**An Acad Bras Cienc (2021) 93(Suppl. 1): e20200883 DOI 10.1590/0001-3765202120200883**
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

**PHYSICAL SCIENCES**

# IKI GRB-FuN: observations of GRBs with small-aperture telescopes

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**Abstract:** Gamma-ray bursts (GRBs) are the most energetic and mysterious events in the Universe, which are observed in all ranges of electromagnetic spectrum. Most valuable results about physics of GRB are obtained by optical observations. GRBs are initially detected in gamma-rays with poor localization accuracy, and an optical counterpart should be found. The faster the counterpart is found, the more it can give to physics. This first phase, as a rule, corresponds to an early afterglow. The next phases of the observations are multicolor photometry, polarimetry, spectroscopy, and few days later the search for a supernova or kilonova associated with the GRB, and finally, observations of the host galaxy. To manage the problem of fast optical observations, telescopes with a small aperture are suitable. They can have a large field of view, which is necessary to cover initial localizations of GRBs. The sensitivity of the telescope+detector may be sufficient to record statistically significant light curve with fine time resolution. We describe one of the networks of telescopes with a small aperture IKI-GRB FuN, and present the results of early optical observation of GRB sources, and discuss the design requirements of the optical observations for effective GRB research in the next decade.

**Key words:** optical observations, optical transients, gamma-ray bursts, optical afterglow, small telescopes.

## INTRODUCTION

Gamma-ray bursts (GRBs) are the most violent extragalactic explosions in the Universe, releasing $10^{48}$–$10^{54}$ ergs (if considered isotropic) in gamma rays typically within a few seconds, and up to a few hours in some instances (Greiner et al. 2015). GRBs may be divided into two classes regarding their nature: GRBs of Type I with duration less than 2 seconds, harder spectrum, and caused by merging of close binary systems with at least one neutron star; and GRBs of Type II with duration longer than 2 seconds, softer spectrum, and caused by death of very massive star during core-collapse. In the final stages of merger or collapse, a highly collimated ejecta is formed, which has a typical opening angle of a few degrees (Racusin et al. 2009, Zhang et al. 2015). An internal dissipation process within the jet is thought to produce prompt gamma-ray emission (Rees & Meszaros 1994, Kobayashi et al. 1997, Hu et al. 2014), while a longer lived, multiwavelength afterglow is expected to be produced as the jet propagates through the circumstellar medium (of constant or a stellar-wind-like density; Mészáros & Rees 1997, Sari & Piran 1997).

In most cases, GRBs are accompanied with an X-ray afterglow and in about 40% of cases an optical afterglow is discovered[1]. The afterglow may last from several hours up to several months (e.g., GRB 030329 (Lipkin et al. 2004), GRB 130427A (Perley et al. 2014)). The light curves of the X-ray and optical afterglows allow astronomers to investigate circumburst medium, properties of the outburst and its progenitor, and determine the distance to the event measuring a distance via cosmological redshift. Nearby long GRBs exhibit in the light curve the feature of the supernova (SN) of Type Ic which confirms the core-collapse nature of these events (Hjorth & Bloom 2012). The observations of SNe allows estimating main physical properties of the progenitor and the ejection (e.g., Volnova et al. 2017). Short GRBs show the kilonova (Li & Paczyński 1998, Metzger et al. 2010, Tanvir et al. 2013) feature originating from the merging compact system of binary neutron stars (e.g., Abbott et al. 2017, Pozanenko et al. 2018, Abbott et al. 2020, Pozanenko et al. 2020). Indeed, one can extrapolate the progenitors of nearby GRBs onto larger distances and it is believed now that the initially found two phenomenological classes are physically confirmed. Both kilonovae and supernovae allows astronomers to investigate the processes of nucleosynthesis and building matter in the Universe.

Space observatories like *Swift*, *Fermi*, *INTEGRAL* and some others discover GRBs approximately 1-2 times a week and transmit coordinates of the new events to the ground-based observatories via The Gamma-ray Coordinates Network[2] within a few minutes. If the X-ray or optical counterpart is discovered by the orbital observatories, the localization is about several arcseconds, and the target may be observed by ground-based telescopes. Discovery of only a gamma-counterpart enlarge the localization area to several arcminutes or even several square degrees, so observations with wide-field small aperture telescopes is necessary for the search of the optical counterpart. Small instruments have an advantage in the reaction time and may catch the optical component in only a few minutes after the beginning of the burst, during the gamma-ray prompt phase (e.g., (Elliott et al. 2014)). Figure 1 shows statistics of the GRBs and their afterglows detections since the first afterglow discovered in 1997 for GRB 970228 (Costa et al. 1997). The boost in detection after 2005 is connected to the launch of the Neil Gehrels' *Swift* space observatory.

Constructing a detailed optical light curve of the GRB is crucial for modeling its energetics, physical properties, studying the environment and progenitors of the events. The first seconds of the GRB are the most valuable, because they hide answers to the enigma of GRB central engine, but they are the most difficult to catch. There are only a few cases known, when optical prompt emission was observed. Quick discovery of the optical counterpart (a few minutes after the burst trigger) and rapid and continuous optical follow-up is required. In the challenge of the prompt emission catching a reaction speed of an instrument is crucial, and this is where small-aperture automated telescopes come on the scene. They gain an advantage because of their fast reaction time and large field of view, which allow covering the whole localization area of the gamma-ray source in one or several mosaic frames. Since at the early phase the optical component may be bright enough to be observed even with 20-cm aperture instruments (the average optical afterglow after 2-10 minutes from the burst trigger has brightness of $\sim 15^m$

[1] E.g., see J. Greiner's web-page http://www.mpe.mpg.de/~jcg/grbgen.html
[2] GCN Circulars; https://gcn.gsfc.nasa.gov/gcn3_archive.html

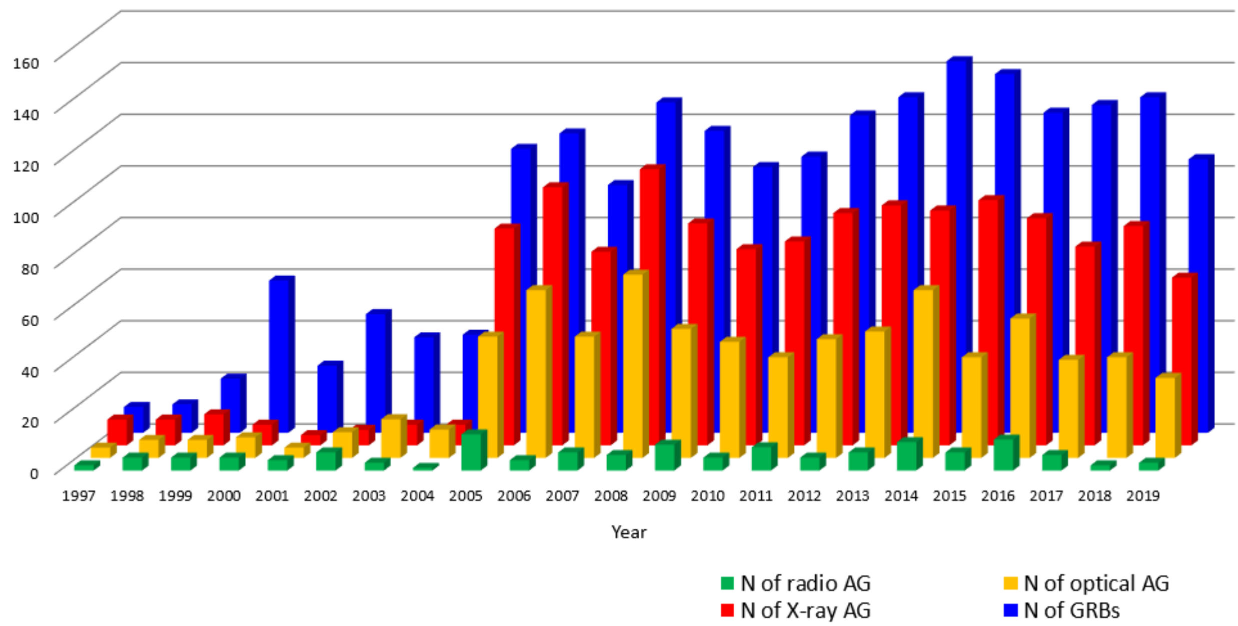


**Figure 1. Statistics of GRB detections with localization in general of better than 3 arcminutes (radius). The bars indicate (from background to foreground) number of total GRBs discovered, number of X-ray, optical, and radio afterglows discovered per year. (The statistics based on J. Grainer webpage https://www.mpe.mpg.de/j̃cg/grbgen.html.)**

(Kann et al. 2010), and the brightest optical afterglow discovered was $\sim 6^m$ (Bloom et al. 2009)). We may list among others: the 0.6-m fully robotic system Super-LOTIS (Livermore Optical Transient Imaging System) (Pérz-Ramírez et al. 2004), and 0.76-meter automated Katzman Automatic Imaging Telescope (KAIT) (Filippenko et al. 2001). Both instruments are dedicated to quickly localize and observe optical transients like GRBs. However, the best way to find and follow-up an optical afterglow of the GRB in the early phase is to use several ground-based telescopes, distributed evenly along all longitudes and in both hemispheres. The most obvious answer for the problem is establishing a network of small automated or robotic telescopes around the globe. We may list several good examples of the networks dedicated to GRBs. Mobile Astronomical System of Telescope-Robots (MASTER) consists of several 40-cm telescopes spreading to five cites, including Russia, South Africa, Argentina and the Canary Islands (Lipunov et al. 2010). Robotic Optical Transient Search Experiment (ROTSE-III) is a multi-telescope experiment designed to observe the optical afterglow of gamma-ray bursts and other transient sources like SNe. The experiment consisted of four 0.45-m telescopes located in Australia, Namibia, Turkey, and at the McDonald Observatory near Fort Davis, Texas (Akerlof et al. 2003). The Burst Observer and Optical Transient Exploring System (BOOTES) is a network of astronomical observatories with sites in Southern Spain, New Zealand, China, and Mexico and mostly 0.6m diameter telescopes, which provide an automated real time response to the detection of GRBs (Castro-Tirado et al. 2012).

In this paper, we discuss the Space Research Institute Gamma-Ray Burst Follow-up Network (IKI GRB-FuN) established by Space Research Institute of the Russian Academy of Sciences.

We mostly concentrate on the small instruments with an aperture less than 1 meter. Almost all small instruments of the IKI GRB-FuN network are at the same time part of the International Scientific Optical Network (ISON) project devoted to space debris observations. We gather the statistics of GRB optical counterparts observation by IKI GRB-FuN small telescopes and emphasize some prominent GRBs observed by the network.

## IKI GAMMA-RAY BURST FOLLOW-UP NETWORK

The Space Research Institute Gamma-Ray Burst Follow-up Network (IKI GRB-FuN) started its operation in 2001 (Volnova et al. 2020). The main idea of the network is not in building new telescopes, but in using dedicated time on the already existed facilities, i.e. IKI GRB-FuN is an overlay network. A core of the network in Space Research Institute (IKI) is automatically sending target-of-opportunity applications to different observatories, planning regular observation of afterglow, searching for SN features in photometric light curve and in spectrum, searching and observing host galaxies. Nowadays the network consists of about 25 telescopes of diameters from 0.2 to 2.6 meters located in different observatories all over the world; the IKI GRB-FuN is also collaborating with other observatories by submitting proposals for large aperture telescopes up to 10 meters. The distribution of the observatories with the longitude allows observing the optical afterglow of the GRB almost without interruption throughout the day and building detailed light curves. All the obtained data are collected in the Space Research Institute in Moscow.

The International Scientific Optical Network (ISON) project is originally constructed to observe space debris and geostationary satellites (Molotov et al. 2008). ISON comprises several worldwide small automated telescopes with apertures less than 1 meter. ISON started optical observations of GRBs in 2010. We list the observatories of ISON network which are part of IKI GRB-FuN network in Table I. The instruments are mostly located on the Eurasian continent, spreading from the Far East of Russia till Italy, performing two instruments on other sides of the Earth: in New Mexico and in Australia. In combinations with other telescopes of the IKI GRB-FuN network, which have apertures of 1 meter and more, we add more in Asia, Europe, South Africa, Chile, and Hawaii and form an almost worldwide cover, including both north and south hemispheres and almost all longitudes.

The astroclimate of the network observatories varies from site to site, however it is possible to make some general remarks. Sites situated at Russian Far East suffer from the influence of oceanic winds and cyclones, therefore the astroclimat there is poor. ISON-Milkovo, ISON-Ussuriysk, have only 70-100 clear nights per year and very unstable atmosphere with poor seeing > $2.5–3$ arcseconds. ISON-Blagoveshensk is located in better place and has $\sim 1600$ clear night hours per year. Still these observational points are very important because of the earliest night time start, and poor seeing is not important for small aperture instruments because of the pixel scale. Middle Asia is represented by ISON-Khureltogot near Ulaanbaatar, Mongolia. This region has a maximum of clear nights and number of clear night hours in Fall and Winter seasons. The mean value of clear night hours is $1400$ hours per year (Pozanenko et al. 2013). Uzbekistan and Tajikistan regions are represented by ISON-Kitab, ISON-Gissar and ISON-Sanglokh sites, where the astroclimate is very good. The region has more than $1650$ clear night hours per year and shows

**Table I. The list of ISON observatories with telescopes with apertures less than 1 meter, which collaborate with IKI GRB-FuN network. Asterisk mark observatories which are not operational at the time. [a] – taken from Kornilov et al. (2010).**

| Site | Telescope | Aperture, m | Number of clear night hours/year | Operational period |
|---|---|---|---|---|
| (M)il'kovo | ORI-22 | 0.22(f/2.45) | n/a | 2011-2012 |
| Si(D)ingSpring | AstroPhysicsV2 | 0.4 (f/2.4) | n/a | 2015-2016 |
| (U)ssuriysk | VT-50 | 0.5(f/2.3) | 900 | 2012-2014 |
| "-" | GAS-250 | 0.25(f/2.45) | 900 | 2007-2012 |
| (B)lagoveshensk | ORI-25 | 0.25(f/2.45) | 1600 | 2012-2013 |
| K(H)ureltogot | ORI-40 | 0.4(f/2.3) | 1400 | Since 2014 |
| (K)itab | ORI-40 | 0.4(f/2.3) | 1650 | 2011-2013 |
| "-" | Astrosib RC-360 | 0.36() | 1650 | Since 2019 |
| (G)issar | AZT-8 | 0.7(f/4) | n/a | 2013-2014 |
| (S)anglokh | VT-78a | 0.19(f/1.54) | n/a | 2012-2013 |
| (A)bastumani | AS-32 | 0.7(f/3) | 1200 | Since 2013 |
| K(I)slovodsk | SANTEL-400A | 0.4(f/3) | 1343[a] | 2012-2016 |
| K(R)asnodar | Astrosib RC-508 | 0.51(f/6.3) | 1200 | 2012-2016 |
| (T)erskol | K-800 | 0.8 (f/2.9) | 1800 | 2016-2017 |
| (C)huguev | AZT-8 | 0.7(f/4) | 1000 | 2012-2015 |
| Caste(L)grande | ORI-22 | 0.22(f/2.45) | n/a | Since 2018 |
| (N)ew Mexico | SANTEL-400AN | 0.4(f/3) | 1800 | 2010-2018 |

seeing of 1.5 arcseconds and better. Caucasian region is represented by ISON-Abastumani, ISON-Kislovodsk, and ISON-Terskol. The region is not cloudy (mean value of clear night hours is $1200$ hours per year), however the atmosphere is not stable, with winds and turbulences, that affect seeing making it worse ($\sim 2.5 - 3.5$ arcseconds) (Pozanenko et al. 2017).

After 10 years of GRB follow-up one can conclude that the network of small aperture telescopes distributed worldwide is an efficient tool for GRB detection and photometry. Since 2010 till May 2020, ISON telescopes observed 158 fields of GRBs localizations, and detected 70 optical afterglows (Table II), and in several cases we succeed to build a dense light curve of early optical afterglow (see some examples in the next Section). Figure 2 gives a comparison between all GRB optical afterglows detected and those observed by ISON telescopes, with both detections and upper limits. It is clearly seen, that the contribution of the network of small-aperture telescopes in the worldwide GRB optical observations may be up to 20%.

**Table II.** **GRBs observed with small aperture telescopes of IKI GRB-FuN network. In the column (1) we report a name of GRB, in the column (2) the time delay between GRB trigger time and start of observation is presented. In the column (3) we provide brightness of the OT at the first detection (or 3$\sigma$ upper limit) with the observatory identified in parentheses (for the identifier see Table I). The last column gives a reference to a GCN circular where result was published. Most of observations are unfiltered. Brightness is estimated against USNO-B1.0 reference stars, *R* magnitude.**

| GRB | Delay | Rmag(jbs.) | GCN circ. number | GRB | Delay | Rmag(obs.) | GCN circ. number |
|---|---|---|---|---|---|---|---|
| 100728B | 16.4m | 18.36(N) | 11012,11045 | 140304A | 8.7m | 17.93(H) | 15918 |
| 101804A | 3.3d | 19.79(N) | 11129,11133 | 140306A | 8.6h | n/a(H) | n/a |
| 100901A | 8.0m | 17.82(N) | 11184,11234 | 140320B | 12.6h | 19.1(N) | 16005 |
| 100906A | 13.5m | 15.89(U) | 11395 | 140320D | 0.9d | n/a(H) | n/a |
| 110719A | 1.1h | 19.70(N) | 12177 | 140709B | 0.01d | >19.5(H) | 16571 |
| 110820A | 15.4m | >19.2(K) | 12321 | 140817A | 0.33d | >18.2(H) | 16729 |
| 111016A | 3.8h | >19.2(K) | 12486 | 141020A | 0.20d | >19.8(H) | 16947 |
| 111029A | 3.6m | >18.3(N) | 12500 | 141109A | 0.84 d | 21.70(A) | 17062 |
| 111205A | 2.9d | >19.8(N) | 12736 | 141109B | 2.4h | 20.70(U) | 17067 |
| 111228A | 0.8d | 19.27(N) | 12832 | 141121A | 0.60 d | 19.00(H) | 17113 |
| 120106A | 4.8h | >18.5(K) | 12830 | 141212A | 0.58 h | >18.5(H) | 17168 |
| 120116A | 21.3m | >19.4(K) | 12899 | 150110B | 0.75 h | >19.3(H) | 17305 |
| 120118B | 45.0m | >19.5(K) | 12900 | 150120A | 72 s | >19.0(N) | 17341 |
| 120119A | 1.3h | 18.97(N) | 12871,12881 | 150203A | 70 s | >18.0(N) | 17399 |
| 120121A | 2.8h | >19.7(N) | 12887 | 150212A | 39 m | >15.8(H) | 17459 |
| 120308A | 3.3m | 17.30(N) | 13019 | 150213B | 0.9 h | 18.98(A) | 17468,17478 |
| 120320A | 12.6m | >16.7(B) | 13198 | 150309A | 3 h | >21.2(A) | 17570 |
| 120402A | 20.9m | >19.8(K) | 13200 | 150323A | 0.85 d | >21.2(A) | 17647 |
| 120404A | 22.0m | 17.35(B) | 13235 | 150323B | 7.2 h | >21.2(H) | 17649 |
| 120802A | 12.5m | >17.5(N) | 13556,13609, | 150413A | 10 m | 14.70(H) | 17692,17695,17718 |
| | | | 13712 | 150607A | 11 h | 21.20(H) | 17915 |
| 120803A | 3.7m | >17.3(N) | 13617 | 150728A | 7.3 h | 20.60(H) | 18094,18097 |
| 120811C | 20.0m | 17.90(K) | 13693,13679 | 150817A | 0.65 d | >22.4(A) | 18160 |
| 120816A | 15.0m | >18.5(R) | n/a | 150831A | 10 m | >18.8(D) | 18211 |
| 120907A | 12.9m | 18.55(I) | 13761 | 150911A | 50 m | >20.9(H) | 18307,18308,18309 |
| 120911A | 2.5m | >18.4(N) | 13759 | 151027A | 79 s | 14.00(N) | 18480 |
| 120923A | 6.4m | >19.7(N) | 13820 | 151118A | 2 m | >18.0(N) | 18618 |
| 121001A | 7.1m | 19.0(R) | n/a | 160104A | 1.5 h | 20.45(U) | 18890 |
| 121011A | 6.2m | 16.46(U) | 13884 | 160223B | 3.6 h | 18.70(H) | 19065 |

| GRB | Delay | Rmag(jbs.) | GCN circ. number | GRB | Delay | Rmag(obs.) | GCN circ. number |
|---|---|---|---|---|---|---|---|
| 121108A | 9.0m | n/a(S) | n/a | 160227A | 6.7 m | 18.00(I) | 19101 |
| 121117A | 1.8h | >18.9(B) | 13978 | 160303A | 80 s | >21.7(N) | 19127 |
| 121123A | 5.2h | 19.01(A) | 13988,14200 | 160314A | 25 m | >20.1(U) | 19199 |
| 121128A | 0.4d | 20.24(A) | 14201 | 160525B | 7 h | >21.0(H) | 19469 |
| 121212A | 2.3m | 20.7(S) | 14071 | 160804A | 11 h | 19.90(U) | 19775 |
| 130122A | 0.5h | 18.0(I) | 14148 | 160816A | 0.8 d | 20.90(U) | 19825 |
| 130131A | 13.0h | >18.1(I) | n/a | 160824A | 40 m | 20.60(T) | 19862 |
| 130131B | 5.5h | >18.8(I) | n/a | 161007A | 1.4 h | >22.4(A) | 20019 |
| 130306A | 2.0h | >20.1(I) | n/a | 161129A | 3.8 h | 19.90(U) | 20224 |
| 130310A | 1.0d | >20.5(I) | n/a | 161214B | 0.98 d | 18.79(A) | 20279 |
| 130327A | 57.0m | >20.0(N) | 14337 | | 1.1 d | 18.76(T) | |
| 130313A | 1.2h | >19.3(B) | n/a | 161219B | 9 m | 16.68(T) | 20309 |
| 130420A | 2.5m | 16.1(N) | 14428 | 170112A | 0.6 d | 17.50(A) | 20472 |
| 130427A | 2.8m | 11.0(N) | 14450 | 170115A | 0.78 d | >22.5(A) | 20479 |
| 130505A | 12.5h | 19.4(C) | 14585 | 170121B | 2.1 d | 17.76(A) | 20516 |
| 130528A | 20.0m | >17.3(K) | 14712 | 170317A | 0.77 h | 18.95(U) | 20886 |
| 130603A | 44.0m | 18.8(A) | 14806 | 170405A | 45 m | 17.27(T) | 20992 |
| 130604A | 1.8m | >19.7(N) | 14756,14758 | 170531B | 26 m | 18.90(T) | 21189 |
| 130606A | 16.2h | 20.3(A) | 14813 | 170607A | 1.02 d | 18.50(T) | 21237 |
| 130608A | 48.0m | >18.1(I) | 14861 | 170705A | 0.71 d | 19.84(T) | 21300 |
| 130610A | 41.0m | 19.3(N) | 14860 | 170711A | 1.6 h | >19.1(T) | 21333 |
| 130612A | 34.0m | 20.7(N) | 14890 | | 1.6 h | >17.0(A) | |
| 130822A | 6.4h | >19.3(I) | 15137 | 170810A | 0.81 d | >18.2(A) | 21471 |
| 130829A | 13.2h | >20.6(A) | 15136 | 170822A | 0.58 d | >22.2(A) | 21654 |
| 130831A | 10.3m | 13.7(U) | 15185 | 170903A | 1.16 h | >20.4(U) | 21805 |
| | 0.2d | 18.3(G) | 15186 | 171102B | 1.3 h | >21.7(A) | 22039 |
| 130903A | 34.0m | 20.4(I) | 15171,15241 | 180111A | 0.32 d | 20.70(A) | 22331 |
| 130912A | 15.7h | >22.3(A) | 15239 | 180205A | 1.5 d | 20.32(A) | 22403 |
| 131002A | 58.0s | 15.2(N) | 15290 | 180224A | 3.6 h | 21.88(A) | 22448 |
| 131011A | 1.2d | 21.3(A) | 15341 | 180331B | 2.7 h | >22.3(A) | 22577 |
| 131026A | 14.5h | >22.6(A) | 15394 | 180402A | 40 s | >14.5(N) | 22617 |
| 131030A | 15.0h | 19.7(U) | n/a | 180614A | 3.0 h | >21.5(A) | 22789 |
| 131108A | 20.0h | >17.1(B) | 15485 | 180620A | 84 s | 17.10(N) | 22800 |
| 131122A | 7.0m | >20.0(K) | n/a | 180626A | 1.2 m | >17.3(N) | 22853 |

| GRB | Delay | Rmag(jbs.) | GCN circ. number | GRB | Delay | Rmag(obs.) | GCN circ. number |
|---|---|---|---|---|---|---|---|
| 131231A | 3.5h | 20.3(A) | 15711 | 180720B | 8.6 h | 17.40(L) | 23020 |
| 140102A | 2.1d | >22.5(A) | 15730 | 180904A | 1.4 h | >21.5(A) | 23206 |
| | 2.0h | n/a(R) | n/a | 181013A | 0.54 d | >21.0(A) | 23341 |
| 140103A | 0.9h | 21.1(A) | 15735 | 181103A | 0.47 d | >20.5(A) | 23410 |
| | 33.3m | >17.2(R) | 15745 | 181213A | 3.1 h | 18.75(A) | 23539 |
| 140105A | 1.5d | >18.3(H) | n/a | 190220B | 3.6 h | >19.0(K) | 23919 |
| 140114A | 0.5d | >20.6(A) | 15756 | 190219A | 6.9 h | >20.8(A) | 23920 |
| 140129A | 9.2h | >20.0(H) | 15781 | 190515A | 9.4 m | >18.6(K) | 24556 |
| 140129B | 2.6h | >18.7(A) | n/a | 190604A | 7.7 h | >18.6(K) | 24754 |
| | 0.9h | >13.0(H) | n/a | 190613A | 0.54 d | >20.6(K) | 24838 |
| 140206A | 2.1h | 17.7(U) | 15792 | | 0.74 d | >21.0(A) | |
| | 9.0h | >16.4(H) | n/a | 190613B | 0.43 d | >20.0(K) | 24841 |
| | 3.7h | >17.4(B) | n/a | 190630C | 37 m | >18.8(L) | 24947 |
| 140209A | 12.3m | >18.7(N) | 15810 | 190926A | 0.64 d | >20.8(A) | 25862 |
| 140211A | 6.5m | >17.0(H) | 15856 | 191220A | 1.2 h | >19.8(A) | 26525 |
| | 5.0h | n/a(A) | n/a | 200125A | 0.52 d | >21.0(A) | 26889 |
| 140215A | 1.5m | 13.6(N) | 15846 | 200127A | 0.7 h | >20.4(A) | 26899 |
| | 6.3h | n/a(A) | n/a | 200131A | 1.0 h | 18.35(L) | 26965 |
| 140219A | 0.8d | >19.5(B) | n/a | 200216B | 0.29 d | >21.8(A) | 27122 |
| 140304A | 8.7m | 17.93(H) | 15918 | 200421B | 0.42 d | 18.31(A) | 27566 |
| 140306A | 8.6h | n/a(H) | n/a | | 1.65 d | 20.70(A) | 27574 |
| 140320B | 12.6h | 19.1(N) | 16005 | | 4.58 d | >22.2(A) | 27604 |
| 140219A | 0.8d | >19.5(B) | n/a | 200519A | 9.4 h | >19.0(K) | n/a |
| | | | | 200524A | 0.61 d | 20.48(K) | 27820 |

## RESULTS

Here we discuss some most interesting results of the GRB optical afterglows observations held by the IKI GRB-FuN network.

**GRB 130427A.** The optical afterglow of GRB 130427A was one of the brightest (in total fluence) GRBs of the past 29 years. The *Swift*/BAT was triggered by this event on 2013 April, 27 at 07:47:57, and the optical counterpart of $\sim 11^m$ was discovered by ISON-New Mexico telescope in 2.8 minutes after the trigger (Elenin et al. 2013). IKI GRB-FuN network followed-up the event for $\sim 80$ days using 14 instruments of the net located in USA (New Mexico), Russia (Ussuriysk, Blagoveshensk, Mondy, Crimea, Caucasus), Uzbekistan (Kitab, Maidanak), Georgia (Abastumani), and India (ARIES). The multicolor light curve consists of several hundreds of original data points (Fig. 3). The detailed sampling of the light curve during the first day of the event together with observations in

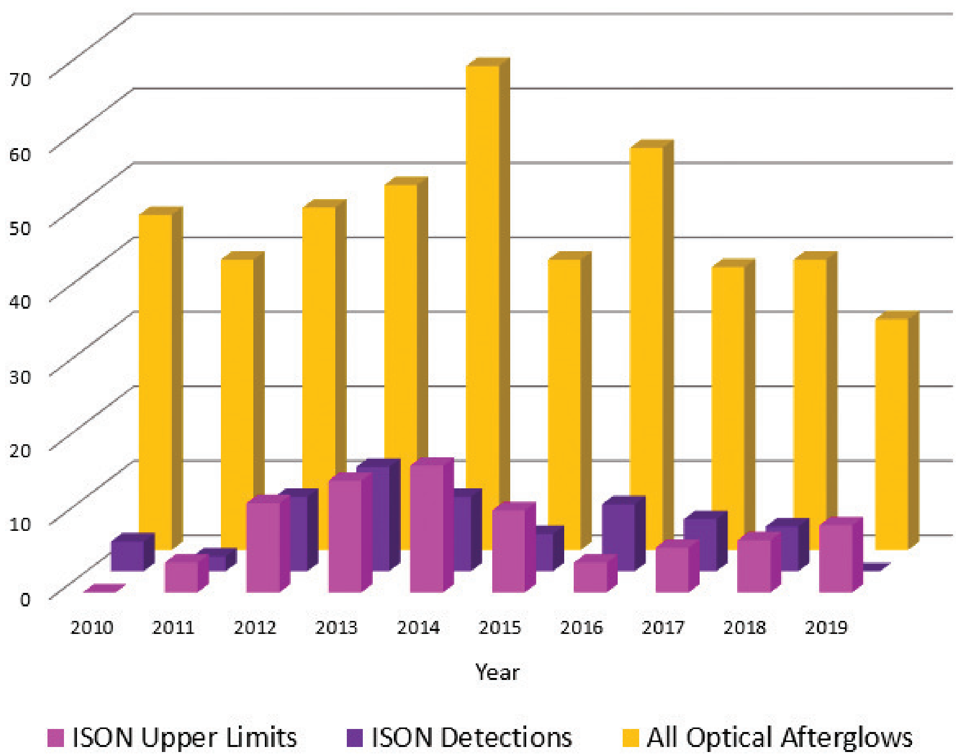


**Figure 2. Statistics of the ISON network contribution to the worldwide optical observations of GRB afterglows. The bars indicate (from background to foreground) worldwide amount of GRB optical afterglows discovered, the detections made by ISON network, and the upper limits obtained by the ISON telescopes without detecting any optical counterpart.**

other energy ranges allow modeling the physical processes of the early afterglow, the behavior of the optical light curve can be understood as a result of the gradual transition from reverse to forward shock simultaneously with the movement of the forward shock peak frequency through the optical band (Perley et al. 2014).

**GRB 130702A.** GRB 130702A at z=0.145 had a very bright associated SN, which emerged on the 4th day after the burst trigger. Instruments of our network observed the source from Maidanak Observatory, Abastumani Observatory, Crimean Astrophysical Observatory, Mondy Observatory, National Observatory of Turkey, and Observatorio del Roque de los Muchachos. A combination of original data with published data allowed building a multicolor light curve, which contain more than 280 data points in *uBgrRiz* filters until 88 day after the burst. We modeled numerically the multicolor light curves using the one-dimensional radiation hydrodynamical code STELLA, previously widely implemented for the modeling of typical non-GRB SNe. Figure 4 shows the combined multicolor light curve of the event, the physical parameters obtained and the modeling process are described in (Volnova et al. 2018, 2017).

**GRB 130831A.** The optical afterglow of GRB 130831A was discovered by *Swift*/UVOT in 191 s after the trigger and was observed till $\sim$ 100 days, including supernova phase of SN 2013fu, which emerged after 10 days. The combination of early optical and X-ray light curves shows a rare behavior, which cannot be

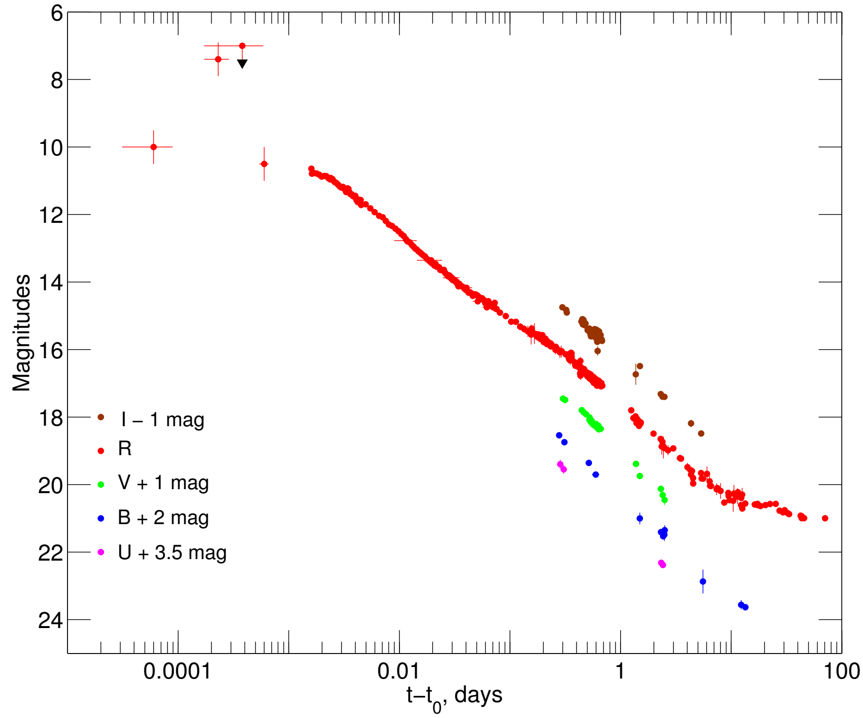


**Figure 3. The multicolor optical light curve of GRB 130427A obtained by the instruments of IKI GRB-FuN (USA – New Mexico; Russia – Ussuriysk, Blagoveshensk, Mondy, Crimea, Caucasus; Uzbekistan – Kitab, Maidanak; Georgia – Abastumani; India – ARIES) and some other observatories (SAO RAS, BOOTES-3, OSN).**

explained by the standard forward shock (FS) model and indicates that the emission must be of 'internal origin', produced by a dissipation process within an ultrarelativistic outflow. It was proposed that the source of such an outflow is a newly born magnetar or black hole (De Pasquale et al. 2016). The observations of the SN phase allowed modeling of SN physical parameters like energetics, mass of the ejecta and synthesized nickel, and estimating its photospheric velocities (Cano et al. 2014). Figure 5 shows the optical light curve of the afterglow obtained only by IKI GRB-FuN instruments.

**GRB 160625B.** GRB 160625B was extraordinarily bright and was simultaneously observed in gamma-rays and optical wavelengths. The optical counterpart was observed by instruments of IKI GRB-FuN (Abastumani, Tien-Shan, Mondy, Maidanak, Crimea) and by instruments of BOOTES network (Zhang et al. 2018). The prompt emission consists of three isolated episodes separated by long quiescent intervals. Its high brightness allows us to conduct detailed time-resolved spectral analysis in each episode, from precursor to main burst and to extended emission. The spectral properties of the first two sub-bursts are distinctly different, allowing us to observe the transition from thermal to non-thermal radiation between well-separated emission episodes within a single GRB. Such a transition is a clear indication of the change of jet composition from a fireball to a Poynting-flux-dominated jet (Zhang et al. 2018).

**Afterglow light curve inhomogeneities.** GRB 140801A was detected by GBM/*Fermi* with poor localization error-box of about 1.2 degrees

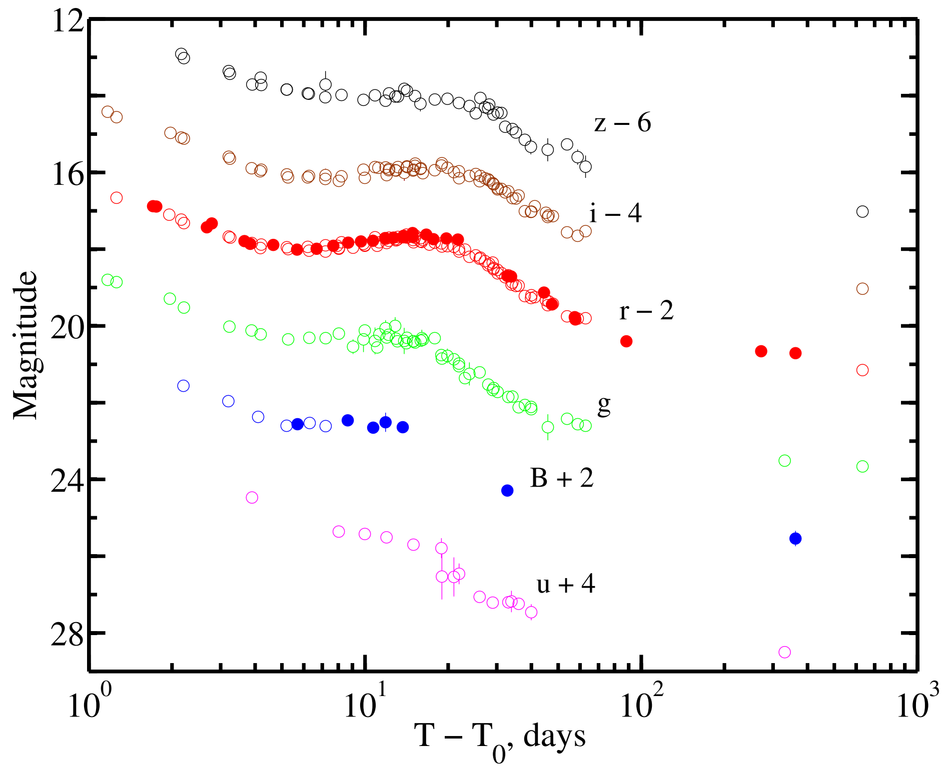


**Figure 4. Multicolor light curve of GRB 130702A and associated supernova SN 2013dx, constructed from IKI GRB-FuN data and data from the literature (adopted from (Volnova et al. 2017).) Data obtained by our network are shown with filled circles.**

(radius, statistical only) on August, 1, 2014 (UT) 18:59:53. MASTER robotic telescope in Tunka valley discovered a bright optical source 98 seconds after GBM/Fermi trigger (Lipunov et al. 2016). Our observations started on the same night at Maidanak observatory and continued up to 23rd days after GRB trigger using Abastumani, Tien Shan, and Crimean instruments. Using our data and data from the paper (Lipunov et al. 2016) we constructed the light curve. The light curve consists of afterglow phase, and a host galaxy with brightness of about $24.6^m$. It is evident that the light curve is non-monotonous, and at least three bumpy episodes are evident, on $\sim 0.1$ days, $\sim 1$ days, and $\sim 6$ days after trigger. The last bump on $\sim 6$ days cannot be a supernova feature since it is too early and too bright in comparison with known GRB supernova, especially taking into account the redshift of the GRB 140801A source of $z = 1.32$. The bumpy light curve is not a rare event in GRB afterglows, see e.g. well sampled GRB 030329, GRB 100901A, GRB 151027A, GRB 160131A, GRB 160227A. The optical data were obtained by Crimean Astrophysical Observatory (CrAO), Sayan Solar Observatory (Mondy), Tian Shan Astrophysical Observatory (TShAO), Maidanak High-Altitude Observatory, Abastumani Astrophysical Observatory (AbAO), Special Astrophysical Observatory (SAO), ISON-Kislovodsk, ISON-Khureltogoot, ISON-NM observatories. All five GRBs have well-sampled light curves, which exhibit inhomogeneities, i.e. deviations from standard power-law decay

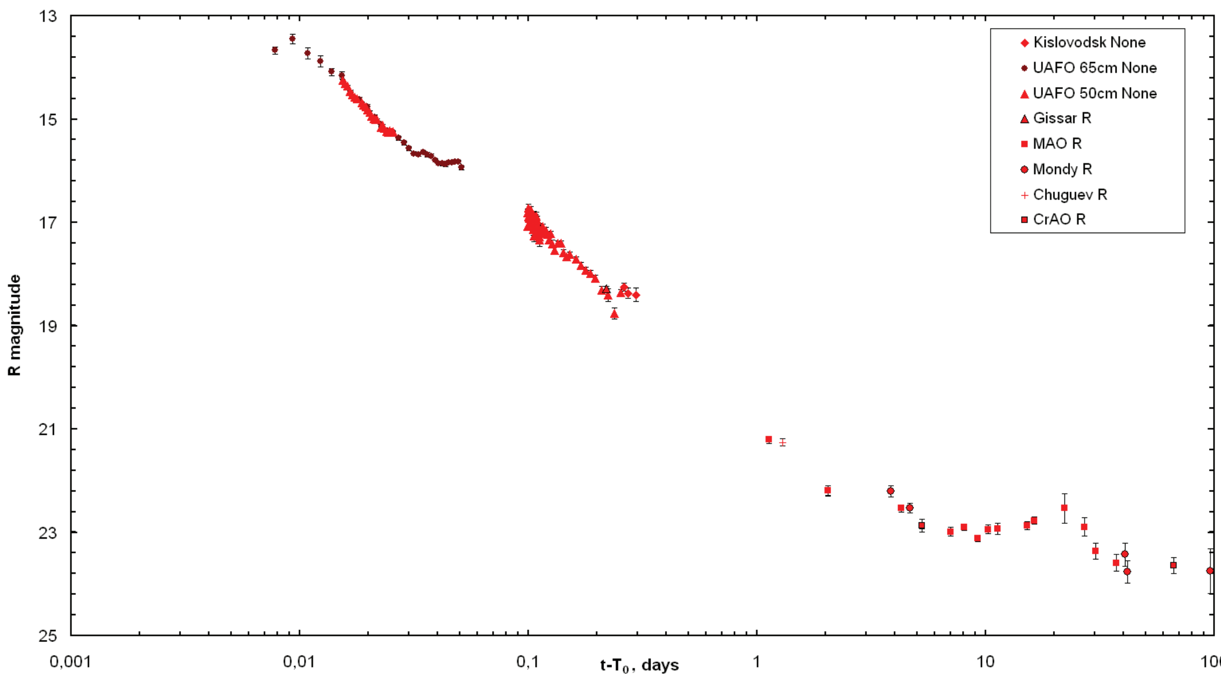


**Figure 5. Optical light curve of GRB 130831A afterglow and associated SN 2013fu, constructed using IKI GRB-FuN observations in *R*-band.**

(Mazaeva et al. 2018a, b). A nature of bumpy (non-monotonous) behavior of afterglow light curves is not yet established.

## DISCUSSION

There is no ideal telescope / network for GRB observations. The phase of prompt emission is still *terra incognita* for two reasons. Any observation by an alert takes some additive time to calculate localization coordinates of a detected object, distribute alert signal, slew telescope and take an image. It takes at least 60-80 seconds since GRB detection by any space-borne gamma-ray burst experiment. This is unavoidable time period and it cannot be eliminated or even reduced with present technologies. Hence there is no chance to observe short duration GRBs with total duration of prompt emission of about 2 sec. To avoid this problem B. Paczynski (Paczynski 2001) suggested to monitor the whole sky. In this case one can look not into prompt emission but obtain information even preceding the GRB trigger. Following that suggestion, the Pi of the Sky project was developed for simultaneous observation a large part of visible hemisphere (Burd et al. 2005). The necessary FOV of an optic telescope may be significantly reduced if we will require only synchronous observation of the FOV of gamma-ray telescope (Pozanenko et al. 2003).

Fast slewing robotic telescopes, leaded by ROTSE project and followed by a lot of analogous projects (BOOTES (Castro-Tirado et al. 2012), KAIT (Filippenko et al. 2001), MASTER (Lipunov et al. 2010), and many more) can catch up only a tail of prompt emission for some long duration GRBs.

Sensitivity, which depends on effective aperture of a telescope, is another important parameter. To be able to detect optical counterpart with a brightness of $16^m$ within two-three minutes after GRB trigger one need

0.5m - 0.7m aperture telescope. Next important parameter is a sampling time. The sampling depends on the goal of investigation, and in case of GRB typical variability scale is about 0.1 s in the phase of prompt emission and seems to be independent of time since GRB trigger at the prompt phase (Mitrofanov et al. 1998). The scale of variability increases linearly with time at the afterglow phase (e.g., (Mazaeva et al. 2018)), so typical time sampling after tens minutes could be minute and it corroborates the necessity of exposure duration of about one minute to have a sufficient sampling.

It's important to obtain spectroscopy of the optical counterpart, when the source is sufficiently bright. Spectroscopy is necessary to determine redshift by identifications of known absorption lines while optical continuum emission of a counterpart propagates through a host galaxy. However, this case can be addressed to large aperture telescopes. Most of the spectroscopic redshift till now was obtained by spectroscopy with large aperture telescopes. Last but not least are dedicated pipelines for near real-time data reduction, search and classification of candidates into counterpart.

The current optimal GRB observation scheme and initial analysis would be developing as follows. Alert system contains an array of lenses of about 0.2–0.3m effective aperture to cover substantial part of the sky. For the reference can be considered total FOV of the array of 1.5 steradian (it is approximately the FOV of *Swift*/BAT gamma-ray telescope). The time resolution of the alert system should be of about 0.1 s. This alert system provides independent real time search for fast optical transients that might be, but are not limited to GRB counterparts. The second part of the system is a robotized fast slewing telescope with aperture 0.7-1m receiving coordinates of optical transients registering by the alert system. Indeed fast slewing telescope can be activated by any external trigger such as BACODINE alerts coming from space observatories like *Swift* or from gravitational wave detectors LIGO/Virgo/KAGRA. Needless to say, such systems, consisting of two components (wide filed alert array and fast slewing telescope), must be unified and located in different parts of the world with a suitable astroclimate.

Analogous system was considered years ago (Beskin et al. 2005), but not realized till now in the full design. Some predecessors and prototypes of a wide-field of view monitoring system are RAPTOR (Vestrand et al. 2002), FAVOR (Beskin et al. 2005), MINIMEGATORTORA (Beskin et al. 2017), and GWAC array, which are equipped with lenses of 180 mm diameter and can cover simultaneously of about 5000 square degrees (Wan et al. 2016).

## CONCLUSIONS

We discussed the applicability of small aperture telescopes for GRB search and observations. Using IKI GRB-FuN network as an example, consisting of various types of telescopes, including those with a small aperture, the efficiency of using telescopes with a small aperture for the initial stage of GRB observations was shown. The results of photometric observations of GRB by the IKI GRB-FuN network from 2010 are presented. We also gave a brief history of creating robotic systems for optical transients searching and discussed the requirements for effective observations and investigations of GRBs, proposed as one subsystem of the BRICS flagship tentative project "The BRICS Intelligent Telescope and Data Network".

**Acknowledgments**

Authors are grateful to RFBR grants No 17-51-44018, 17-52-80139 for the support of the work.

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**How to cite**

VOLNOVA A, POZANENKO A, MAZAEVA E, BELKIN S, MOLOTOV I, ELENIN L, TUNGALAG N & BUCKLEY D. 2021. IKI GRB-FuN: observations of GRBs with small-aperture telescopes. An Acad Bras Cienc 93: e20200883. DOI 10.1590/0001-3765202120200883.

*Manuscript received on June 7, 2020; accepted for publication on August 30, 2020*

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All of the co-authors were participated in observations and data analysis presented in the paper, and assisted the lead authors (AV and AP) with elaborating some elements of conception for future development of transient objects observations.