

# Spectral and Photometric Monitoring of Distant Core-Collapse Supernovae in the SAO RAS

A. S. Moskvitin,<sup>1</sup> T. A. Fatkhullin,<sup>1</sup> V. V. Sokolov,<sup>1</sup>

V. N. Komarova,<sup>1</sup> A. J. Drake,<sup>2</sup> R. Roy,<sup>3</sup> and

D. Yu. Tsvetkov<sup>4</sup>

<sup>1</sup>*Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia*

<sup>2</sup>*California Institute of Technology, 1200 E. California Blvd, CA 91225, USA*

<sup>3</sup>*Aryabhata Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital, 263 129, India*

<sup>4</sup>*Sternberg Astronomical Institute, University Ave. 13, 119992 Moscow, Russia*

This paper describes the aims, objectives and first results of the observational program for the study of distant core-collapse supernovae (SNe) with redshifts  $z \lesssim 0.3$ . This work is done within the framework of an international cooperation program on the SNe monitoring at the 6-m BTA telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences, and other telescopes. We study both the early phases of events (SN type determination, redshift estimation, and a search for manifestations of a wind envelope), and the nebular phase (the effects of explosion asymmetry). The SNe, associated with cosmic gamma-ray bursts are of particular interest. An interpretation of our observational data along with the data obtained on other telescopes is used to test the existing theoretical models of both the SN explosion, and the surrounding circumstellar medium. In 2009 we observed 30 objects; the spectra were obtained for 12 of them. We determined the types, phases after maximum, and redshifts for five SNe (SN 2009db, SN 2009dy, SN 2009dw, SN 2009ew, SN 2009ji). Based on the obtained photometric data a discovery of two more SNe was confirmed (SN 2009bx and SN 2009cb). A study of two type II supernovae in the nebular phase (SN 2008gz and SN 2008in) is finalized, four more objects (SN 2008iy, SN 2009ay, SN 2009bw, SN 2009de) are currently monitored.

## 1. INTRODUCTION

Core-collapse supernovae are usually considered as massive stars (a star on the main sequence with more than 8 solar masses) at the final stages of evolution, followed by a core collapse and a powerful explosion (types Ib, Ic and II). An interest to these SNe is driven primarily by the fact that they are suppliers of heavy

elements into the interstellar environment, and hence play an important role in the processes of star formation in the galaxies. In addition, compact relativistic objects are formed precisely in the process of core-collapse SN explosions, giving a chance to investigate the state of superdense matter, as well as the conditions for the formation of such objects as pulsars and micro-

quasars.

Despite the ongoing active research of the SN phenomenon worldwide, we are very far from understanding the processes before and during the explosion. A new look at the problem appeared after it was found that at least some Ib-c type SNe are associated with cosmic gamma-ray bursts (GRBs) [1]. This discovery allows tracing the event straight from its onset, what previously could only be done in isolated instances. For example, it was discovered that at the onset of its explosion a SN can develop a jet [2].

Nevertheless, there are many problems that still do not have any decisive answers. We formulate some of these problems, and lay out the possible solutions for the 6-meter BTA telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) in Section 2. A specific observational strategy of our program is considered in Section 3. The main results of observations and interpretation of the data obtained is presented in Section 4. The final Section 5 discusses the plans for future observations. Note that our research will mainly concern the SNe with collapse of a massive core.

## 2. PROBLEM DEFINITION

### 2.1. *Explosion Asymmetry*

Observations demonstrate that in a statistically significant number of cases (30–40%) an expansion of the SN envelope may be asymmetrical

(different from spherical) [3–7].

Model calculations explain the observational data within the torus or disk-shaped geometry of matter ejection during the explosion [8]. In this case the line profiles in the nebular (more than 150 days after the maximum) SN stage serve as the indicators. The following forbidden lines are usually used: the [FeII] blend around 5200 Å, [OI] 6300, 6363 Å and [CaII] 7291, 7324 Å. An obvious problem needing to be fully examined here is which mechanisms are responsible for the explosion asymmetry. To answer this question, we perform spectral observations at the BTA for a detailed study of line profiles. A set of statistics of such events is very important to be able to make any conclusions. An analysis of the existing data shows a variety of possible explosion geometry variants [7]. Spectropolarimetric observations, now possible with the BTA [9] are as well challenging. Such observations will expressly allow, firstly, to examine the explosion geometry, and, secondly, to trace the distribution of various elements in the outburst.

### 2.2. *Early Phase and Outburst Interaction with Surrounding Stellar and Circumstellar Matter*

In some rare cases, the observations of SNe can be performed at the earliest phase: SN 1993J [10], SN 2006aj [11], SN 2008D [12], SNLS-04D2dc and SNLS-06D1jd [13], SNLS-04D2dc [14]. An interpretation (and previously

detailed modeling, see, e.g., [15]) of the light curves in the ultraviolet, visible light and X-rays allowed to discover an earlier predicted effect of heating and acceleration of the progenitor star’s envelope by the shock wave and an egress of this shock onto the surface of the star (a “shock breakout” [16]). The most important effect of early observations is a possibility of direct, outside the model presentations, estimations of the size of the emitting region, and, hence, the size of the presupernova [11]. It is extremely important for the understanding of which stars go supernova, as well as the mechanism of the explosion itself. It is known that in the spectra of type I SNe, in contrast to type II, there are no visible hydrogen lines. It is believed that the type I SN progenitor stars during the evolution loose their hydrogen envelopes, and in the case of type Ic SNe, their helium envelopes as well [17]. It would be natural to expect the manifestations of this envelope in the spectra, especially in the early ones, as evidenced by Elmhamdi et al. [18]. The authors interpret the absorption feature near  $6300 \text{ \AA}$  as a shifted hydrogen line  $H\alpha$  of the envelope, while their method allows estimating the hydrogen mass as well.

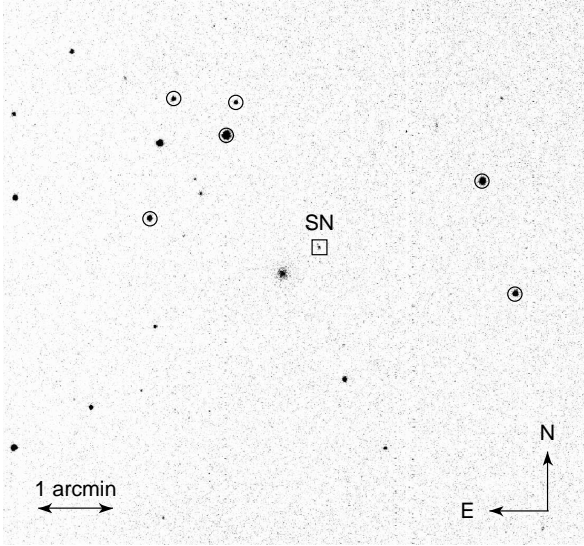
Interestingly, the fact of existence of supernovae changing their type in the course of time (e.g., SN1987K and SN1993J, [18]) can be fairly easily explained within the framework of a simple model. According to the present-day perceptions, the most widely recognized type Ib-c

SN progenitors are: a) relatively low-mass stars ( $8 - 20M_{\odot}$ ) in binary systems (that loose their envelopes as a result of mass transfer) [19], and b) Wolf-Rayet stars (loosing their envelopes due to the stellar wind). A direct observational task is to find the answer to the question: which evolutionary scenario of the type Ib-c SN progenitor stars is preferable? An interpretation of the whole set of data (an estimation of dimensions plus evaluation of mass of the hydrogen envelope) would evidently be able to give a definite answer. In light of the foresaid, a task for the BTA is the earliest possible spectroscopy followed by mandatory monitoring of such events. We consider that one of the most important components of this task is the detection of the  $H\beta$  line, which would become a decisive argument in favor of the model discussed.

### 2.3. A Wide SNe Luminosity Spread

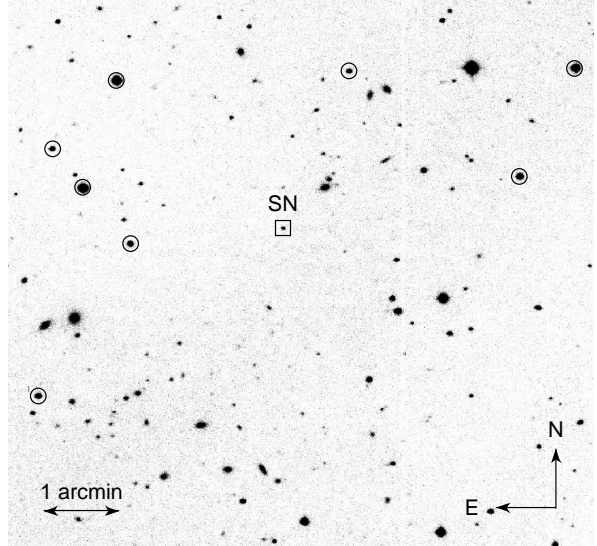
The brightness of type II SNe at maximum (for example, the events SN 2005ap, SN 2006gy and SN 2008es) can reach  $M = -22^m$  [20, 21]. However, it was found that the luminosity of SNe of this type can be  $M_B = -14^m$  and even fainter. In this respect, questions arise: how many such weak flares occur, which percentage of them do we miss, and what effect will the registration of such events have on the overall rate of SN explosions in the galaxies?

In this case, another question seems natural: what is the mechanism of powerful explosions



**Figure 1.** Direct image of the CSS090216:100910+075434 (SN 2009bx) field in the  $V$  band, obtained with the Zeiss-1000 telescope on 27.840 February 2009 UT. In this and subsequent figures the SN is marked with a square, while the circles encircle the standards.

At the time of observation the SN brightness amounted to  $B = 18.83 \pm 0.23$ ,  $V = 18.90 \pm 0.11$ ,  $R_C = 18.45 \pm 0.23$  [36].



**Figure 2.** Direct image of the CSS090319:125916+271641 (SN 2009cb) field in the  $R$  band, obtained with the Zeiss-1000 telescope on 29.987 March 2009 UT. At the time of observation the SN brightness amounted to

$$R_C = 19.78 \pm 0.10 \text{ [37].}$$

#### 2.4. *Supernovae at Moderate and High Redshifts*

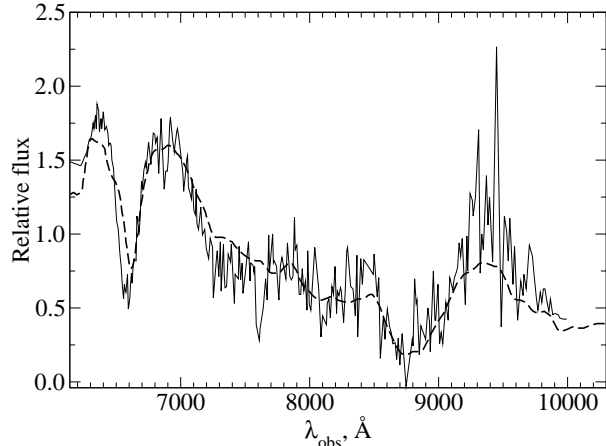
and does it differ from the “classical” scenario? Within the framework of the stated program, we carry out spectral monitoring of such events at the BTA accompanied by multi-color photometry on the 1-meter Zeiss-1000 telescope of the SAO RAS and on other telescopes in the context of international cooperation. The aim is to build detailed light curves in different filters to be further used for the estimates of mass and total energy of the progenitor, as well as for a comparison of the observed characteristics (velocity, line width, etc.) in the spectra of SNe with different luminosities.

Important in understanding of both the phenomena of SNe and gamma-ray bursts is a direct association of SNe with optical afterglows of GRBs. However, spectroscopically such an association was carried out only for the nearby events: GRB 030329 / SN 2003dh ( $z = 0.1687$ ), GRB 031203 / SN 2003lw ( $z = 0.1055$ ), and GRB 060218 / SN 2006aj ( $z = 0.0335$ ) [22]. Apparently, in the visible range such association can be reliably done for the events at redshifts up to  $z \sim 0.5$ , when the brightness of SNe (especially at peak brightness) will still dominate in the overall radiation. It appears to be interesting to compare the prop-

erties of SNe with and without GRBs. Here the researchers are facing a problem: why are not all the nearby GRBs associated with SNe [23]? Is this an effect of observational selection linked with the above mentioned luminosity difference, or is it a distinction in the nature of the phenomena? Within our observational program we perform spectroscopic observations of distant SNe, where the monitoring of events from their earliest phases is viewed essential. The most important here are the measurements of velocities and widths of the detected lines (the estimates of the total explosion energy), and a comparison of the results obtained for the two events studied (SNe associated with GRBs, and SNe not revealing this connection).

It is obvious that the study of SNe at high redshifts is very important for the understanding of the star formation history, in particular, for an independent evaluation of its rate in the Universe [24], the evolution of the initial mass function, etc. Modern specialized surveys can detect type IIIn SNe (the brightest in the ultraviolet) up to the redshifts  $z \sim 2$  [25, 26]. In this case a perceivable task for the BTA would be multi-color photometric observations, and construction of detailed light curves in the context of international monitoring. From the data of broadband photometry in four bands we may estimate the redshift and object type (see, e.g., [27, 28]).

According to the above, the main observational objective of the program is spectral and photometric monitoring of SNe. Express ob-



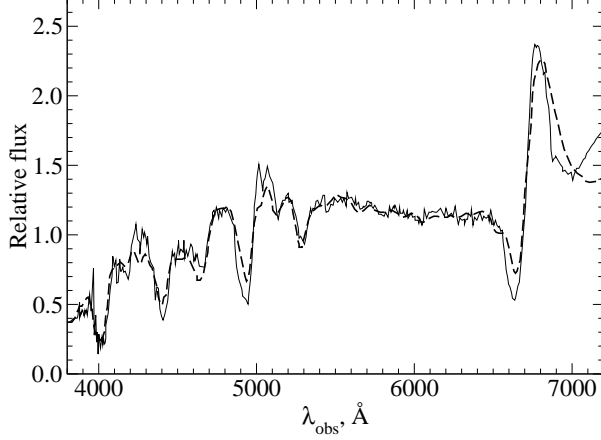
**Figure 3.** A comparison of the spectrum of CSS090319:142155+260102 (SN 2009db), obtained on April 3, 2009 with the BTA (the thin solid line) with the spectra from the SNID database [35]. The closest spectrum belongs to the type Ia supernova SN 1999ee 11 days after maximum (the dashed line) [39]. An estimation of redshift from broad spectral features:

$$z = 0.078 \pm 0.012.$$

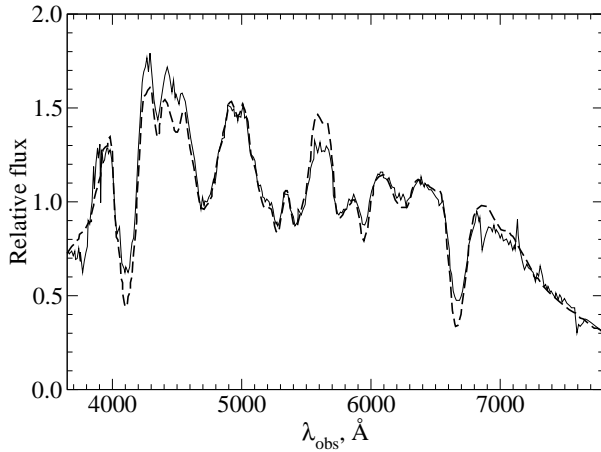
servations of SNe were recently made possible thanks to the constantly updated and accessible on-line data, obtained in the course of specialized sky surveys (see, e.g., [29]).

### 3. OBSERVATIONAL STRATEGY

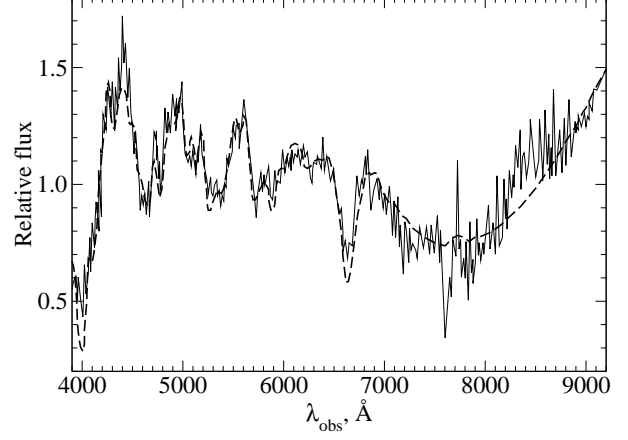
An estimation of the number of the expected and accessible for observations in the SAO events per year ( $\delta > -10^\circ$ ) is: SN Ia—82, SN Ib—5, SN Ic—8, SN Ib-c—3, SN IIIn—11, SN IIP—10, other type II SNe—39 (to be precise the evaluation was done for 2008 from the CRTS [31] data). The classification of objects as core-collapse SNe is possible as early as at the detection stage from the color estimates [27–29]. Since the main pur-



**Figure 4.** A comparison of the spectrum of CSS090421:133609+340319 (SN 2009dw), obtained on April 23, 2009 with the BTA (the thin solid line) with the spectra from the SNID database. The closest spectrum belongs to the type II-P supernova SN 2004et 15 days after maximum (the dashed line) [40]. Redshift estimation:  $z = 0.042 \pm 0.003$ . SN brightness at the time of observation:  $R_C \approx 19.0$ .



**Figure 5.** A comparison of the spectrum of CSS090422:150104+431314 (SN 2009dy), obtained on April 24, 2009 with the BTA (the thin solid line) with the spectra from the SNID database. The closest spectrum belongs to the type Ia supernova SN 1994ae 6 days after maximum (the dashed line) [40]. Redshift estimation:  $z = 0.089 \pm 0.003$ . SN brightness at the time of observation:  $R_C = 18.63 \pm 0.20$ , the USNO-B1 standards were used for calibrations.

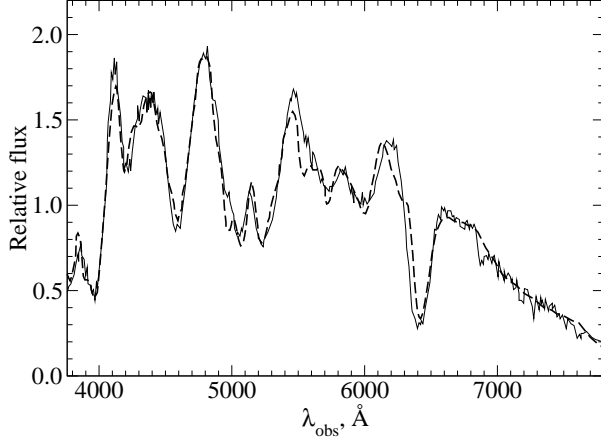


**Figure 6.** A comparison of the spectrum of CSS090516:163900+175858 (SN 2009ew), obtained on May 17, 2009 with the BTA (the thin solid line) with the spectra from the SNID database. The closest spectrum belongs to the type Ia supernova SN 2003du 7 days before maximum (the dashed line) [41]. Redshift estimation:  $z = 0.085 \pm 0.006$ .

pose of the program is a study of precisely this type of SNe, we expect a small percentage of type Ia SNe in our data. According to the estimates of the detection rate we can expect about 1–2 events a week.

The program observations are performed since 2009 in the framework of international cooperation for the studies of core-collapse SNe on more than 10 telescopes in the USA, Italy, Spain, India, Turkey and Russia.

In the SAO RAS the main observations are conducted on the 6-m BTA telescope with a multimode device SCORPIO [9, 30], which is optimal for the program owing to the capability of fast switching between the observational modes. A large telescope is needed to achieve the required quality of the data, as the expected apparent magnitudes of the objects vary from  $15^m$



**Figure 7.** A comparison of the spectrum of CSS090923:155452+320506 (SN 2009ji), obtained on September 25, 2009 with the BTA (the thin solid line) with the spectra from the SNID database. The closest spectrum belongs to the type Ia supernova SN 2003du 11 days after maximum (the dashed line) [42]. Redshift estimation:  $z = 0.048 \pm 0.004$ .

to  $25^m$ . The observational strategy of the program looks as follows:

- 1) the early phase (the “shock breakout”),  $R = 15^m - 19^m$ : spectroscopy with a resolution of  $5 - 10 \text{ \AA}$  (VPHG550G, VPHG550R, VPHG1200R, VPHG1200G, VPHG1200B grisms [30]),  $UBVR_CI_C$  photometry;
- 2) the early phase (SNe at moderate and high redshifts),  $R = 21^m - 25^m$ :  $BVR_CI_C$  photometry, for the brightest events—spectroscopy with a resolution of  $10 - 15 \text{ \AA}$  (VPHG400, VPHG550G, VPHG550R);
- 3) the late phase (nebular),  $R = 17^m - 22^m$ : for bright events ( $R = 17^m - 19^m$ ) spectroscopy with a resolution of  $5 - 10 \text{ \AA}$

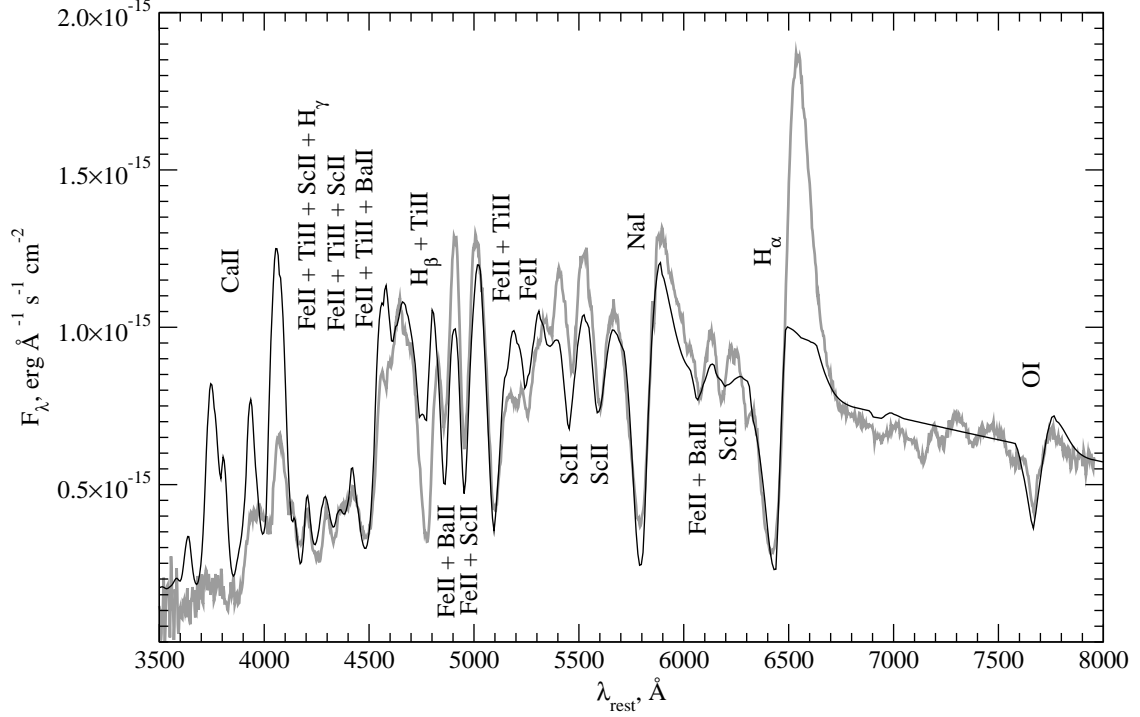
(VPHG550G, VPHG550R, VPHG1200R),  $UBVR_CI_C$  photometry.

The list of potential objects includes both the scheduled for study and recently discovered events (the main sources of data are the CRTS [31], CBET [32], and ATEL [33] catalogs). The selection of objects in a particular night is determined by the task and conditions of observations.

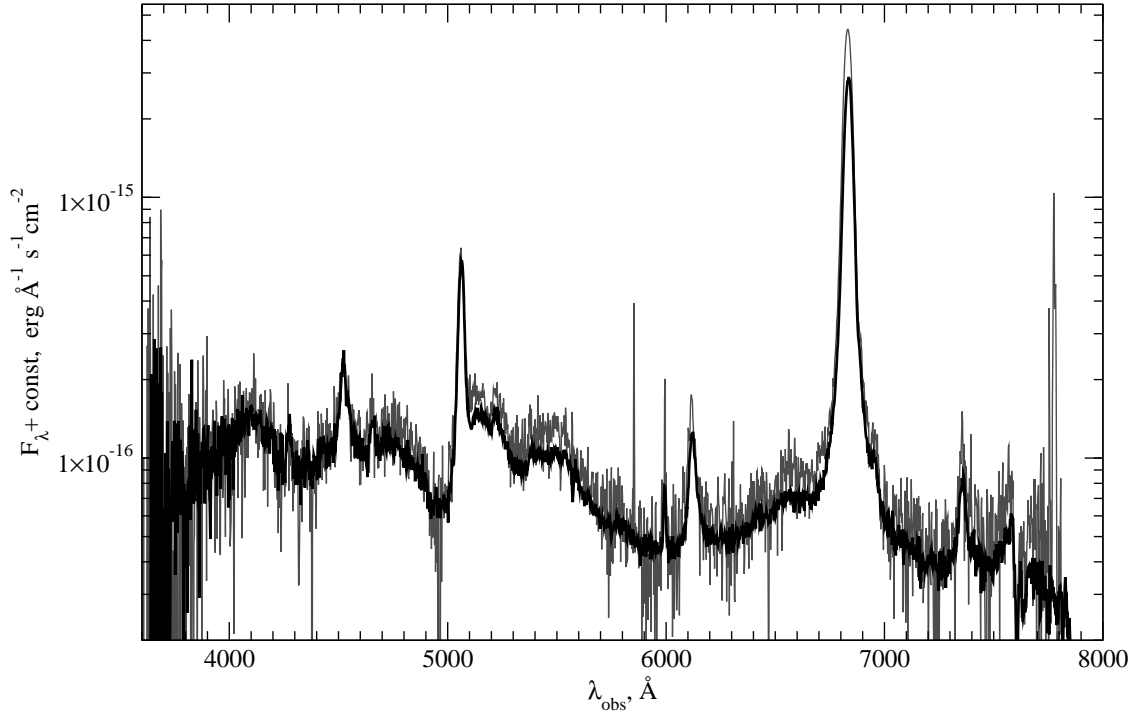
Data reduction is done in a standard way. The spectrum obtained is compared with the SNID [35] spectral library of the nearby SNe and if its belonging to the SNe class is confirmed, then the object type, its phase relative to the peak brightness, and redshift are determined and published in the form of CBET [32] or ATEL [33] telegrams. The spectra may be used for a more detailed analysis, e.g. with the SYNOW code [34]. The photometric data can be used for the absolute calibration of the spectra by flux, the construction of light curves and for the estimations of physical parameters of SNe.

#### 4. RESULTS

The observational program is carried out since the first half of 2009. We perform the photometry of core-collapse SNe on the Zeiss-1000 telescope of the SAO RAS as a follow-up program. In 2009, 30 objects were observed, for 12 of them the spectra were obtained, and for 5 newly detected SNe (SN 2009db, SN 2009dy, SN

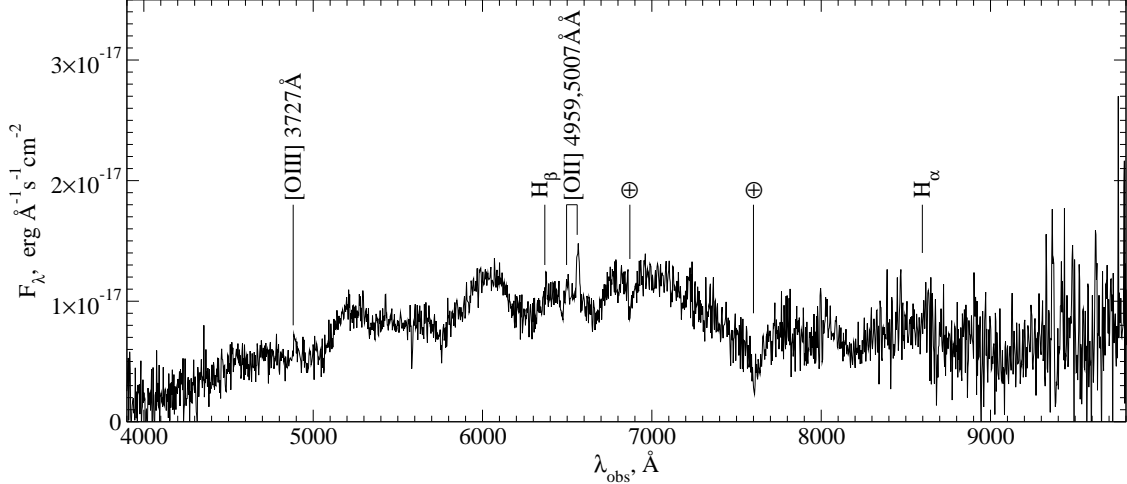


**Figure 8.** The spectrum of SN 2008gz, obtained on November 11, 2008 with the TNG+DOLORES telescope (the thick grey line). The thin line demonstrates the best fit by the model spectrum generated with the SYNOW code.



**Figure 9.** The spectra of SN 2008iy, obtained with the BTA+Scorpio on April 23 (the black line) and September 25 (the grey line), 2009. The object's redshift, measured from the BTA spectra  $z = 0.041$  is consistent with the data cited in [21].





**Figure 10.** Identification of the host galaxy emission lines in the spectrum of SN 2009de, obtained with the BTA. We identified the [OII] 3727 Å, H $\beta$ , [OIII] 4959, 5007 Å lines, the traces of the H $\alpha$  line were confirmed in the spectrum of the host galaxy recently obtained with the Keck I telescope [48]. Redshift estimation,  $z = 0.311$ , is close to the value determined by fitting the broad features of the SN spectrum with the SNID code.

2009dw, SN 2009ew, SN 2009ji) we determined the types, the phases after maximum, and redshifts. The discovery of two more supernovae (SN 2009bx, SN 2009cb) was confirmed photometrically. We completed the study of the nebular phase of two type II SNe (SN 2008gz and SN 2008in), the observations of four more objects (SN 2008iy, SN 2009ay, SN 2009bw, SN 2009de) are ongoing.

#### 4.1. Express Observations: Determination of Supernova Types and Redshifts

The CRTS catalog [31] was used as a source of objects for express observations. The belonging of two objects (SN 2009bx, SN 2009cb) to the SNe class was tested photometrically at the Zeiss-1000 telescope (see Figs. 1 and 2). A transition from stellar magnitudes of the standards in

the *ugri* system of the SDSS-DR7 catalog to the *BVR<sub>C</sub>* system was made via the formulae from [38]. For SN 2009db, SN 2009dy, SN 2009dw, SN 2009ew and SN 2009ji we obtained the spectra, compared them with the SNID database spectra, identified the SN types, estimated the phases relative to the maximum, and redshifts from the broad spectral features (see Figs. 3 – 7).

#### 4.2. SN 2008gz and SN 2008in—Nearby Type II Supernovae

In addition to the express observations of the newly discovered SNe, the monitoring of the scheduled objects under study is underway. In collaboration with the Indian and Italian members of our international team we traced the spectral evolution of SN 2008gz and SN 2008in. Light curves in the B, V, R, I bands were obtained. The

bolometric light curve of SN 2008gz was compared with the light curves of the same type SNe: SN 2004et and SN 1987A. The explosion energy of SN 2008gz appeared to be comparable with that of SN 2004et. In the spectra close to the maximum, the lines had the P Cyg profiles. They were studied using the multiparameter `SYNOW` code [34]. The fitting result of the earliest spectrum of SN 2008gz is presented in Fig. 8 as an example. The modeling revealed that the code restrictions are strong for the later spectra: the emission part of hydrogen profiles is poorly described. To construct the curves of the envelope and photosphere velocity drop for SN 2008gz, we measured the positions of the absorption minima. All the details of the study of SN 2008gz are presented in [43].

#### 4.3. SN 2008iy—Type II<sub>n</sub> SN or Quasar?

One of the most interesting SNe studied in the framework of the program is SN 2008iy [44–46]. It is intriguing owing to the fact that its spectra, obtained at intervals of about 5 months, changed very little (see Fig. 9). There comes a question on the nature of this object. The light curve of SN 2008iy shows a record long ascend—about a year in duration, and a very slow decline after the maximum [47]. The active phase of the outburst lasts as long as several years. A decisive clue to the nature of this object may be the detection of spectral features typical of the nebular phase of SNe.

#### 4.4. Type II Supernovae SN 2009ay and SN 2009bw

Along with our Italian and Moscow colleagues we studied the spectral evolution of type II supernovae SN 2009ay and SN 2009bw, and noted an unusual behavior of brightness of these two type II-P SNe at late phases (around the “plateau” on the light curves). Extensive photometric data was obtained for both objects; for SN 2008bw we as well obtained the spectra at the BTA and other telescopes.

#### 4.5. Cosmological Peculiar Type Ic Supernova SN 2009de

SN 2009de was discovered in the context of the CRTS survey and was studied photometrically and spectroscopically (Fig. 10) on the telescopes of this survey, as well as with the Palomar 60, Palomar 200, BTA, Zeiss-1000 and Keck I. The study of such objects is important for the cosmological problems of the program. In the near future we are planning to obtain deep images on the BTA with the aim of detecting and studying the spectral energy distribution of the SN 2009de host galaxy. At the moment from the results of observations on the Zeiss-1000 and BTA telescopes it is known that the galaxy is weaker than  $R_C = 23.5$  and  $I_C = 24.0$ . However, the noisy spectrum obtained with the Keck I showed the presence of the  $H\beta$ , [OIII] 4958, 5006 Å, and  $H\alpha$  emission lines [48], suggesting

the possibility of obtaining with the BTA of the photometric data for modeling the spectral energy distribution of the host galaxy.

## 5. CONCLUSION

We suppose that the data obtained in the context of our international monitoring will significantly improve the understanding of a yet largely mysterious connection of gamma-ray bursts with core-collapse supernovae [49, 50]. In an attempt to answer the questions on the nature of the progenitors and the explosion mechanisms of SNe and GRBs, as well as about their similarities and distinctions, it is necessary to conduct observations of both the most early phases, closest to the onset of the explosion, and the later phases (a link with asymmetry). Statistical estimates of the rate of SN and GRB explosions, and a comparison of these data with the star formation rates play an important role. Hence a separate objective emerges to study the regions of host galaxies and the host galaxies themselves that are undergoing these explosions.

Given the characteristic times during which an almost complete fade-out of the SN brightness occur, we can say that the program for studies of distant core-collapse SNe at the BTA has just

begun. At this stage, in addition to the early observations of new objects, we have to continue the observations of individual objects for their detailed study. In particular, it is important to study the properties of the host galaxies of SN 2008iy and SN 2009de with the means of broadband photometry.

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