Contrib. Astron. Obs. Skalnaté Pleso **43**, 351 – 356, (2014)

Photometric monitoring of bright supernovae

D.Yu. Tsvetkov[1], **N.N. Pavlyuk**[1], **I.M. Volkov**[1,2] **and S.Yu. Shugarov**[1,2]

[1] *Sternberg Astronomical Institute, M.V. Lomonosov Moscow State University, Universitetskii pr. 13, 119992 Moscow, Russia (E-mail: tsvetkov@sai.msu.su)*

[2] *Astronomical Institute of the Slovak Academy of Sciences 059 60 Tatranská Lomnica, The Slovak Republic*

Received: November 1, 2013; Accepted: January 28, 2014

Abstract. The program of CCD photometric monitoring of bright supernovae (SNe) is carried out at 0.4 – 1.0 meter telescopes of the Sternberg Astronomical Institute, Crimean Astrophysical Observatory and Stará Lesná Observatory since 1998. We have observed more than 250 SNe of different types. We present the results of observations of SNe Ia 2003du, 2009nr and 2011fe, type IIb SNe 2008ax, 2011dh, type II SNe 2004ek and 2005kd and discuss physical parameters of the explosions.

Key words: supernovae, photometry

1. Introduction

Supernova (SN) outbursts represent the final, explosive stage in the evolution of certain classes of stars. SNe occur in several spectroscopically distinct varieties. Type I SNe are defined by the absence of obvious hydrogen in their optical spectra. SNe II all prominently exhibit hydrogen in their spectra.

Type II SNe are the most common class of exploding stars. They are thought to arise from the deaths of massive stars with $M > 8M_{\odot}$, when the nuclear burning does not provide thermal pressure to support the star. Their main feature is the presence of strong hydrogen lines.

SNe II-P (Plateau) SNe are distinguished by the long period of constant luminosity. Another type II SNe present a steeper decline over a few weeks past the maximum and are named "Linear" (SNe II-L). Thanks to direct identifications of several SN precursors in deep pre-explosion images, recent studies support the idea that most SNe II-P originate from explosions of red supergiants with $8 < M < 16 - 17M_{\odot}$.

Type IIn SNe represent a distinct subclass of SNe II that are characterized by narrow emission lines in the spectra, along with intermediate-width and broader components. The narrow component is believed to arise from a circumstellar material (CSM) shell around the exploding star. SNe IIn are often very bright and their luminosity declines slowly.

Type I SNe are divided into Ia, Ib and Ic classes according to their spectral features near maximum light: SNe Ia exhibit prominent lines of Si II, SNe Ib are characterized by He I lines, while SNe Ic lack both in their spectra.

SNe of types II, Ib and Ic are the result of the core-collapse of massive stars (CCSN), while SNe Ia are the thermonuclear explosion of a CO white dwarf which loses stability by accreting matter from the companion (thermonuclear SNe).

Recently, new classes have been added to this classification scheme: SNe Ia were divided into "normal", "1991T-type", "1991bg-type" and "Iax". The class IIb was introduced for objects which behave like SNe II at early stages of evolution, but then become similar to SNe Ib. Extremely luminous SNe were discovered, with maximum luminosity exceeding $M_V \sim -21$ mag, they are named "Superluminous SNe" (SLSN). A subtype of SNe Ic with enlarged explosion energy are named "Hypernovae", some of them are connected with GRBs.

Light curves and spectra are the basic observational characteristics of SNe.

Obtaining a good-quality light curve demands continuous monitoring of an object for a period from several months to a few years, while the brightness decreases by 5-10 magnitudes. This is an appropriate task for small telescopes with CCD photometers.

We have carried out the program of systematic CCD photometric observations of SNe since 1998. We choose only sufficiently bright ($<$ 16 mag at discovery) SNe with declination $\delta > 0$ to ensure long-time monitoring. 260 SNe of different types have been observed during the last 15 years, among them 138 SNe Ia, 91 SNe II, 31 SNe Ib/c. Definite light curves were collected for 13 SNe Ia, 16 SNe II and 6 SNe Ib/c.

For some objects we carried out coordinated observations, taking part in international collaboration.

We present the data for the most interesting objects among those studied in the course of this program. The light curves are shown in Figure 1.

2. SN 2003du

SN Ia 2003du was investigated in the framework of an international cooperation program (Stanishev et al., 2007).

An extensive set of optical and NIR photometry and low-resolution long-slit spectra was obtained using a number of facilities. The observations started 13 days before the B-band maximum light and continued for 480 days with exceptionally good time sampling.

The $UBVRIJHK$ light curves and the color indices of SN 2003du closely resemble those of normal SNe Ia. Modeling of the *uvoir* bolometric light curve indicates that the mass of synthesized ^{56}Ni is in the range of $0.6 - 0.8\,M_{\odot}$.

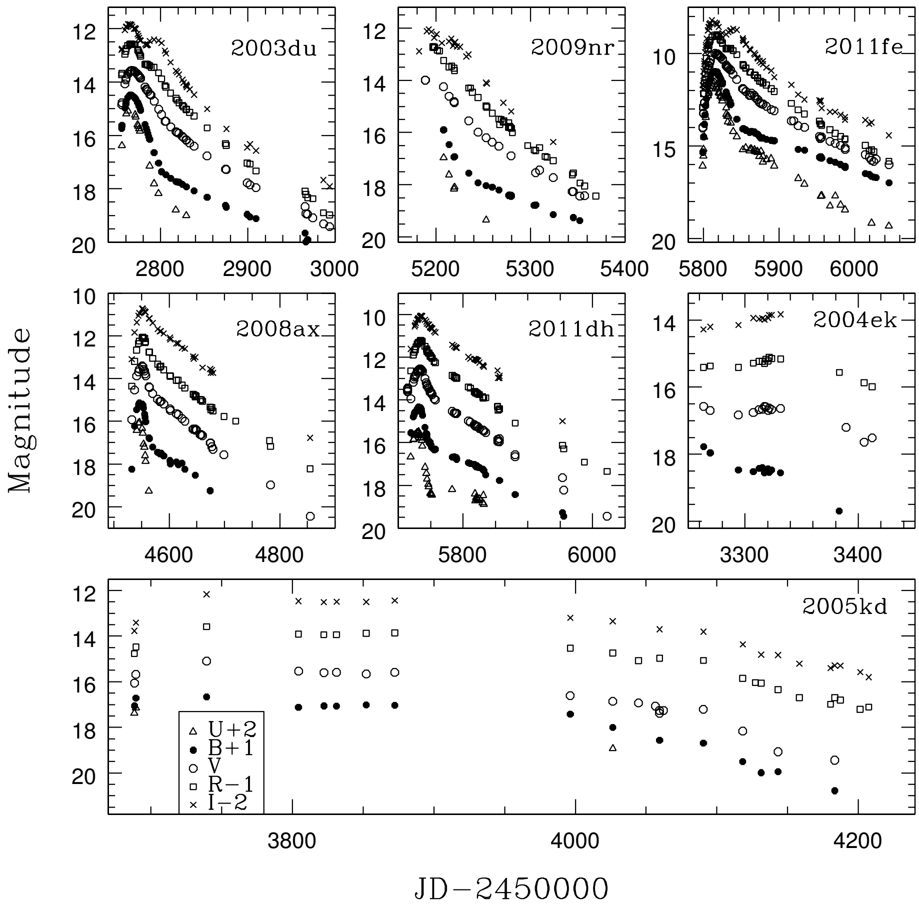

Figure 1. The light curves of SNe.

3. SN 2009nr

SN Ia 2009nr was discovered in the CCD images obtained with the telescope of the MASTER robotic network in Blagoveshchensk on December 22, 2009. The observations were carried out in cooperation with the MASTER team (Tsvetkov et al., 2011). The light and color curves and bolometric light curves for SN 2009nr have been constructed. SN 2009nr is shown to be similar in the light-curve shape and maximum luminosity to SN 1991T, which is the prototype of the class of supernovae Ia with an enhanced luminosity. SN 2009nr exploded far from the center of the spiral galaxy UGC 8255 and most likely belongs to its old halo population. We hypothesize that this explosion is a consequence of the merger of white dwarfs.

4. SN 2011fe

The photometry of SN Ia 2011fe in the *UBVRI* passbands was collected at five sites, starting one day after the discovery and continuing for a span of 647 days. Most of the data were obtained at the Stará Lesná Observatory of the Astronomical Institute of the Slovak Academy of Sciences. The other observing sites were the Crimean Laboratory of the Sternberg Astronomical Institute (SAI)(Nauchniy, Crimea, Ukraine); the Simeiz Observatory of the Crimean Astrophysical Observatory (Simeiz, Crimea, Ukraine); Moscow Observatory of SAI (Moscow, Russia); the Special Astrophysical Observatory of RAS (Nizhniy Arkhyz, Russia) (Tsvetkov et al., 2013)

The light and colour curves for SN 2011fe show that it belongs to the "normal" subset of type Ia SNe and is nearly unreddened. The decline rate parameter $\Delta m_{15}(B) = 1.10$ is close to the mean value for SNe Ia. The comparison of light, colour curves and spectrum show that SN 2011fe is nearly identical in all observed parameters to the well-studied "normal" SNIa 2003du for the first ∼200 days of evolution.

We found out that the rate of brightness decline in the *BVR* bands is higher than average for SNe Ia in the interval of phases 180–430 days. Afterwards the decline for V, R and "quasi-bolometric" light curves slows down. This may be caused by the emergence of the light echo (see e.g. Wang et al., 2008), but some models of late-time luminosity evolution also predict slowing of the decline at that phase.

5. SN 2008ax

We started photometric monitoring of SN IIb 2008ax 4 days after the discovery and continued observations for 250 days (Tsvetkov et al., 2009).

The photometric behavior of SN 2008ax is typical for core-collapse SNe with a low amount of hydrogen. After the maximum the brightness of SN declined very fast. At the phase of 15 days past the maximum the B magnitude declined by 1.67 mag. The fast drop continued for about 25 days, and at about JD 2454580 the onset of the linear decline is observed. We determined the absolue peak V magnitude of -17.45 mag, which is quite typical for SNe of similar classes.

We computed the model light curves in *UBVRI* bands using our code STELLA, which incorporates implicit hydrodynamics coupled to a time-dependent multi-group non-equilibrium radiative transfer (Blinnikov et al., 1998). The model was derived from a 13 $M_\odot$ main sequence star that lost most of its hydrogen envelope to a nearby companion. The main parameters of the model are: total mass 3.8 $M_\odot$, radius $600R_\odot$, mass of ^{56}Ni 0.11 $M_\odot$, explosion energy 1.5×10^{51} erg. The model light curves give a very good fit to the observed maximum, concerning both the luminosity and the shape. The differences are on the rising branch, where the computed early-time peak is brighter than observed, and on the tail, especially for the U and B bands.

6. SN 2011dh

We carried out observations of SN IIb 2011dh in M51 from June 1, 2011 until April 4, 2012 (Tsvetkov et al., 2012). The light curves are similar to those for SN IIb 2008ax, but the initial flash is stronger and very short, the rise to the first peak took only about 0.4 days, and a local minimum was reached 2.6 days after the peak. There are humps on the light curves in U and B at the onset of linear decline. We attempted to model the quasi-bolometric light curve as well as the light curves in $UBVRI$ bands using our code STELLA. The parameters of the best-fitting model are radius 300 $R_{\odot}$, mass 2.24 $M_{\odot}$, explosion energy 2.0×10^{51} erg.

7. SN 2004ek

We observed this SN from September 14, 2004 (5 days after discovery) until Ferbuary 10, 2005 (Tsvetkov, 2008a). SN 2004ek certainly belongs to the class of SN II-P, but the differences between the light curves of SN 2004ek and those for typical SNe II-P are evident. In the B band SN 2004ek has a long period (JD 2453290-340) of constant brightness, while all normal SNe II-P have nearly linear decline at that stage. In the V there are two peaks on the light curve, one immediately after the outburst and the second at about JD 2453330. In the R and I bands after the period of constant brightness there is a prominent increase of luminosity, amounting to 0.3 mag in R and 0.4 mag in I. The absolute magnitude at maximum is $M_V = -18.5$, which is a high luminosity for SNe II-P.

8. SN 2005kd

SN IIn 2005kd was discovered on November 12.22 UT, and we started photometric observations immediately after its discovery, on November 13, 2005 and continued until April 16, 2007 (Tsvetkov, 2008b). Our first two observations were on the rising branch of the light curve. The rate of brightness increase is about 0.3-0.4 mag day^{-1} in all bands. The outburst most likely occurred on November 10 or 11, 2005.

Our next observation was only on January 3, 2006 and on this date this SN was the brightest among our data set. After a small drop from the maximum the SN entered a plateau stage, which lasted for at least 192 days, from day 119 until day 311 past the explosion. Another gap in observations does not allow to determine the length of the plateau more definitely. Since September 17, 2005 (day 341) until the end of our observations at day 522 the SN is gradually fading, but at different rates. Until day 405 the decline is slow, with rates (in units mag/100 days) 0.77 in the R and I bands, 0.87 in the V and 1.3 in the B band. The late decline is about two times faster: 1.7 in R and I bands, 2.5 in the B and V bands. We estimate the absolute magnitude at maximum $M_V \approx -20.5$; SN 2005kd is among the most luminous SNe ever observed. The plateau lasting at least 192 days observed for SN 2005kd is a unique feature for SNe IIn.

9. Conclusions

The program of photometric monitoring of SNe proved to be effective and yielded a lot of valuable results. Since 1998 we have published 23 papers, among them 2 in The Astrophysical Journal, 3 in Astronomy and Astrophysics, 4 in MNRAS.

References

Blinnikov, S.I., Eastman, R., Bartunov, O.S., Popolitov, V.A., Woosley, S.E.: 1998, *Astrophys. J.* **496**, 454

Stanishev, V., Goobar, A., Benetti, S., Kotak, R., Pignata, G., Navasardyan, H., Mazzali, P., Amanullah, R., Garavini, G., Nobili, S., Qiu, Y., Elias-Rosa, N., Ruiz-Lapuente, P., Mendez, J., Meikle, P., Patat, F., Pastorello, A., Altavilla, G., Gustafsson, M., Harutyunyan, A., Iijima, T., Jakobsson, P., Kichizhieva, M.V., Lundqvist, P., Mattila, S., Melinder, J., Pavlenko, E.P., Pavlyuk, N.N., Sollerman, J., Tsvetkov, D.Yu., Turatto, M., Hillebrandt, W.: 2007, *Astron. Astrophys.* **469**, 645

Tsvetkov D.Yu.: 2008a, *Perem. Zvezdy* **28**, 3

Tsvetkov D.Yu.: 2008b, *Perem. Zvezdy* **28**, 6

Tsvetkov, D.Yu, Volkov, I.M., Baklanov, P.V., Blinnikov, S.I., Tuchin, O.: 2009, *Perem. Zvezdy* **29**, 2

Tsvetkov, D.Yu., Balanutsa, P.V., Lipunov, V.M., Volkov, I.M., Tuchin, O.A., Kudelina, I.P., Pruzhinskaya, M.V., Gorbovskoy, E.S., Kornilov, V.G., Belinskii, A.A., Tyurina, N.V., Yurkov, V.V., Sergienko, Yu.P., Tlatov, A.G., Parkhomenko, A.V., Dormidontov, D.V., Senik, V.A., Krushinskii, V.V.: 2011, *Astron. Lett.* **37**, 775

Tsvetkov, D.Yu., Volkov, I.M., Sorokina, E.I., Blinnikov, S.I., Pavlyuk, N.N., Borisov, G.V.: 2012, *Perem. Zvezdy* **32**, 6

Tsvetkov, D.Yu., Shugarov, S.Yu., Volkov, I.M., Goranskij, V.P., Pavlyuk, N.N., Katysheva, N.A., Barsukova, E.A., Valeev, A.F.: 2013, *Contrib. Astron. Obs. Skalnaté Pleso* **43**, 94

Wang, X., Li, W., Filippenko, A.V., Foley, R.J., Smith, N., Wang, L.: 2008, *Astrophys. J.* **677**, 1060