Multi-frequency Observations and Discovery of a Supernova Associated with the GRB 181201A

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Abstract. Despite the explosive growth in the amount of data in astronomy, one of the main cases is the search for new objects (and identification of its parameters) with a limited number of observations. We discuss the possibilities of making a decision in the conditions of a limited amount of information (data set) obtained as a result of a large number of observations and identifying the optimal number of independent parameters that allow exploring and describing the phenomenon. These cases are well known in astrophysics, e.g. when searching for electromagnetic counterparts of gravitational-wave events detected by LIGO/Virgo detectors and searching and classifying supernova associated with Gamma-Ray Bursts (GRB). We describe observations and discovery of the supernova (SN) associated with gamma-ray burst GRB 181201A and present preliminary parameters of the SN. The positive decision about SN was generated based only on five high-precision observations. This is one more discovery of SN among only about thirty cases of photometric confirmation of the SN associated with GRBs. The discovery is made possible due to networked telescopes in both Southern and Northern hemisphere.

Keywords: Gamma-ray burst, Afterglow, Supernova, Photometry, Multi-frequency observations

1 Introduction

Nowadays, the problem of recovering the parameters of a phenomenon on a limited amount of data is important in cases, when we cannot obtain more input data for any reasons. Nevertheless, this problem is also a crucial point in a situation of determining the optimal amount of experimental data necessary to describe the phenomenon. Both of these items could be solved when we have a prior information about a number of independent parameters of the phenomenon under study. Such a need arises, for example, in cases of a transient phenomenon, when we cannot repeat the observation. It is obvious that the solution of the problem of optimizing the number of observations is necessary and in demand when planning the search for transient sources in future projects ground-based optical telescope LSST [1] and space-born X-ray observatory SRG [2].

Two last decades of observations and investigations of gamma-ray bursts (GRBs) and their optical counterparts led to the unambiguous association between at least some long GRBs and the death of massive stars. The observational connection of long GRBs with type Ic supernovae (SNe) supports this evidence. The first reliable association between GRB 980425 and type Ic SN 1998bw with broad spectral lines was both positional and temporal, and spectral data of the two events showed the same redshift of 0.0085 ($\sim$ 40 Mpc) [3–5]. The next confirmation of GRB-SNe associations occurred in 2003, with the discovery of very bright GRB 030329 associated with type Ic SN 2003dh [6–8]. The kinetic energy of both these SNe exceeded 10^{52} erg, so they were hypernova (the name of unusual SN suggested by B. Paczynski [9]). The launch of the Swift space observatory [10] changed the way of GRBs investigation dramatically. An early discovery of GRBs optical counterparts and their fast follow-up with ground-based telescopes allowed to build detailed multicolor light curves and to obtain valuable spectroscopic data.

Generally, the optical light curve (LC) of a long GRB may be described by four prominent phases. The first phase is related to the prompt phase when the central engine is still producing energy. This phase is very hard to observe because of the relatively slow reaction of optical instruments: usually, when optical telescopes begin to observe the localization region of the burst, the prompt phase is already finished, that's why there are rather few cases of the prompt phase observations in the optical domain. The second phase is usually the longest and is related to the afterglow. A simple power law or a broken power law with two different decay indices can describe it as a good model, and a break is a geometric effect related to the collimation of the GRB jet. This phase may also demonstrate some flares or wiggles [11]. On the 7–20th day the SN feature may appear. It may look like a bump or a slight re-brightening on the light curve, which deviates significantly from the afterglow power law. Spectra obtained during this phase usually show broad lines common for Ic type SNe. After the end of all activities, the source fades away, and the host galaxy may be observed at its location.

Today there are only a few dozens of GRB-SNe discovered, and 23 of them are confirmed with spectroscopic observations and 28 are detected only by photometric evidence. The observed flux from the GRB-SN is composed of the afterglow flux, the SN itself and the constant flux of the host galaxy. A careful decomposition of the three components is necessary to obtain the LC of the SN for further determination of its bolometric properties. The decomposition should also take into account the line-of-sight extinction in the Milky Way (e.g., by using the extinction maps by Schlafly and Finkbeiner [12]) and in the host galaxy (e.g., by modeling its spectral energy distribution and comparing it with models of well-studied galaxies). Every listed component may be included in the fitting procedure as an additional parameter or a set of parameters [13–15]. This phenomenological approach is based on the standard GRB theory, which states that the light powering the AG is synchrotron in origin, and therefore follows a power-law behavior in both time and frequency [16].

2 Observations

Optical observations of the source

After registration of GRB181201A with INTEGRAL [17], LAT/Fermi [18], Konus-WIND [19], XRT/Swift [20], Insight–HXMT [21], AstroSAT CZTI [22], we observed this source over the next month. Optical data were made by observatories located in Chile, South Africa, Crimea and Tien Shan, which are part of our IKI GRB Follow-up Network.

The astronomical observatory Gemini [23], which is not a part of our network and located in Hawaii, also made a significant contribution to the construction of the light curve. Because the observations on Gemini were made on the Gemini-North telescope, which is 8.1 meters in aperture. That is much bigger than telescopes in other observatories (D=0.7–2.6m). This fact made observations possible even when the culmination of the object was almost gone for the daytime.

XRT observations of the source

When gamma-ray burst triggers our space vehicles, we must make as many observations in different ranges of energy as possible. In a prevailing number of cases, the space X-ray telescope discovers the x-ray afterglow and provides an accurate localization of the source within an error circle about several arcseconds. This allows optical telescopes to be more productive in optical component searches.

The same thing happened in the case of GRB181201A, whose position was observed by Swift/XRT 4 hours after INTEGRAL trigger time [20]. The results of observations of that source are shown in Fig. 3.

Optical observation of the host galaxy

The observation of the source's host galaxy, which was made six months after the GRB happened on ZTSh telescope in Crimea. This observation was carried out in order to further taking into account the contribution of the host galaxy to the flux from our source. This is necessary for accurate parameter evaluation of the studied phenomenon. Comparison of the host photometry and latest photometry of the afterglow we found that the host influence of the light curve is no more than 15% of any part of the light curve in r'- filter. This small influence alone cannot explain the flattening of the light curve proposed by Laskar et al. [24] instead of the discovered supernova in our study.

3 Data Processing

Before we began to analyze the observations, which had been obtained, we had made a preliminary reduction (dark subtraction and flat-field correction) of all the images from all observatories we collaborated with. This had been made by using the task "ccdproc" of NOAO' IRAF software package which is stands for Image Reduction and Analysis Facility. This is a general-purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation [25]. Images from each epoch of observations in corresponding filters had been combined by "imcombine" task with the purpose of providing a better signal-to-noise ratio. All magnitudes had been obtained using aperture photometry by APPHOT package within IRAF.

All our instrumental magnitudes had been calibrated according to the SDSS-DR12 photometric catalog. The reference start was chosen so that between observations in two epochs there was no significant change in the magnitude of the filter we need. If this condition is met, then we can say that this star is not a variable and can be used as a reference. The second criterion for choosing a reference star is that it should not be overexposed on our images. It provides us an accurate determination of the magnitude of our reference star.

The reference star we had used has coordinates 319.29508 and -12.618443, which stands for RA(J2000) and DEC(J2000) respectively.

4 Observation Results

As a result of three weeks of observations [26] and data processing, we discovered the supernova [27] and constructed a multicolor light curve, which is shown in Fig. 1.

We know the redshift of this source and it is z=0.45 [33]. We also know that most of the gamma-ray bursts with red-shift less than 0.4 are characterized by the presence of a supernovae feature. Considering these facts, we want to check if there is a signature of supernovae in the case of GRB181201A.

To do this, we build the light curve in fluxes and fit it with a power function with a slope of –1.2, which well describes the afterglow stage in all filters (see Fig. 2).

Assuming that the optical afterglow evolves achromatically and using the information about the slope of the afterglow stage in r'-filter, we can also describe this stage in z' filter where we have only one point on a period of afterglow stage.

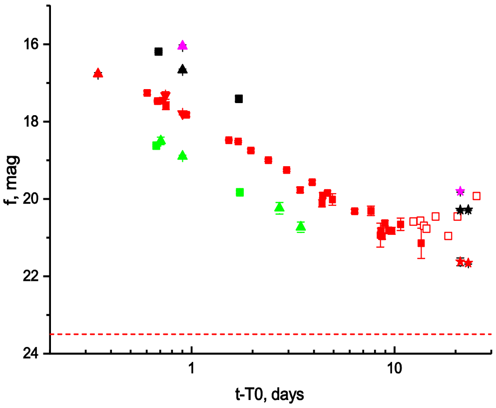

Fig. 2. Multicolor light curve in magnitude units obtained by different scopes. Where pink, black, red and green colors indicate observations on z’, i’, r’ and g’ filters respectively. Punctured points stand for the upper limits of observations made in the r’ filter. The dotted line shows us the magnitude of the host galaxy in R filter. The points in filters i’ and z’ were raised up and in filter g’ lowered by 1 magnitude for ease of viewing the graph. Here, squares represent the data obtained from the observatories of our network, empty squares stand for upper limits in r’-filter, triangles show values taken from circulars and stars show values from the Gemini Observatory. We also used data on this source, obtained at other observatories by other groups and published on GCN circulars [28–32]

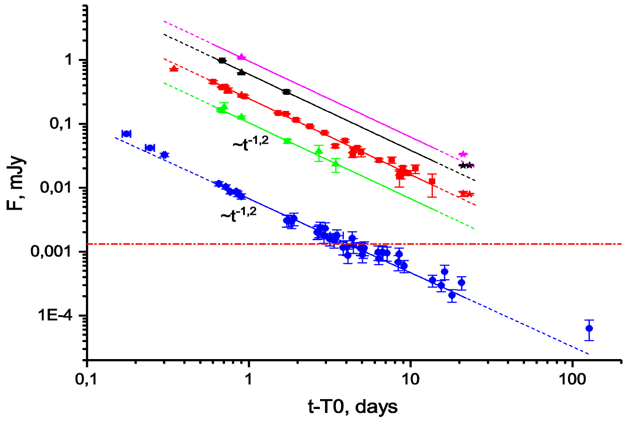

Fig. 3. Multicolor light curve in mJy fitted by a power law. Here, squares represent data obtained from observatories of our network, triangles denote data taken from circulars, stars show data taken from Gemini Observatory and circles denote XRT observations. Dashed red line shows the level of the flux from the host galaxy in filter r’. The power law index of both optical afterglow and XRT afterglow fitted in the same time interval (0.7–15 days) is equal to –1.2

Fig. 2 gives us the values of the fluxes in different filters only from our source, because after the source had faded we observed and calculated the magnitude and flux of the host galaxy, which is equal to 23.55 in magnitudes in filter R (equivalent of 0.001131 mJy), which was subtracted from data in the corresponding filter.

Further, to determine if there are any deviations of our dots from the afterglow, we will construct the graph of residuals. It means that we need to subtract from our light curve the model curve of the afterglow stage described by a power law. Before that, contribution to the flux from the host galaxy must be subtracted. It is shown in Fig. 3.

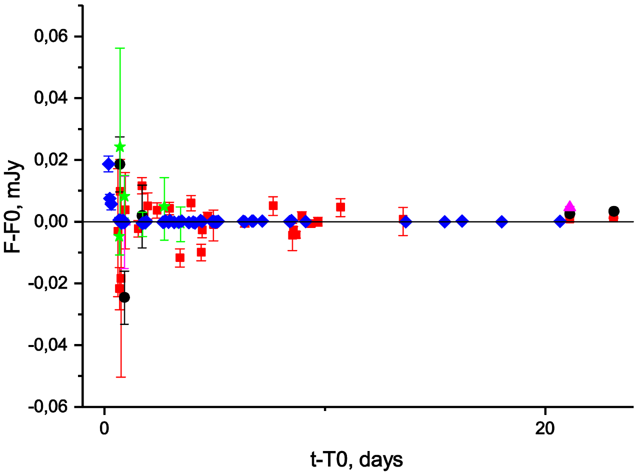

Fig. 4. Residuals of the multicolor light curve. Squares mean deviations our observations from the power law, which describe afterglow stage on the whole range of time since triggerring in r' filter, circles in the i' filter, triangles in the z' filter, stars in the g' filter and rhombus in the x-ray range of wavelength

It is noticeable that there is a deviation of our points from the power law extrapolation on 22–24th days which can be better seen if we enlarge this part of a graph (see Fig. 4).

Fig. 4 shows that there is a deviation of our observations from the extrapolation of the afterglow stage and what is more important is that deviation is manifested not only in one point but in several, in both epochs and even in three filters. This fact gives us a hint that there is some phenomenon other than just only power decay after the gamma-ray burst happened. However, before we talk about the presence of physics in this phenomenon, we must make sure that it is not associated with any kind of error. To do this we construct a graph of the deviation of our observations from the power law, expressed in units of standard deviation, from the time since the trigger of the gamma-ray burst.

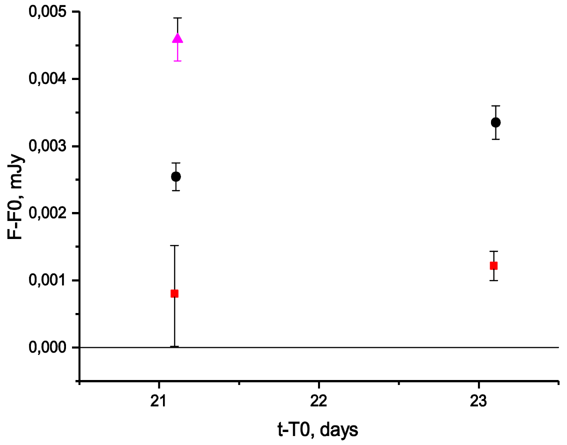

Fig. 5. Residuals of the multicolor light curve (enlarged)

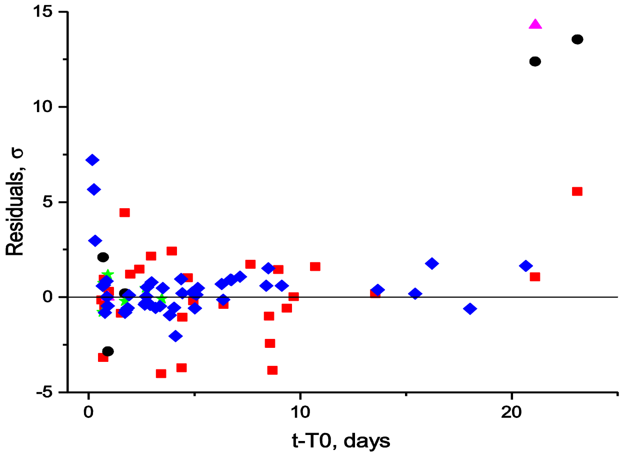

Fig. 6. Significance of deviation of our data from the light curve described by the power law, expressed in standard deviation. Here squares denote observations in r’ filter, circles in i’ filter, triangles in z’ filter, stars in g’ filter and rhombus in x-ray range of wavelength

Fig. 5 makes us understand that our data after the 21st day after the gamma-ray burst happened deviates from the light curve described by power law and its deviations are significant. That, in turn, allows us to explore that phenomenon further, rather than link it with the preset error and put it on the back burner.

Now we can go back to Fig. 4 and try to fit any curve to estimate the parameters of the proposed supernova. One of the variants of the fitting curve is lognormal distribution, which with such small input data (just 2 points in the filter i' and r') allows us not precisely calculate, but only estimate some of the parameters of that phenomenon. The result of fitting lognormal distribution in our data is in the Fig. 6.

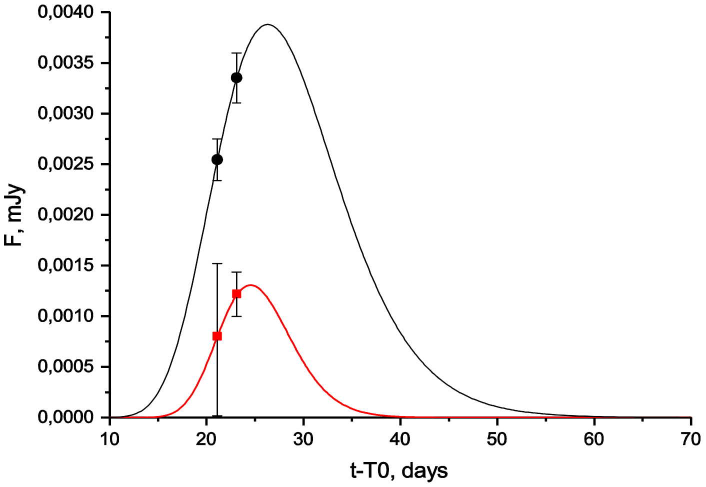

Fig. 7. Supernova light curve in i' (circles) and r' (squares) filters

It is known that there are 4 parameters in lognormal distribution and it is impossible to fit this function in only two dots without any operations with free parameters of the function like fixing one of the parameters or limiting in some range of values. All these manipulations led us to the evaluation of such parameters of that phenomenon like:

- Absolute magnitude in filter V: M_V=–19.6;
- Time from the beginning of the burst to the maximum of the supernova on observer's reference frame: t–T0=26.3 days;
- Time from the beginning of the burst to the maximum of the supernova on the rest frame: t–T0=18.138 days.

Now we are able to compare our estimation of parameters of the supernova with those mentioned in Cano's paper [34] on supernova associated with gamma-ray bursts. Based on this work of Cano, it is possible to plot the dependence of the absolute magnitude in the filter V on the time from the beginning of the gamma-ray burst to the maximum of the supernova in the rest frame (see Fig. 7).

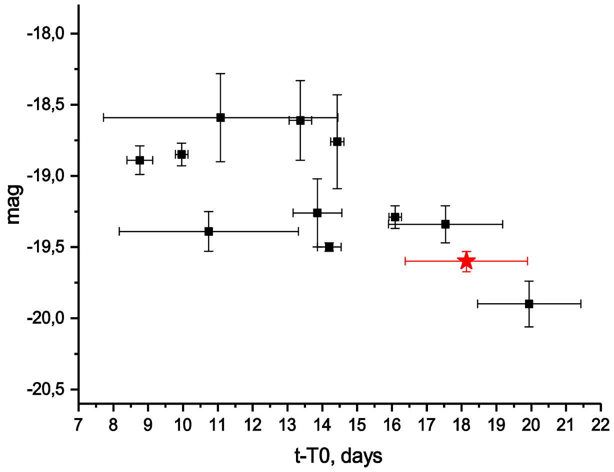

Fig. 8. Comparison of the absolute magnitude in filter V and time of maximum brightness of the SN associated with GRB181201A with the same parameters of previously studied corresponding SNs. Here squares represent SNs' parameters from paper [34] and star shows where among the parameters of other supernova are the parameters of our

It is noticeable from Fig. 8 that the parameters of supernova, which were discovered by our group, are well placed in a row for already known supernova associated with gamma-ray bursts. This is another additional, among 27, photometric confirmation of the presence of supernova in gamma-ray bursts.

5 Discussion

We reported a preliminary analysis of an observational campaign of the GRB 181201A. Multicolor afterglow observations and a targeted search for a Supernova for this gamma-ray burst were conducted. For these observations, we used IKI GRB Follow-up Network and observations were completed with 7 observatories from all hemispheres, i.e. North, South, East, and West one. Using non-homogeneous data obtained by different observatories we build uniform multicolor light curves in g', r', i' and z' Sloan photometric filters. We also used long-term XRT/Swift X-ray observations.

Based on a few (5) high-precision optical observations on the Gemini-North telescope, a systematic significant excess above the afterglow light curve model was found. We suggest that these excesses are due to emerging supernova. Found properties, namely the absolute magnitude and the time of the supernovae maximum in the rest frame, are within the known values [34], which also confirm the discovery of the SN.

Because of that, we are able to summarize that with the mentioned earlier amount of observable data we can make a qualitative conclusion about the presence of a photometric signature of a supernova. Moreover, by observing the afterglow and at least two photometric points, one can determine the position of the maximum and the amplitude of the supernova. Minimal necessary conditions for all of this are the availability of at least two observations in each photometric filters at the assumed supernova appearance time interval, as well as a reasonably large number of observations at the afterglow stage and host galaxy observations. Provided these conditions are fulfilled one can not only qualitatively identify the supernova, but also find bolometric luminosity and time of maximum which is necessary for minimal quantitative description of the supernova. Of course for identification of the type SN, modeling of physical parameters of SN (mass of progenitor and remnant, abundances of Ni and other chemical elements; see e.g. [35]) one need much more photometric observation for detailed light curve building and spectroscopic observation for measurement of photosphere velocity. Despite the long history of GRB observations since the first SN/GRB discovery in 1998, this is one more supernova associated with GRB among only a few dozen (28+23) previously known cases. Moreover, the Supernova is one of the most distant Supernovae (z=0.45) associated with GRB 181201A.

Most photometric discoveries and confirmations of the SNs are based on a limited data set. This dictates the need to develop robust decision criteria for photometric SN confirmation using a small amount of useful data based on existing data. More data cannot be obtained for various reasons: faint source, low flux of the SN over bright afterglow, inability to conduct long-term observations due to transition of the culmination of the source in the daytime and weather conditions.

In our case of supernova search, there are such criteria as simultaneous excess of the flux over the model in different photometric filters, chromatic behavior of the light curves, i.e. color change at the time of SN rise, approximate coincidence of the time of our supernovae's maximum with the same time of known supernovae associated with GRBs. Of course, the quality and significance of the parameters of the SN obtained will be dependent on the density of the light curve and precision of photometry. The discovery of the SN and obtaining a dense light curve can be provided only by networked telescopes to ensure a long-term observation of the source.

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