficient in hydrogen, for example, a non-degenerate helium star or a white dwarf. They utilized data from several telescopes and instruments to study this object across different wavelength ranges, including X-ray, optical, and near-infrared. They also performed spectroscopic analysis to characterize the accretion disk around this compact object. One of the key findings of the study is that Swift J0840.7-3516 exhibits transitional behavior both in the X-ray and in the optical/near-infrared ranges. This is consistent with expectations that UCXBs experience thermal-viscous instabilities in their accretion disks. They suggest that this object might be a new member of the UCXB population (Coti Zelati et al. 2021).

Another group investigated the nature of the unusual X-ray transient Swift J0840.7-3516 to determine whether it is an unusual low-mass X-ray binary or a tidal disruption event(Shidatsu et al. 2021). They conducted X-ray observations of the source using various tools, including MAXI, Swift, NICER, and NuSTAR, and analyzed the X-ray data to determine the photometric and spectroscopic properties of the source during its outburst and fading phase. The team also searched for any radio emission from the source and compared it with the known correlation between radio and X-ray fluxes from low-mass X-ray binaries. Based on the analysis of these observations, they concluded that Swift J0840.7-3516 possesses unusual X-ray properties that are difficult to explain in terms of any known class of objects. They hypothesize that a plausible explanation might be an LMXB with several extreme properties or a tidal event where a star is destroyed by a supermassive black hole or an asteroid by a galactic neutron star. Their estimates suggest that the black hole's mass ranges from 10^4 to 10^5 solar masses, depending on its rotation, which aligns with their previous estimates based on the observed decay period. Following the mass estimation (van Paradijs & McClintock 1994), we conclude that this should be a binary system of low-mass stars with periods ranging from a few minutes to several hours. Compared with the distinctive features of various binary systems, for instance, we suggest that this is a binary system containing a white dwarf. However, due to limitations, we can only determine the period, but not other important properties. Observation and analysis of distant binary systems also require more specialized telescopes, such as the Gaia satellite launched by the European Space Agency (ESA) in 2013, which provides astrometric data with an accuracy of 7-20 microarcseconds for stars brighter than 15th magnitude (Kornilov et al. 2012), as well as larger precise telescopes, particularly a 10-meter optical infrared telescope for medium and high-resolution spectroscopic observations.

6. CONCLUSIONS

The MASTER telescope network excels in observing short optical transients, rapidly detecting and analyzing transient astronomical events like gamma-ray bursts (GRBs). A notable achievement is the swift detection of the Swift J0840.7-3516 source, demonstrating its quick response to space-based alerts and effective ground follow-up. This quick reaction and high sensitivity make MASTER invaluable for observing fleeting cosmic events.

Looking ahead, robotic telescopes in the MASTER network symbolize a major leap in astronomical research. These automated systems operate continuously, responding instantly to transient events without human intervention, enhancing observational efficiency and data quality. Future advancements are expected to increase sensitivity and autonomy, with artificial intelligence playing a key role in decision-making based on real-time data and research needs.

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