How to Extract Information from What We Cannot Observe?

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Abstract. Methods of complex investigations of optically dark gamma-ray bursts are discussed. These astronomical objects are remarkable due to their non-detections or lack of detection in optical domain. We describe the process of comprehensive study of these objects and give some ideas why the information obtained may be valuable for future science.

Keywords: gamma-ray bursts; optical observations; host galaxies; dark gamma-ray bursts.

1 Introduction

The main basis of modern observational science is data. Appropriate data reduction and analysis allow to extract different information about the nature of observed process and to determine the properties of its source. In astronomy, the only observable magnitudes are flux in different energy ranges, time and positional coordinates in the sky of the object of interest. In many cases, the object may be transient, i.e., it is not stationary in space and/or in time and will disappear in a while. The examples from the nearest space are asteroids and comets, cataclysmic variables in the Galaxy, and distant objects are gamma-ray bursts, supernovae, kilonovae.

The amount and variety of the data we can obtain depends on the observational instruments, which are designed and constructed according to previously adopted theories. Thus, if something theoretically observable is not really observed in practice, this fact should also be analyzed and interpreted.

In this paper, we consider dark gamma-ray bursts (GRBs) as an example of objects, for which the information usually is extracted based on their non-detection or lack of detection. Note, that here we only describe the methods used for optical studies of transient objects with the lack of optical detection. These methods strongly need to be automated.

2 Dark GRBs: bursts without optical counterpart

2.1 The problem overview

Cosmic gamma-ray bursts (GRBs) are extremely powerful explosions in distant galaxies related to deaths of massive stars (long GRBs [19]) or to binary neutron stars mergers (short GRBs [9]). They last for periods from few milliseconds to hundreds of seconds, and the principle amount of energy ($\sim 10^{51}$ erg) releases in gamma-ray domain, but in many cases an afterglow in other energy bands (X-rays, ultraviolet, optics, infrared, millimeters, radio [8]) may be observed up to several months (e.g., GRB030329 [21]). In many cases, the underlying host galaxy may be discovered and investigated. The search and study of GRBs optical counterparts give information about the nature of its progenitor, physical properties of the burst processes and surrounding medium, and emphasis the galaxies, which produce GRBs.

The optical counterpart of a GRB (short or long) consists of four main phases.

(I) The prompt emission – an optical emission radiated simultaneously with gamma-rays and related to the central engine activity [e.g. 24].

(II) The afterglow phase – an echo of the GRB jet interacting with the circumburst medium, which flux decreases with time. The optical afterglow may last for several months. There may be an achromatic break during this phase, which depends on a jet-opening angle (a jet-break [e.g. 17,29]).

(III) The late phase may include supernova (for long GRBs [e.g. 7]) or kilonova (for short ones [e.g. 35,36]) feature. It demonstrates itself as a broad late chromatic bump with a very specific spectrum.

(IV) When all activities and afterglows of the explosion finish, the constant flux of the underlying host galaxy may be observed [e.g. 12].

The first optical counterpart of a GRB was discovered in 1997 (GRB 970228 [3]). Currently accepted fireball model [30] establishes connections between the behaviors of afterglows in different energy bands and predicts the presence of an optical afterglow in the case of the presence of an X-ray one. However, more than a decade of operation of the *Swift* space observatory [13] shows, that the optical afterglow is observed only in 60%

Proceedings of the XX International Conference "Data Analytics and Management in Data Intensive Domains" (DAMDID/RCDL'2018), Moscow, Russia, October 9-12, 2018

of GRBs with X-ray afterglow discovered [11].

The GRBs with the lack of an optical afterglow are called dark bursts. The main criterion of differentiation between optically dark and bright bursts is based on a relation between X-ray and optical afterglows, and its numerical equivalent is an X-ray-to-optics spectral index β_{OX}. The fireball model sets limits for the value β_{OX} from 0.5 to 1.25. Jakobsson et al. [15] proposed to define as dark all GRBs with $\beta_{\mathrm{OX}} < 0.5$.

A possible factor for a GRB to be dark is the immediate neighborhood of its source. The "extinction scenario" [31] assumes that the emission of the OA is strongly absorbed in the host galaxy. The absorbing medium may lie either around the burst progenitor (gas-and-dust cocoon, wind-like medium produced by a Wolf-Rayet progenitor star) or may be found somewhere on the line of sight inside the galaxy.

Another potential origin of dark bursts is a high redshift. The emission with wavelengths shorter than $912(1 + z)$ Å in the observer frame is efficiently absorbed due to the Lyman-cutoff when it passes through the intergalactic medium [18]. For $z \geq 4$, this Lyman drop-out falls into the *R* band in the optics in which most rapid searches for GRB afterglows are carried out. Such GRBs can only be localized through rapid, deep near infrared (NIR) follow-up, e.g., as in the case of GRB 080913 [14, 25].

2.2 Methods overview

Despite the lack or total absence of the optical counterpart, the observations of dark GRBs in this domain may also give useful information about the nature of these events, which can effectively support current physical models of many different astronomical objects, including star formation, stellar and galactic evolution, supernovae, kilonovae and their progenitors, interstellar and intergalactic absorption, etc. The key point is to connect properly optical non-detections with detections in other energy ranges on different time-scales. This involves multi-frequency observations and complex approach to the methodology of the investigations.

GRBs are transient objects with unpredictable coordinates observed in alert mode. When a dedicated gamma-ray space experiment triggers the burst, the best strategy is to produce the fastest possible observations in different energy ranges and modes. In about 70% of cases [11] the space X-ray telescope (XRT [5]) discovers the X-ray afterglow and provides localization of the source with the error of several arcseconds. This allows optical instruments to search effectively for the possible optical counterpart. Usually the burst may be categorized as dark during the first several hours after its trigger. By this time the dark GRB optical afterglow brightness may by fainter than 23 magnitude in *R*-band, or the afterglow may be undetectable due to its faintness.

The next step is the search of the host galaxy. This involves large and medium ground-based telescopes with apertures larger than 1.5 meters. Archival deep surveys like SDSS may be useful in this search too, since SDSS is complete down to $r = 22.2^{\mathrm{m}}$ and contains more than 200 million of galaxies [32].

One of the most important characteristics of GRBs is the distance to their sources, so the estimates of the redshift *z* are significant. In the case of ordinary GRB, *z* may be measured directly with spectral observations of the optical afterglow. When the afterglow is faint or even absent, the only way to determine the redshift is the host galaxy investigation.

Recent research on large populations of dark GRB host galaxies has shown that generally, they do not differ from the host galaxies of GRBs that suffer from little dust extinction [26], with the darkness being mostly due to local extinction around the progenitor in galaxies of low to medium redshift. However, very dusty hosts are not excluded [27]. Redshift of detected host galaxies vary in a wide range from $z = 0.0085$ (GRB 980425 [33]) to $z = 6.327$ (GRB 140515A [23]) with a median value of z_{host} about 1.4. About 20% of discovered GRB host galaxies lie at redshift more than 2.5. The search for and spectroscopic observations of galaxies with $z \sim 2.5$ is a non-trivial problem. In these cases, techniques of photometric redshift estimation are useful. This involves, besides of optical observations in different filters, a cross-matching of different multi-wavelength catalogues, which contain, in general, non-homogeneous information about different galaxies.

These techniques of photometric redshift estimations are based on the comparison of broad-band photometry and observed colours of galaxies with those expected from template spectral energy distributions (SEDs), either observed or theoretical or a combination of the two, shifted to different *z* [4]. The theoretical template SEDs are constructed according to the models of stellar evolution, different types of galaxies, their starformation rate, age, average metallicity and dust extinction law. Template SEDs, built on a set of these parameters, are shifted to different redshifts with some step of δz. As a result, one obtains a library of few × 10^5 spectra, which can be used to derive the colours as a function of redshift for all the model galaxies with an age smaller than the Hubble time at the given redshift. These spectra are then convolved with transmission curves of filters used for the observations of the galaxy of interest. To measure the photometric redshift a standard χ^2 minimization procedure is used comparing the observed fluxes (and corresponding uncertainties) with those computed from templates. The minimization of the functional χ^2 allows to choose the most appropriate template SED and to determine the redshift and main physical parameters of the galaxy.

The quality of the fit strongly depends on the number of observational points, i.e. filters used. In the case of the photometric redshift, the greater is the number of filters, the less is the resulting error of the estimated redshift. However, the homogeneity of obtained photometric data is crucial: data obtained using different instruments need to be re-calibrated and translated to the same photometric system with the same zero-point. It involves additional studies of secondary standard objects using information from different catalogues and surveys [31]. It is always better if all observations of a galaxy of interest are obtained by the same instrument, e.g., SDSS catalogue, which consists of data obtained in 5 optical filters *ugriz* using the same instrument. However, the studies of photometric redshift based on SDSS-DR12 have efficient coverage only up to redshift of $z \sim 0.8$ [2], which is not enough for GRB hosts investigations. Additional colour data may improve the fit, and in this regard, multi-colour observations are needed. Ultraviolet [6] and infrared [16] surveys of galaxies are always helpful.

2.3 GRB 051008 as an example

In this section, we give an example of a complex study of a dark GRB 051008 and its host galaxy.

The gamma-ray burst GRB 051008 was detected by the *Swift* space observatory on October 8, 2005 UT [22], and the discovery of the X-ray afterglow provided a very tight localization of 1.2". The optical observations of this region started in ~30 minutes after the trigger, and the 2.6-meter Shajn telescope of the Crimean Astrophysical Observatory [28] did not detect any optical afterglow up to limiting magnitude of $R = 23.3^m$. Further observations at the same telescope allowed to discover a host galaxy of GRB 051008 [37].

The discovery of the X-ray afterglow together with optical afterglow non-detection allowed to estimate the spectral index $\beta_{OX} \leq 0.02$, and hence the GRB 051008 may be classify as dark.

The intrinsic faintness of the galaxy and the presence of a bright star ($R \sim 5.5^m$) in ~ 3 arcminutes of its location did not allow to obtain a spectrum of a proper quality, and thus, did not allow to measure the redshift of the galaxy directly. This galaxy is absent in SDSS catalogue due to the same neighbor bright star. In 2006-2012, this region was observed by several ground-based facilities including large telescopes Keck I and Gemini North [38] in 9 filters (*UBg'VRiIZK'*).

We used the *Le Phare* software package [1] with the PEGASE2 population synthesis models library [10] to estimate the photometric redshift of the galaxy of $z = 2.77$ (+0.15, -0.20; 95% confidence level), the best-fitted SED, and the other required parameters. According to this, the host is a dwarf young galaxy of ~60 million years old and mass of $1.2 \times 10^9\ M_\odot$ with very prominent Lyman-break feature. It has a starburst type (i.e. the galaxy with an intensive star formation), moderate internal extinction of $A_V \sim 0.3^m$, with dust distribution typical for irregular starforming galaxies and rather high starformation rate of SFR ~ 60 $M_\odot$/year.

The determined redshift value may be used for the estimates of total burst energetics $E_{\rm iso}$ – an isotropic equivalent energy of the burst source, which depends on the luminosity distance and the burst fluence [20]: $E_{\rm iso} = (1.15 \pm 0.20) \times 10^{54}$ erg.

The X-ray afterglow light curve of GRB 051008 exhibits an achromatic jet-break at the time $t_b = 0.41$ days after the burst trigger. Together with the redshift and $E_{\rm iso}$ estimates, it allows to calculate the jet opening angle [29,20]: depending on the assumed ISM density distribution the opening angle varies from 1.7 degrees (for constant ISM) to 2 degrees (for wind-like medium). The collimation angle determines total energy released in the gamma-ray domain during the burst, which varies from $(4.80 \pm 1.52) \times 10^{50}$ erg to $(7.20 \pm 1.54) \times 10^{50}$ erg for constant and wind-like medium density, respectively.

The fit of X-ray spectra provided the value of the host hydrogen column density of $N_{\rm H,host} = (7.9 \pm 1.6) \times 10^{22}$ cm^{-2}. This value is two orders of magnitude higher than that in our Galaxy. The combination of this value with the best-fitted galaxy SED and best-fitted extinction law provided the estimation of the line-of-sight absorption toward the burst source $A_{V,\rm LOS} > 2^m$. This allows to conclude, that the darkness of the GRB 051008 is connected to the significant absorption at the line of sight.

3 Conclusions and further prospects

The example described above is only one case among many. The main problem is, that every particular dark GRB and its host galaxy need to be studied separately, and there is no any optimal automation of this process. Until now, there are only a few tens of dark GRBs with discovered and well-studied host galaxies among ~650 dark bursts detected. This sample may be increased if any conceptual approach to the methods can be proposed.

The study of the dark GRBs with a faint or absent optical afterglow attracts the attention to distant galaxies with moderate-to-high extinction with redshift more than 1, which often are not included in the surveys due to their faintness. Multi-wavelength observations and complex investigations of these objects allow to define a handful of properties of both the GRB progenitor and its surroundings, adding new information to the total GRB sample. The aggregation and summation of the variety of the GRB properties give opportunities to verify existing theoretical models and to propose updates for them. The enlargement of well-studied dark GRBs sample may be useful for future all-sky surveys (like LSST, SRG, etc.) in the sense of detection and classification of possible discovered transients. In addition, the increase of the number of the galaxies with determined redshift is a key point in the investigations of large-scale structure of the local Universe.

Acknowledgements

This work is supported by RFBR grant 18-32-00784 and partially supported by RFBR grant 17-42-92018.

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