The stellar-wind envelope around the supernova XRF/GRB 060218/SN 2006aj
massive progenitor star

E. Sonbas,¹,² A. S. Moskvitin,¹ T. A. Fatkhullin,¹ V. V. Sokolov,¹ A. Castro-Tirado,³ A. de Ugarte Postigo,³,⁴ J. Gorosabel,³ S. Guziy,³ M. Jelinek,³ T. N. Sokolova,¹ and V. N. Chernenkov¹

¹Special Astrophysical Observatory of R.A.S.,
Karachai-Cherkessia, Nihniy Arkhyz, 369167 Russia
²University of Cukurova, Department of Physics, 01330 Adana, Turkey
³Instituto de Astrofsica de Andalucia (IAA-CSIC), P.O. Box 03004, 18080 Granada, Spain
⁴European Southern Observatory (ESO), Chile

Abstract. In BTA spectra of the supernova SN 2006aj, identified with the X-ray flash (XRF) and gamma-ray burst XRF/GRB 060218/SN 2006aj, we detected details interpreted as hydrogen lines, which is a sign of stellar-wind envelope around a massive progenitor star of the gamma-ray burst. Results of modeling two early spectra obtained with the BTA in 2.55 and 3.55 days after the explosion of Type Ic supernova SN 2006aj (z=0.0331) are presented. The spectra were modeled in the Sobolev approximation with the SYNOW code (Branch et al. 2001; Elmhamdi et al. 2006). In the spectra of the optical afterglow of the X-ray flash XRF/GRB 060218 we detected spectral features interpreted as (1) the $H\alpha$ PCyg profile for the velocity $33000\,\text{km}\,\text{s}^{-1}$ — a wide and almost unnoticeable deformation of continuum in the range of $\approx 5600 - 6600\,\text{Å}$ for the first epoch (2.55 days) and (2) a part (“remnant”) of the $H\alpha$ PCyg profile in absorption blueshifted by $24000\,\text{km}\,\text{s}^{-1}$ — a wide spectral feature with a minimum at $\approx 6100\,\text{Å}$ (the rest wavelength) for the second epoch (3.55 days). Taking into consideration early BTA observations and spectra obtained with other telescopes (ESO Lick, ESO VLT, NOT) before 2006 Feb. 23 UT, it can be said that we observe evolution of optical spectra of Type Ic core-collapse supernova SN 2006aj during transition from the short phase related to the shock breakout to outer layers of the stellar-wind envelope to spectra of the phase of increasing brightness corresponding to radioactive heating. Signs of hydrogen in spectra of the gamma-ray burst afterglow were detected for the first time.

I. INTRODUCTION

On Feb. 18.149, 2006 UT the space observatory Swift detected a peculiar gamma-ray burst (GRB) with a powerful component of supernova (SN) emission in spectra and in the light curve of the GRB afterglow. Therefore, this burst is simultaneously classified both as GRB060218, and as SN2006aj: GRB060218/SN 2006aj. But since in this case the X-ray emission was prevailing in the GRB spectrum, the GRB is also classified as XRF (X-Ray Flash), and the event is denoted either as XRF/GRB 060218/SN 2006aj, or as XRF 060218/SN 2006aj. Below we will
mostly use the latter notation to emphasize the circumstance which is important for this work that in the case of SN 2006aj the SN event itself started with observation of a powerful X-ray flash (XRF).

For this XRF/GRB, direct observational signs of an early phase of expansion of shock arising due to explosion of a compact core of a pre-SN and the shock breakout to the outer boundary of the stellar-wind envelope surrounding the SN progenitor star were obtained for the first time. During the first 2 hours, the shock-wave was observed as the mostly X-ray flash XRF 060218, and afterwards, when the envelope became optically thin, as a powerful ultraviolet (UV) burst with the maximum brightness in 11 hours after GRB detection (Campana et. al., 2006; Blustin 2007). During first 2800 seconds, beside non-thermal emission typical of GRB afterglows, XRF 060218 also demonstrates in its X-ray spectrum a powerful thermal component whose temperature falls, and with time the emission maximum shifts to the UV and optical spectral range (see Fig.1 in Campana et. al., 2006 and Fig. 2 in Blustin 2007).

XRF/GRB 060218 is one of the nearest GRBs with its redshift $z=0.0331$. In this respect it can be compared to GRB 030329/SN 2003dh having the redshift $z=0.1683$ which was also identified with the Type Ic SN. Both events have aroused considerable interest because such coincidences (GRB and SN) happen rarely, only once every two-three years (Chapman et al. 2007), when GRBs revealed SNe starting from the moment of star core explosion. It can be said that the study of GRBs is a new phase of investigation of the same core-collapse SNe, but from the very beginning of this remarkable phenomenon. That is why in these cases early spectral observations turn out to be very important for understanding the mechanism of both core-collapse SN explosion itself and GRB source. When such early observations are successful, the 6-meter telescope, with its large accumulating area and eastern location relatively other large European observatories, can play an important role in implementation of the international program of spectroscopic observations (monitoring) of quickly-fading optical GRB afterglows.

Fig. 1 represents the spectra obtained with the 6-meter telescope (Fatkhullin et al. 2006). Like the case of GRB 030329/SN2003dh (Sokolov et al. 2003), the spectra of XRF 060218/SN2006aj are among the earliest spectra obtained with a high signal/noise ratio (as is shown in Table 1), which permits applying the interpretation methods usually used for spectra of Type Ic SNe (Branch et al. 2001; Elmhamdi et al. 2006).

As was shown by Campana et al. (2006), both the XRF itself and the UV burst in about 10-11 hours after XRF 060218, and then the UV excess in early spectra of the afterglow can be explained by interaction between the SN shock and a stellar-wind envelope around the massive progenitor star. This is a so-called “shock breakout”
effect (the shock breaks out through an envelope around a collapsing and exploding star core).

Such an effect for core-collapse SNe Ib/c and SNe II has been known for a long time already (Colgate, 1968; Imshennik and Nadezhin, 1989; Calzavara and Matzner, 2004). It can be observed as a relatively short phase of the SN explosion which, after beginning with an X-ray flash (XRF), ends with a bright UV burst, which announces arrival of the shock to surface of the exploding star. It can be also said about the shock breakout to upper layers or to an optically-thin “surface” of the extended stellar-wind envelope surrounding the collapsing and exploding cores of Type Ib or Ic SNe. Below, the term “shock breakout” will be used. Like two famous SN 1993J and SN 1987A, in the case of XRF 060218/SN2006aj this effect was observed as a sharp and short early peak in the optical light curve — see Fig.2 in Campana et al. 2006 and Fig.2 in this paper. We mentioned the same effect when explaining the very first spectra of the GRB 030329/SN2003dh afterglow obtained in ≃10 hours after GRB 030329 (Sokolov 2003). Due to detecting XRF 060218/SN2006aj in the beginning of the SN burst, i.e. before the shock breakout, we managed to observe motion of the shock inside the stellar-wind envelope (the shock breakout effect) during the first two hours as an X-ray flash (XRF) with thermal spectrum.

From Table 1 it is seen that BTA spectra refer to minimum in the light curve, i.e. we observe the transition from phase 1 of thermal emission related to the shock breakout to “surface” of the stellar-wind envelope (the first peak in Fig.2) to phase 2 of the subsequent increasing of SN brightness with maximum in ≃10 days in Fig.2, which corresponds to the (non-thermal) radioactive heating of the expanding SN envelope caused by the decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$.

Thus, during our observations, physical conditions have been changing quickly, and this paper is dedicated to interpretation of spectra of this remarkable transitional phase. But before comparing observational and theoretical spectra in Section 2 of this paper, we adduce estimates of typical energy, temperature, size and velocity which directly follow from results of Swift observations of XRF 060218 in the X-ray and UV ranges obtained before the beginning of the BTA spectral observations.

1) Energy of the X-ray and UV flashes:

Light curves of the XRT (0.3-10 keV) and UVOT ranges are given in the paper by Campana et al. (2006). Ibidem, there is an estimate of energy radiated in gamma- and X-rays during the first two hours when the shock has been still moving (breaking out) through the wind. Energy release in the X-ray (XRT) flash is equal to $\sim 6 \times 10^{49}$ erg. Then, in about 8-11 hours, the UV (UVOT) light curve shows a powerful peak (the first maximum in our Fig.2) caused by the shock breakout to the surface or, more exactly, to the outer boundary of the stellar-wind envelope when it becomes sufficiently transparent. It is this UV burst that is the Colgate shock break-
out effect (Colgate 1968). Energy released in this UV flash in the Swift/UVOT range during $\approx 28$ hours and estimated from data of the paper by Campana et al. (2006) gives the number of the same order $\sim 3 \times 10^{49}$ erg, which directly says about identical nature of the X-ray (XRT) and UV (UVOT) flashes/bursts.

2) Evolution of temperature:

At first, when the shock breaks out through the wind envelope and energy is released mostly in X-rays, the thermal spectrum corresponds well to the temperature $kT \approx 0.17$ keV ($\approx 2 \times 10^6$ K). The temperature falls to 0.03 - 0.05 keV (350 000 - 580 000 K) or lower, by the time of the UV (UVOT) flash in $\approx 11$ hours after the GRB (the first maximum in our Fig. 2) taking into consideration the $kT$ measurement uncertainties with Swift/UVOT in this period (only a part of the black-body peak gets into the UVOT range, see Blustin, 2007). Then the temperature of the thermal component decreased down to $\approx 43000$ K or to $kT \approx 3.7 +1.9/-0.9$ eV (Campana et al. 2006, Fig. 3) in the subsequent $\approx 22.5$ hours. Thus, it is thought that the temperature can be even lower, less than 10 000 K, by the moment of our first spectral observation (2.55 days after GRB, see Table 1), in accordance with estimates of the temperature decrease rate adduced in the paper by Campana et al..

3) Size of the stellar-wind envelope:

From the data given in the paper by Campana et al. (2006), one can also estimate radius of the wind envelope surrounding the Wolf-Rayet (WR) star before the explosion. (For example, the arguments in favor of the WR star surrounded by an extended stellar-wind envelope as a progenitor star of XRF 060218/SN 2006aj are given by Blustin, 2007). It is natural to connect the size of this envelope to the bright UV (UVOT) flash observed in $\approx 11$ hour after GRB. At this moment the shock which was observed before that only in X-rays becomes visible in UV and optical at last, since layers of the wind envelope over the shock become optically thin and the shock breaks out to the “surface” (more exactly, to upper layers) of this extended envelope related to the GRB progenitor star or pre-SN. At this moment, according to Swift/UVOT data about evolution of temperature and radius of the thermal component of the GRB/XRF 060218 afterglow, i.e. at a temperature of $kT \sim (0.03—0.05)$ keV ($</\sim 580 000$ K) at the moment ($\sim 10^4$ s) of the luminosity maximum, the size of the wind envelope around the pre-SN must be equal to $>/\sim 300 R_\odot$ at the bolometric luminosity ($4.6—35.5 \times 10^{45}$ erg/s).

4) Velocity of the shock:

While the shock moves inside this stellar-wind envelope, the radius corresponding to the thermal radiation component (related to the shock breaking out from the center) is constantly increasing from $\approx 5.7 R_\odot$ to $\approx 17 R_\odot$, as it follows from the same data (Campana et al., 2006) of the X-ray observations carried out with Swift/XRT before maximum of the UV flash. The radius of the thermal component continues increasing to
≈ 4700R⊙ in 1.4 days (see Fig. 3 in Campana et al.), i.e. by the time of observation carried out with Swift/UVOT after the flash maximum. At this time the shock has already broke out to the “surface” of the stellar-wind envelope and luminosity of the thermal component has decreased (see Fig. 2). Dividing the path of the shock (or the radius \( \approx 3.29 \pm 0.94/-0.93 \times 10^{14} \) cm of the thermal component at \( kT \approx 3.7 \pm 1.9/-0.9 \) eV) by the time (1.4 days) one can obtain expansion velocity of the photosphere related to the shock by the moment of the spectral observations: \( (2.7 +/- 0.8) \times 10^9 \) cm s\(^{-1}\) (Blustin 2007). Such a velocity is typical of core-collapse SNe, and it is comparable with line widths observed in the spectrum of SN2006aj (Pian et al. 2006).

Further it will be shown that the above estimates of the energy, size and velocity obtained from the observations of the shock breakout effect by the Swift/XRT/UVOT observatory are also confirmed when analyzing our optical spectra of XRF 060218/SN 2006aj obtained in 2.55 and 3.55 days after the beginning of the SN explosion, i.e. when contribution of the thermal component of radiation of the shock was still determining, which is also indicated by strong blue excesses in our spectra (Fig. 1). But, as is seen from the UBVR light curves (Fig.2), in 5 days the GRB afterglow has been already noticeably reddening, which is related to the change of the mechanism of the SN radiation by this time, when the classical photospheric phase of the SN envelope expansion begins. This phase is usually observed in the core-collapse SNe and it was described in reviews many times (see, for example, Imshennik and Nadezhin, 1988).

Section 2 describes early spectral observations of the XRF 060218/SN 2006aj optical afterglow carried out with the 6-meter SAO RAS telescope. Section 3 describes the modelling of spectra with the SYNOW code and discusses spectral manifestations of the wind envelope as wide absorptions near 5800Å and 6100Å (rest wavelengths with \( z=0 \)) corresponding to the PCyg absorption in the \( H\alpha \) hydrogen line. Section 4 contains the discussion of results in the context of: 1) an obvious evolution of the \( H\alpha \) traces by data for XRF 060218/SN 2006aj obtained with BTA and other telescopes; 2) manifestations of the Colgate shock-breakout effect in the light curves, spectra, sizes and luminosities of “usual” Type Ib/c SNe; and 3) asymmetry of explosion of the core-collapse SNe. Conclusions are formulated in Section 5.

II. EARLY SPECTRAL OBSERVATIONS OF THE OPTICAL AFTERGLOW OF XRF 060218/SN 2006AJ WITH THE 6-METER SAO RAS TELESCOPE

Within the context of the program of follow-up observations of GRB optical afterglows, the variable object detected with Swift/UVOT and associated with the XRF 060218 event was spectroscopically observed with the 6-meter SAO RAS telescope. We used the Spectral
Camera with Optical Reducer for Photometrical and Interferometrical Observations (SCORPIO) mounted in the BTA primary focus [http://www.sao.ru/hq/lsfvo/devices/scorpio/scorpio.html]. There were two sets of observations: at the epochs 16:31-17:18, Feb. 20, 2006 UT and 16:31-17:16, Feb. 21, 2006 UT. The dispersing element was a combination of a transparent grid and the prism VPHG550G with the spectral operational range and resolution (FWHM - Full Width at the Half Maximum) of 3500 - 7500Å and 10Å, respectively.

The processing of data was standard. It included subtraction of electronic zero, correction for flat field, wavelength calibration with the help of comparison spectrum of a Ne-Ar lamp, correction for atmosphere extinction and calibration by an absolute flux with the use of observations of a spectrophotometric standard at every night. To detect a possible short-time variability and to control calibration of absolute fluxes from night to night, a bright stellar-like object was set at the input slit together with the optical transient (see Fig. 3). In all, 4 exposures were obtained in the first and second periods. We did not detect any short-time variability within these observational periods, therefore we summed all 4 individual spectra to get a higher signal/noise ratio. Figure 1 shows average spectra in every night, Table I lists average epochs of these spectra.

Then observational spectra (Fig. 1) were corrected (Figs. 5 and 6) for galactic extinction according to the dust distribution maps of Schlegel, Finkbeiner, & Davis (1998). The value of $E(B-V)$ in the direction of the object ($\alpha_{2000} = 03^h21^m39^s.683$, $\delta_{2000} = +16^\circ52'01".82$) was equal to 0.14. When accounting for extinction, the dust-screen model was accepted, in which the expression for extinction has the form $F_{\text{int}}(\lambda) = F_{\text{obs}}(\lambda)10^{0.4-k(\lambda)E(B-V)}$, where $F_{\text{int}}(\lambda)$ and $F_{\text{obs}}(\lambda)$ are issued (without the extinction) and observed fluxes respectively. The extinction curve of the Milky Way ($k(\lambda)$) was taken from the paper Cardelli, Clayton, & Mathis (1989).

III. THE COMPARISON OF THE OBSERVATIONAL SPECTRA OF XRF 060218/SN 2006AJ WITH SYNTHETIC SPECTRA

To interpret spectra we used the “SYNOW” code calculating synthetic spectra of SNe (Branch et al. 2001). This multiparametric code was already applied many times for a direct analysis of spectra of core-collapse SNe, when hydrogen was detected in the phase of radioactive heating of the expanding SN envelope (Branch et al. 2002, Baron et al. 2005, Elmhamdi et al. 2006). The computation algorithm of model spectra is based on the following assumptions: spherical symmetry, a homological expansion of layers and a sharp photosphere. When interpreting early spectra, this optically-thick photosphere emitting a continuum blackbody spectrum in some cases can be identified
with the shock. At least this is valid in the first days ($T_{sp}=1.95\text{d}$ and $2.55\text{d}$ from Table 1) after XRF 060218, when spectra (Fig.1) and photometry (Fig.2) still demonstrate a large blue excess, which is related with influence of the thermal component of radiation from the first short and powerful UV flash. It is assumed that spectral lines are formed over this expanding photosphere as a result of resonance scattering which is interpreted in the SYNOW code in the Sobolev approximation (Sobolev 1958, Sobolev 1960, Gorbatsky and Minin 1963, Sobolev 1967).

This code allows us to identify lines, to estimate velocity of the photosphere expansion and the velocity range (or scatter) for lines of every ion detected in the spectrum. The detailed description of the SYNOW code can be found in the fore-quoted papers Branch et al. 2001, Elmhamdi et al. 2006. To understand our results, the fact is essential that in the SYNOW code the velocity of layers expansion over the photosphere is proportional to distance from every point of an expanding layer to the center ($v \sim r$).

Judging by the form of observed spectral features, there are two cases: the undetaching (“the undetached case”) and detaching (“the detached case”) of the layer, in which a spectral line forms, from surface of the expanding sharp photosphere. If matter of moving gas layers located over the photosphere does not detach from it (i.e. all layers radiate and screen photosphere starting from its level), then a line is observed in absorption or in emission like the case of here-considered case (Fig. 3) of a line of the classic PCyg profile. We have chosen this model of layers undetached from photosphere (“the undetached case”) to interpret our first spectrum ($T_{sp}=2.55\text{d}$, see Fig. 1). Besides, apparently, at this moment the expanding photosphere still can be identified with the shock, because our first spectrum (with a larger excess in its blue part) was obtained closer to the moment when the shock breaks out to the “surface” of the stellar-wind envelope surrounding the pre-SN — the first maximum in Fig. 2.

A layer detached from the photosphere manifests itself in spectrum as a smoothed emission and a strongly blue-shifted absorption — a “remnant” (part) of the PCyg profile — as is shown in Fig. 3. The “detached case” is realized when velocity of the layer in which the line forms noticeably exceeds velocity of the photosphere. If $v \sim r$, then the absorption part of the PCyg profile is a result of screening photosphere by a narrow layer; and the narrower is this layer (radiating a spectral line), the closer is the emission to the photosphere continuum. Such a model corresponds to our second spectrum ($T_{sp}=3.55\text{d}$), at least, for HI lines which can be connected to the wind envelope. It may be assumed that the shock provoked the motion and “detachment” of the uppermost layers of this extended wind envelope surrounding the GRB/SN progenitor star.

In 3.55 days after the SN explosion, when the contribution of the thermal component deceases
and the expanding envelope of SN becomes more and more transparent, the shock cannot be already identified with the photosphere totally. The so-called photosphere phase of the SN explosion begins. The SYNOW code was applied mostly to interpret spectra of this phase (Elmhamdi et al. 2006, see also references ibidem).

In Figs. 5 and 6 the BT A spectra of XRF060218/SN2006aj, obtained in 2.55 and 3.55 days after the event are compared to synthetic spectra modeled with the SYNOW code. The first spectrum taken right after the bright UV burst (Fig. 2), is easily modeled for a rather simple set of parameters. We have chosen temperature of the photosphere \( t_{bb} \) used in fitting the energy distribution in the spectrum in Fig. 5 (rest wavelengths) to be equal to 9000 K. This corresponds also to the temperature fall rate by results of Swift/XRT/UVOT observations (Campana et al. 2006), according to which by the time of our spectral observation the temperature must be less than 10000 K. In the spectrum taken in 2.55 days the SYNOW model shows the photosphere velocity equal to 33000 km s\(^{-1}\). This parameter is within errors of estimates of the photosphere expansion velocity connected with the shock, which is obtained from the same Swift/XRT/UVOT data \((2.7 \pm 0.8) \times 10^9\) cm s\(^{-1}\).

This means that by the moment of our spectral observations and approximately in a day after the last Swift/UVOT observation of the fading UV flash (the shock breakout), the shock velocity remained within the same limits. Furthermore, a wide and hardly noticeable depression in continuum (see Fig. 1 with observed wavelengths) at \( \approx 5900 - 6300\) Å, and an almost unnoticeable excess of flux within the wavelength range \( \approx 6300 - 6900\) Å is best fitted by a wide \( H\alpha \) PCyg profile (see Fig. 5) at the same velocity 33000 km s\(^{-1}\). In the SYNOW code this corresponds to “the undetached case” in Fig. 4.

It may be supposed that at this time a part of the stellar-wind envelope located over the photosphere or an extended layer over it moves together with the photosphere (the shock), and we observe acceleration or detachment of upper layers of this envelope. This is one more result (in \( \sim 2 \) days after the bright UV (UVOT) flash) of the shock breakout to “the surface” of the massive circumstellar envelope which was (almost) resting before the SN explosion. According to estimates given in Introduction, the size of this envelope was \( \sim 300 R_{\odot} \), at least at the moment of the shock breakout in \( \approx 11 \) hours after the event. To demonstrate that an almost unnoticeable oscillation of flux in Fig. 1 within the range \( \approx 5900 - 6900\) Å of the observed spectrum may be indeed a very wide \( H\alpha \) PCyg profile for velocities about 0.3x10\(^{10}\) cm s\(^{-1}\), in Fig. 5 we give a model spectrum with the classic PCyg profile, but for a much less velocity equal to 8000 km s\(^{-1}\). (The laboratory \( H\alpha \) wavelength is marked by a narrow emission of the host galaxy.)

We made fitting of this undetached case by
different synthetic spectra, but velocity of the photosphere \(V_{\text{phot}}\), all elements and their ions (vmine) was identical and equal to 33000 km s\(^{-1}\). Basic parameters of calculation are given in Table 2 for the “undetached case” in Fig. 5.

The only difference is in effective depths of ion line formation \(\tau\) (tau1), which can be chosen relatively small \((\tau < 0.5)\) for all elements and their ions, for the observed spectrum to be described satisfactorily. Within the wavelength range \(\approx 4500 - 7200\,\AA\) it is hydrogen that has the largest value \(\tau=0.2\). Other elements and their ions were taken into account in the synthetic spectrum with even smaller \(\tau\), which may reflect small variations in relative abundance of other elements in comparison with the most abundant one. This may be connected with the fact that in this first spectrum \((T_{sp}=2.55\text{ days})\) the contribution of the stellar-wind envelope is still determinant.

It should be said that we were trying to get the best agreement between the observed and synthetic spectra in their range where observations give the best signal/noise ratio and the theoretic spectrum is within the grass or in its nearest proximity. In particular, the outlining deficit of flux to the left of the emission line of the host galaxy \([\text{OII]}\,3727\,\AA\) (in Fig. 5) can be described by influence of CaII with \(\tau=0.5\). This is the largest values of the effective depth of formation that we used in this paper dedicated to interpretation of the earliest spectra of the XRF 060218/SN 2006aj afterglow.

In our second spectrum for \(T_{sp}=3.55\text{ days}\) (see Fig. 1 with observed wavelengths) we see some absorption at 6300\,\AA\ interpreted here as a strongly blue-shifted “remnant” of the \(H\alpha\) PCyg profile. The best fitting of the synthetic spectrum to the observed one corresponds to the case denoted as “the detached case” in Fig. 4 when a part of the wind envelope has already detached from the photosphere. I.e. contribution of the thermal burst (Fig. 2) is quickly decreasing and the shock is becoming more and more transparent — the photosphere phase of the SN envelope expansion begins (Branch et al. 2001).

We were modelling this second spectrum within the velocity range \(18000\,\text{km s}^{-1} < v < 24000\,\text{km s}^{-1}\) (see Fig. 4 of rest wavelengths with \(z=0\)). The synthetic spectrum which is the closest to the observed one is the spectrum with parameters of the model from Table 3, where the photosphere velocity is equal to 18000 km s\(^{-1}\), and its temperature is \(t_{bb} = 8200\,\text{K}\). In the synthetic spectrum we took into consideration the contribution of lines with small \(\tau(<0.3)\) of such elements as HI, HeI, FeII, SiII, OI, CaI, CaII, TiII, NI, CI, CII, MgI, MgII, NaI. Fig. 5 shows location of some of these lines in those spectral regions where the contribution of the ion into the spectrum is essential with given parameters of the model from Table 3. The list of lines used in the SYNOW code (“the reference lines”) is given in Elmhamdi et al. (2006), detailed information is given directly in the SYNOW code http://www.nhn.ou.edu/~parrent/synow.html.
A wide absorption with minimum near 6100 Å (Fig. 6) can be described by influence of HI for “the detached case” (Fig. 4) at $\tau = 0.16$. In this region ($\approx 5700 - 6500$ Å in Fig. 6) the synthetic spectrum is characterized by a smoothed emission from the red side and a strongly blue-shifted absorption with minimum near 6100 Å — “the remnant” of the $H\alpha$ PCyg profile of the line HI.

Thus, in $T_{sp} = 3.55$ days, hydrogen has already detached from the photosphere and the corresponding layer moves at a velocity of 24000 km s$^{-1}$ (see Table 3). Here also all ions were taken with the small values $\tau < 0.3$. But we failed to describe totally this observed spectrum with identical values of all other parameters, as was made in Table 2 (“the undetached case”). The layers where lines of other elements mainly form either move at the velocity identical to that of the photosphere ($18000$ km s$^{-1}$ for the lines of OI, CaI, CaII, TiII, Ni, NaI), or at the velocity of hydrogen ($24000$ km s$^{-1}$ for the lines of HI, HeI, FeII, SiII, CI, CII, MgI, MgII). For the best description of the observed spectrum, typical velocity values (the parameter $v_e$ in Table 3) determining the characteristic thickness of layers occupied by every element should also be chosen different. It may be assumed that this spectrum is already affected more by the chemical composition of the scattering SN envelope (or envelopes) which changed as a result of evolution and explosion of a far-evolving massive core of the progenitor star.

IV. DISCUSSION OF THE RESULTS

4.1 Evolution of spectrum of SN 2006aj and other core-collapse SNe.

A wide and low-contrast feature in the spectrum of the XRF060218/SN2006aj afterglow with minimum at $\approx 6100$ Å (in rest wavelengths) can be traced in all early spectra obtained with our and other telescopes starting from Feb 21.70 UT (see Table 1). The spectrum which is the closest in time (Feb 21.93 UT) to our second spectrum from Table 1 is the spectrum obtained with NOT (see Fig. 2 in Sollerman et al. 2006), which also contains minimum at the same wavelength $\approx 6100$ Å. The same feature is also seen in the ESO Lick spectrum obtained on Feb 22.159 UT, but its signal/noise ratio (it is the second spectrum in Fig. 1 in Mazzali et. al. 2006) is noticeably less than for two above-mentioned spectra. From data adduced in Fig. 1 in the paper Mazzali et. al. (2006) it is seen that this feature obviously evolves starting from the very first VLT spectrum and becomes the deepest in the spectrum obtained with VLT on Feb 23.026 UT, i.e. in about 5 days after XRF 060218. Later spectra obtained after minimum in the light curve (see our Fig. 2) are more and more affected by the increasing wide absorption related to SiII near 6000 Å, as was noted by Mazzali et. al. (2006). But the narrow minimum at 6100 Å is still seen even in the March’s VLT spectra. This is very similar to what is observed in spectra of some Type Ib SNe (Parrent et al.
2007), where the narrow absorption related to $H\alpha$ is also detected and evolves in the spectra obtained in the beginning of the long rise identical to that in our Fig.2 to the typical (of Type Ib and Ic SNe) maximum of brightness.

The start of evolution of the spectral feature at 6100Å which is then traced for XRF 060218/SN 2006aj in the data from other telescopes is also confirmed in our above-mentioned spectra. But we also include here the first BTA spectrum of Feb 20.70 interpreting the wide and almost unnoticeable depression of continuum within the range 5600−6600Å (5800−6800Å are observed wavelengths in Fig.1 for $T_{sp}$=2.55d) as the $H\alpha$ PCyg profile for velocities of 33000 km s$^{-1}$. The same small oscillation of continuum can be seen also in the very first VLT spectrum of Feb. 21.041 UT (see the same Fig. 1 in Mazzali et. al. 2006) obtained in 8 hours after our first spectrum. As to the MDM spectrum obtained in 14.5 hours before us (see Table 1), here also one can see a weak change of continuum at $\sim$ 5700Å which is noticeable even at the low signal/noise ratio (Mirabel et al. 2006). Here also the same very wide $H\alpha$ PCyg profile for velocities of $\sim$30000 km s$^{-1}$ is quite competitive to the identification suggested by these authors. Thus, taking into account all early observations from Table 1, it may be said that we do observe evolution of the optical spectrum — a transition from the phase of the Colgate shock breakout effect and the powerful (thermal) burst related to it to spectra of the phase of the SN brightness increasing which corresponds to radioactive (non-thermal) heating at the decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$.

Maybe, this is the main difference and novelty of our approach to interpretation of early spectra of XRF 060218/SN 2006aj to that represented in the paper by Mazzali et. al. (2006), where the VLT/Lick spectra of this SN were identified and where the question is only on theoretic spectra for the phase of radioactive heating — see the light curve (Fig. 2) in their paper. And when analyzing spectra of usual Type Ib-c SNe (“stripped-envelope SNe”), the authors of the SYNOW code (Branch et al. 2001, Branch et al. 2002, Baron et al. 2005, Elmhamdi et al. 2006) were calculating their synthetic spectra with traces of the $H\alpha$ line, but yet not for so early phases with a considerable contribution of the thermal radiation from the UV flare and so large expansion velocities which were observed for XRF 060218/SN 2006aj.

The evolution of all 16 ESO Lick and ESO VLT spectra of SN2006aj (Pian et. al. 2006) was modeled up to March 10, 2006 (20 days after XRF 020618) in the fore-quoted paper by Mazzali et al. (2006) with the help of a more sophisticated code of synthesis of SN spectra by the Monte Carlo method based under the same assumptions as the SYNOW code, but with consideration of model distributions of density and temperature in the envelope over the photosphere, radiation transfer in terms of transitions in lines and electronic scattering (details of
the method are expounded in the papers Mazzali and Lucy (1993), Lucy (1999), Branch et al. (2003). All typical signs of Type Ic SNe increases in spectra before the wide maximum in the SN 2006aj light curves ($\approx$10 days after GRB in Fig. 2) and after it. The spectra were modeled for the velocity range $20000 \text{ km s}^{-1} < v < 30000 \text{ km s}^{-1}$. The strongest features mentioned by the authors are the lines of FeII, TiII, and at later phases — CaII ($< 4500\text{Å}$), FeIII FeII (near $5000\text{Å}$), SiII (near $6000\text{Å}$), OI (near $7500\text{Å}$) and CaII (near $8000\text{Å}$).

We also took into consideration all this list of lines when interpreting our early spectra with the SYNOW code (see Fig. for almost identical range of velocities, but we also included contributions of the HI HeI lines. From calculations adduced in Mazzali et al. (2006) it is seen that in the very early spectra of Feb 21, Feb 22, Feb 23 the authors did not take into consideration obvious traces of the $H\alpha$ line, and in later spectra only the increasing influence of SiII near $6000\text{Å}$ was considered — see Fig. 1 in Mazzali et al. (2006) and the caption to it. At the same time, as was mentioned above, the absorption with minimum at $\approx 6100\text{Å}$ can be traced in the observed spectra up to March, 4. It is the most noticeable feature near $6000\text{Å}$ in the early spectrum of Feb.23 in the whole range from $\sim 5000\text{Å}$ to $\sim 8500\text{Å}$, where the Monte Carlo method does not fix any absorption at $\approx 6100\text{Å}$.

4.2 The signs of hydrogen in core-collapse SNe spectra.

The signs of hydrogen in spectra of Type Ib and Ic (Ib-c) SNe are no news. In particular, the signs of hydrogen and evolution of the blueshifted $H\alpha$ line were already found with the help of the same SYNOW code in the analysis of a time series of optical spectra for usual core-collapse Type Ic and Ib SNe. In this analysis, special attention addressed to traces of hydrogen in observations of especially these stripped-envelope Type Ib-c SNe. Though, by (formal) definition, the Type Ic and Ib supernovae does not have conspicuous lines of hydrogen in its optical spectra. The Ib-c SNe are usually modelled in terms of the gravitational collapse of massive and bare carbon-oxygen cores which stripped envelope before collapse, and, apparently, signs of this envelope must be present always in spectra of these SNe as hydrogen lines. Though most often hydrogen can be identified more or less reliably only in sufficiently early spectra of Ib-c SNe, as was shown in Branch et al. 2002, Baron et. al. 2005, Branch et al. 2006, Elmhamdi et al. 2006, Parrent et al. 2007.

A competitive hypothesis for description of the spectral feature with minimum near $6100\text{Å}$ may be its interpretation as an absorption component of the PCyg profile of the line CII 6580Å (Branch et al. 2006). But if the whole extended ($>/\sim 300 R_\odot$) stellar-wind envelope was seen at first in X-rays and subsequently as a UV flare in the XRF 060218/SN 2006aj afterglow, then it is hydrogen that should be connected at least to that part of the relic envelope which did not
evolve and refers to the stellar-wind stage of evolution of the core-collapse progenitor star, and which originated long before the SN explosion. The fact that it is hydrogen that always shows the largest contrast of velocity between the HI layer and the photosphere in comparison with other elements in spectra of Type Ib-c core-collapse or “stripped-envelope” SNe (Branch et al. 2002 (see Fig. 23), Branch et al. 2001 (Fig. 9), Elmhamdi et al. 2006 (see Fig. 5)) also is in favour of the idea that it is these layers related to the wind envelope that are the first to come into motion as a result of SN explosion. One can estimate also the mass of this moving part of the envelope (the mass of gas in the $H\alpha$ or HI layer) with the help of the equation from the paper Elmhamdi et al. (2006) in the following way:

$$M(M_\odot) \simeq (2.38 \times 10^{-5})v_4^3t_d^2\tau(H\alpha)$$

where time after the explosion $t_d$ is in days, the velocity of layer $v_4$ is in units of $10^4$ km s$^{-1}$, and $\tau(H\alpha)$ is the depth of line formation. In this equation deduced for the Sobolev optical depth in the expanding envelope (Castor 1970; Elmhamdi et al. 2006), we used the velocity 24000 km s$^{-1}$ which refers only to that part of the HI layer which came into motion (see data in Table 3). This corresponds to the detached case in Fig. 4. As a result, the mass of the HI layer turns out to be $\sim 0.0006M_\odot$, and its distance to the center by this time — 3.55 days after the beginning of the SN explosion — is in any case not less than $7.36 \times 10^{14}$ cm.

### 4.3 The Colgate shock-breakout effect in XRF 060218/SN 2006aj and in other SNe — light curves, spectra, luminosities and sizes.

The Type Ib and Ic SNe have long been observed, it is has already long been considered that their progenitors are most probably the WR stars surrounded by more or less dense wind envelope which resulted from evolution of a core-collapse star. The shock arising in explosion of evolved star core passes through the envelope and leads to a bright and short X-ray and UV flash which can last several hours — duration of the flare depends on how massive and extended was the wind envelope surrounding the progenitor star before the SN explosion. Interaction between the shock caused by the SN explosion and the envelope (the shock breakout effect) has also been predicted and comprehended long ago (Colgate 1968, Bisnovatyi-Kogan et al. 1975, Blinnikov et al., 2002). In particular, the paper by Calzavara and Matzner (2004) is dedicated to future systematic observations of this effect. But so far, before the event XRF 060218/SN 2006aj, observations of the almost total effect has been gained for only small amount of the core-collapse SNe.

The shock breakout effect which was very short due to the compactness of the blue supergiant ($20-30R_\odot$) was observed (though not from the very beginning) in the famous Type II SN 1987A: there are quite a few data and the physics is described rather well — see the large
review by Imshennik and Nadezhin (1988). During a long time (2-3 weeks), one could observe the shock breakout effect in a very extended ($\sim 10^{15}$ cm) envelope of Type II In SN 1994W (see, for example, in Chugai et al. (2004)). In other cases of the Type Ib-c SNe the shock breakout effect was observed only in its very ending, before the subsequent increasing of the SN brightness corresponding to the radioactive heating $^{56}$Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe — for SN 1999ex, Stritzinger et al. (2002). Identical “remnants” of the shock breakout effect were seen (in the R band) even in SN 1998bw, which is usually related to GRB 980425 (see Galama et al., 1998).

**SN 1993J in M81:** It can be said that SN 1993J was observed almost in the very beginning of explosion. “Almost” because in this case the moment of the SN explosion beginning is known with an accuracy of $\pm 12$ hours, but not to seconds as in XRF/GRB SNe. Initially, this SN was classified by spectrum as the Type II SN because of appearance of hydrogen lines in its early spectra (Fig. 7), but after a time, the SN type changed to Ib (Flippenko, Matheson and Ho, 1993), when hydrogen in spectra stopped being detected reliably. Early spectra of SN 1993J in Fig. 7 show a strong UV excess typical of the shock breakout effect and a smoothed continuum almost without lines above 5000 Å, similar to the spectrum of XRF 060218/SN 2006aj in Fig. 5 though in the case of SN 2006aj the expansion velocities are much higher (see below the remarks about possible asymmetry of explosion of SNe identified with GRBs). Besides, SN 1993J had an unusual light curve, when luminosity quickly increased to the first maximum and then headily fell during several days and then is has been slowly increasing for the second time during the subsequent two weeks. The behavior is analogous to that shown in Fig. 2 for XRF 060218/SN 2006aj. The SN 1993J light curve has been long and well modeled by many groups: Nomoto et al. (1993), Young et al. (1995), Shigeyama et al. (1994). These papers say that the shock breakout in SN 1993J is naturally explained by interaction between the shock and the extended ($300R_\odot \simeq 2.1 \cdot 10^{13}$ cm) hydrogen envelope of mass $\sim 1M_\odot$ around the progenitor star. Here the luminosity achieved in the peak of the first/quick maximum which lasts only 4-5 hours can achieve a value of $\sim 10^{45}$ erg/s with the total photon energy release $\simeq 5 \cdot 10^{49}$ erg.

No wonder that approximately identical parameters of the envelope explain the shock breakout burst in the case of XRF/GRB 060218/SN 2006aj. Here also the total energy turns out to be of the same order of $\sim 10^{49}$ erg. But in the case of SN 1993J there was no gamma-ray burst, and, most probably, this is caused by asymmetry of the SN explosion (see below about that).

If GRB/XRF 060218/SN 2006aj is another case when the Colgate shock breakout effect was observed in pure form *from the very beginning* of the SN explosion, then it may be understood
as quite a definite hint that the GRB itself is the first signal in gamma-rays that the collapse of a massive core started, which is followed by the total process — an anti-collapse and explosion of a massive SN: after the GRB an X-ray flash (XRF) and then a powerful UV flash can be observed. Then the key moment in optical observations of transient sources related to XRF/GRBs can be the search for all manifestations of wind envelopes around core-collapse progenitor stars in early spectra and in photometry of the XRF/GRB afterglows, because interaction of the SN shock and these envelopes is the very first event in optical after the beginning of collapse of the massive stellar core. Here one may expect observing new effects related, for example, to the same asymmetry of explosion.

4.4 Asymmetry of the Type Ib and Ic SNe explosions.

The burst XRF 060218/SN 2006aj was a classical XRF event indeed (Heise et al. 2001, Campana et al., 2006). The fact that in the case of usual and nearby SNe the explosion does not begin with a GRB is naturally explained by an asymmetric, axial-symmetric or bipolar (with formation of jets) explosion of the core-collapse SNe. Now one of the most popular conceptions (see references in the paper by Soderberg et al., 2005) proceeds from the idea that in the case of flashes of the XRF type an observer is out of the beam in which the most gamma-ray radiation is concentrated for one reason or another.

The farther is an observer from the SN explosion axis, the more of X-ray radiation and the less gamma-ray quanta are in the spectrum of the flash — GRBs transform to X-ray Rich GRBs (like GRB 030329) and become X-ray Flashes (Sokolov et al. 2006). When observing at an angle close to 90° to the SN explosion axis, no GRB is seen; one observes only an XRF (X-ray Flash) and then a powerful UV flash caused by interaction in the shock and the envelope surrounding the pre-SN as was in the case of SN 1993J.

Thus, if an SN is observed close to the explosion equator (and this situation is the most probable) and if there is a sufficiently dense stellar-wind envelope around a massive collapsing star core, then only the shock breakout effect is to be observed in X-rays and in optical. In that case the contribution of GRB afterglow into a light curve of a “usual” SN can be unnoticeable. One way or another, but it must be much less than for classical GRBs observed close to the SN explosion axis (the least probable situation). In this connection, Filippenko et al. (2006) noted recently that a substantially asymmetric explosion can be a genetic feature of core-collapse SNe of all types, though it is not clear yet if the mechanism generating the GRB is also responsible for the star explosion.

V. CONCLUSION

The paper gives additional arguments in favor of the stellar-wind origin of the shock
breakout effect detected previously from Swift/XRT/UVOT data (Campana et al., 2006) on XRF/GRB 060218. In our optical spectra of the XRF/GRB 060218 afterglow we detected features interpreted as hydrogen lines which were also observed in early ESO Lick, ESO VLT and NOT spectra (Pian et al. 2006, Sollerman et al. 2006). Hydrogen was detected in spectra of a GRB afterglow for the first time, which is a direct sign of a relic wind envelope around a core-collapse progenitor star.

Results of modelling two BTA spectra obtained in 2.55 and 3.55 days after explosion of SN 2006aj related to the X-ray flash XRF/GRB 060218 are represented. The spectra were modeled in the Sobolev approximation with the help of the SYNOW code (Branch et al. 2001; Elmhamdi et al. 2006). In these early spectra of the Type Ic SN 2006aj we detected spectral features interpreted as:

1. the $H\alpha$ PCyg profile for velocities of $\sim 33000 \text{ km s}^{-1}$ — a wide and almost unnoticeable deformation of continuum in the range of $\approx 5600 - 6600 \text{ Å}$ for rest wavelengths ($z=0$) at the first epoch (2.55 days), and

2. a part of the $H\alpha$ PCyg profile in absorption blueshifted by $24000 \text{ km s}^{-1}$ — a wide and low-contrast spectral feature at $\approx 6100 \text{ Å}$ (rest wavelength) at the second epoch (3.55 days).

Evolution of the same spectral features can be traces also by spectra of SN 2006aj obtained with other telescopes (Pian et al. 2006, Sollerman et al. 2006). Such $H\alpha$ lines can directly confirm the existence of a stellar-wind envelope which was already observed during XRF/GRB 060218 itself as a powerful black-body component first in X-rays and then in the optical spectrum — the so-called shock breakout effect (Campana et al., 2006). Thus, taking into account early observations carried out with BTA and other telescopes (Table 1), it may be said that we observe evolution of optical spectra of the core-collapse SN 2006aj — a transition from the phase of the Colgate shock breakout effect to spectra of the phase of brightness increase corresponding to the radioactive heating.

Our identification of these features with the $H\alpha$ hydrogen line in early spectra of the Type Ic SN 2006aj was also confirmed by spectral observations of usual (non-identified with GRBs) Type Ic and Ib core-collapse SNe and interpretation of their spectra (in which hydrogen was also found) with the SYNOW code (Branch et al. 2002; Branch et al. 2006; Elmhamdi et al. 2006).

If interpretation of the thermal component in the spectrum of GRB/XRF 060218 as interaction between the SN shock and the wind envelope around the SN 2006aj/XRF 060218 progenitor star will be confirmed by observations of afterglow of other bursts, then it will give a new impulse to development of the theory of GRBs themselves and of the core-collapse SNe. The intermediate redshift GRB/SNe are observed relatively rarely (Chapman et al. 2007), but they are the most informative
events (such as XRF/GRB 060218/SN 2006aj or GRB 030329/SN 2003dh) from the point of view of comprehension of relation between GRBs and SNe. And the key moment of the study of these transient sources may be the search for manifestations of wind envelopes around core-collapse progenitor stars of GRBs both in early spectra and in the photometry of GRB afterglows.

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TABLE I: Early spectra of the supernova XRF 060218/SN 2006aj obtained before Feb. 23 2006 UT with different telescopes. The spectrum time is time after XRF/GRB 060218 *Swift* trigger: $T_{sp}$ is in days after 2006 Feb. 18.149 UT. Only spectra with a high signal/noise ratio are given. Early spectra obtained by Modjaz et al. (2006) with the 1.5-meter telescope FLWO in 3.97 days after the burst were not included because of their low signal/noise ratio.

| Telescope | $T_{sp}$ and 2006 UT | References |
|-----------|---------------------|------------|
| MDM (2.4m) | 1.95 days (Feb.20.097) | Mirabal et al. 2006 |
| BTA (6m) | 2.55 days (Feb.20.70) | Fatkhullin et al. 2006 |
| ESO VLT (8m) | 2.89 days (Feb.21.041) | Pian et al. 2006 |
| BTA (6m) | 3.55 days (Feb.21.70) | Fatkhullin et al. 2006 |
| NOT (2.56m) | 3.78 days (Feb.21.93) | Sollerman et al. 2006 |
| ESO Lick (3m) | 4.01 days (Feb. 22.159) | Pian et al. 2006 |
| ESO VLT (8m) | 4.876 days (Feb. 23.026) | Pian et al. 2006 |

FIG. 1: Observational spectra of the XRF 060218/SN 2006aj afterglow obtained with the BTA (Fatkhullin et al. 2006). UT times and observational times after the beginning of the SN explosion are indicated. Emission lines of the host galaxy ($z=0.0331$) are also shown.
FIG. 2: Optical (U, B, V, R, I) and infrared (J) light curves of XRF 060218/SN 2006aj (Jelinek et al. 2007). The first maximum corresponds to the UV flash/burst — the shock breakout effect (see the text). Spectra from Table 1 refer to the transitional region near minimum of the curves. Arrows point times of BTA spectra after the beginning of SN explosion. $T_o$(days) corresponds to 2006 Feb. 18.149 UT.
FIG. 3: Field of the optical transient. BTA optical observations started on Feb. 20.647, 2006 UT (≈ 60 hours after the GRB event) P.A. = 3° is a position angle of slit, $V_{OT} = 18.16$, $(B - R)_{OT} = 0.3$

FIG. 4: Line profiles corresponding to the cases when envelope layers (i.e. layers over the photosphere) detach or do not detach from the expanding photosphere, when the gas expansion velocity increases proportionally to distance to the center ($v \sim r$, see the text).

The shaded regions form the absorption component of the PCyg profile.
TABLE II: The table of model computation parameters in the case of layers undetached from the photosphere for all elements and their ions (“the undetached case” in Fig.4). The parameters correspond to the synthetic spectrum represented by the thick black line in Fig.5 (see the text). More detailed information about setting parameters for the SYNOW code see in

http://www.nhn.ou.edu/~parrent/synow.html

| Parameters | “the undetached case” |
|------------|----------------------|
| $V_{\text{phot}}$ $^a$ | 33000 |
| $V_{\text{max}}$ $^b$ | 70000 |
| $t_{\text{bb}}$ $^c$ | 9000 |
| ai $^d$ | H I, He I, Fe III, Fe II, Si II, Si I, O I, Ca II, Ti II, CII, CI, NI, MgII, MgI, MnII, NeI |
| tau1 $^e$ | .2, .08, .04, .0002, .0002, .002, .02, .0005, .005, .1, .0002, .0002, .0002, .0005 |
| vmin $^f$ | 33.00 for all ions |
| ve $^g$ | 20.00 for all ions |

$^a$ $V_{\text{phot}}$ is velocity of the photosphere in km/s.
$^b$ $V_{\text{max}}$ is the upper limit of velocities in the model.
$^c$ $t_{\text{bb}}$ is temperature of the photosphere in Kelvin degrees.
$^d$ ai are ionization stages of all ions considered in the model.
$^e$ tau1 are corresponding optical depths of line formation of every ion.
$^f$ vmin are the least velocities over the photosphere for every ion (in 1000 km s$^{-1}$)
$^g$ ve are the characteristic velocities ($v_e$) in the used law $\tau(r) \sim \exp(-v(r)/v_e)$ of relation between optical depth of lines of a given ion $\tau$ and $v$, where $v \sim r$. 
FIG. 5: The spectrum of the XRF/GRB060218/SN2006aj afterglow in rest wavelengths (z=0) obtained with BTA in 2.55 days and corrected for galactic extinction. Its fitting for “the undetached case” by synthetic spectra with the velocity of the photosphere (\(V_{\text{phot}}\)), all elements and their ions equal to 33000 km s\(^{-1}\) is shown by smooth lines differing only in the blue range of the spectrum at \(\lambda < 4000\) Å (see the text). Main parameters of calculation of the synthetic spectrum represented by the thick black line are given in Table II. HI denotes the \(H\alpha\) PCyg profile at \(V_{\text{phot}} = 33000\) km s\(^{-1}\). The model spectrum for the photosphere velocity 8000 km s\(^{-1}\) is shown for example by the dashed line as an example of the \(H\alpha\) PCyg profile.
TABLE III: Parameters of the SYNOW model for the case of layers of some elements undetached from the photosphere in the expanding SN envelope ("the detached case" in Fig. 4). The parameters correspond to one of the synthetic spectra shown in Fig. 4 by the thick black line (see the text).

| Parameters | “the detached case” |
|------------|---------------------|
| \(V_{phot}\) | 18000 |
| \(V_{max}\) | 75000 |
| \(t_{bb}\) | 8200 |
| \(a_{i}\) | HI, HeI, FeII, SiII, OI, CaI, CaII, TiII, CII, CI, NI, MgII, MgI, NaI |
| \(\tau_{1}\) | 0.16, 0.02, 0.08, 0.1, 0.3, 0.3, 0.02, 0.0004, 0.04, 0.100, 0.005, 0.03, 0.02 |
| \(v_{mine}\) | 24.00, 24.00, 24.00, 24.00, 18.00, 18.00, 18.0, 18.00, 24.0, 24.0, 18.0, 24.0, 24.0, 24.0, 18.00 |
| \(v_{e}\) | 10.00, 20.00, 20.00, 20.00, 20.00, 10.00, 10.0, 20.00, 10.0, 10.0, 20.0, 20.0, 20.0, 20.0, 20.00 |
FIG. 6: The spectrum of SN2006aj/XRF060218 (rest wavelength at z=0) obtained with BTA in 3.55 days and corrected for galactic extinction. Synthetic spectra are shown by smooth lines. Locations of spectral lines of some ions and blends of their lines are shown in those parts of the spectrum where contribution of this ion into the spectrum is essential for given model parameters. The thick black line is the synthetic spectrum with parameters from Table III at which the absorption with minimum about 610Å is described by suppressing influence of HI for “the detached case”. This is a strongly blue-shifted part of the Hα PCyg profile at the velocity of expansion of the detached HI layer equal to 24000 km s$^{-1}$. 

The CaII, TiII, FeII, HeI, SiII, CII, HI, OI, and Ni CI lines are indicated.
FIG. 7: The earliest optical spectrum of SN 1993J (see the text). The spectrum is taken from the database SUSPECT - The Online Supernova Spectrum Database [http://bruford.nhm.ou.edu/suspect/] (Richardson et. al. 2002)

Early spectra showed an almost featureless continuum, with broad, but weak $H_{\alpha}$ and He I $\lambda$ 5876 lines.

1993-03-31
UT 20:30:00