The core collapse supernovae, gamma-ray bursts and SN 1987A

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Abstract If all long gamma-ray bursts (GRBs) are related to supernovae core-collapse supernovae (SNe) explosions indeed, then a long GRB is the collapse of a massive star core or the beginning of an axially symmetric explosion of SN, and the long GRBs must always be accompanied by an SN explosion (of Ib/c type or other types of core-collapse SNe). Then the total energy release of a burst source in gamma rays is in any case not higher that the total electromagnetic energy radiated by the SN (< or ~ 10^{49} erg). Within the context of the model of asymmetric explosion of such SNe it is discussed when the relation GRB-SN is observed and when it is not observed. The accumulated statistics of GRB + SN coincidences will confirm the GRB compact model more and more. And we tell about the study of GRBs in SAO RAS, about optical identification of the first ten of GRBs.

Keywords: Afterglows, Localization, Supernovae, Asymmetric explosions, Collapse, Quark stars, Cosmology

1. Introduction

Gamma-ray bursts (GRBs) discovered in 1967 by *VELA* spacecraft, are the most violent explosions in the universe [1,2]. It can be divided into two groups, short (~ 0.2s, 25%) GRBs and long (~/> 30s, 75%) GRBs, with a separation at about 2 seconds [3]. The counterparts for all GRBs can be observed in all wavelengths (X, UV, opt, IR, radio), + gravitational waves (GWs) and neutrino (may be).

Detected as brief (0.01−100 s), intense flashes of γ–rays (mostly sub–MeV), GRBs are the brightest electromagnetic explosions in the Universe. The power emitted by GRBs in electromagnetic form can reach luminosities up to $L \sim 10^{52} - 10^{53}$ erg s^{-1}, while active galactic nuclei (AGNs) can have $L \sim 10^{48}$ erg s^{-1} (but for long times), and supernovae (SNe) can have $L \sim 10^{45}$ erg s^{-1} *for the first hundreds of seconds after the explosion*. And the short variability timescales of the γ−ray emission suggest already very small dimensions for the sources, of the order of tens of kilometers, typical of massive compact stellar objects…

Below we tell about the study of GRBs in SAO RAS, about optical identification of the first ten of GRBs and the study of pulsars in the localization areas of the “old” GRB 790418 and GRB 790613. The deepest images of localizations areas of these bright *short* GRBs were first obtained by us with the 6m BTA telescope in 1994. At that time this was the first optical study with a large telescope up to the limit ~25 st.magn. In both cases, faint blue stellar-like objects (with V about 24.5m, and B – V < 0m) were detected in localization areas. Then, in 1994, from the observed brightness and color it was supposed that these can be compact objects of type of neutron stars in our Galaxy with a surface temperature of about 100000 K, located at a distance of about 40 pc.

In those times (before 1997) the prevailing concept of GRB sources was that they are compact objects of NS type (see "Physics of Space, small encyclopedia", pp.206-209 [4]). Then we dedicated a lot of time to the study of our nearest neutron pulsar-stars also, though the galactic origin of GRBs was not confirmed afterwards. But we managed to obtain necessary experience both in observations and processing of data for faint (sometimes extremely faint) objects related to GRBs. Then, at last, the era of optical identification of new GRBs started – the *BeppoSAX* era (it seems that now the same is occurring with electromagnetic identification of sources of gravitational waves (GW) related to short GRBs, see in detail in Section 8).

So, the main ideas of this review paper are as follows:

1) Long GRBs are explosions of massive SNe; light curves of these SNe (SN1987a as a standard) and GRB afterglows are very similar (collected in this review); the model of SNe and GRBs-SNe is an asymmetric explosion and collapse of a massive core; what is the remnant?
2) Short GRBs, merging of compact objects, the problem of identification of GWs [5].
3) GRBs and superluminous SNe, also known as a hypernovae, is a type of stellar explosion with luminosity of 10 or more times higher than that of standard SN (https://en.wikipedia.org/wiki/Superluminous_supernova) – these hypernovae can produce long GRBs (which range from 2 seconds to over a minute in duration).
4) Identification of neutrino and gravitational events related to SNe in the model of asymmetric explosion of SNe, quark stars.

We would like to draw attention to the review [7] addressing to close topics and presenting a large comprehensive catalogue of 70 GRBs with multi-wavelength optical transient data on which a systematic study was performed to find the temporal evolution of color indices. In this review a special study was dedicated to the late GRB-SN bump in GRB afterglow light curves for GRBs related to SNe. See also the review [50].

2. GRBs and their localization

Now GRBs are considered as new cosmological beacons:

1) Long GRBs are the brightest electromagnetic explosions in the Universe, associated to the death of massive stars.
2) GRBs are potential tracers of the evolution of the cosmic massive star formation history (SFH), metallicity, etc.
3) GRBs also proved to be appealing cosmological distance indicators. This is a unique opportunity to constrain the Universe history to redshifts ~ 10 and may be more... The idea prevailing currently is shown in Fig1a.

We specially draw attention to the fact that what is presented in Fig.1b is not evolution of GRBs. The shaded region approximates an *effective threshold* for detection. Only! Demarcated are the GRB subsamples used to estimate the SFR. Because weak low-redshift GRBs cannot be seen at high redshifts, so we can only use *high luminosity GRBs*. (The same is said in Section 7 and in discussion of observed asymmetric explosions of SNe associated with GRBs.)

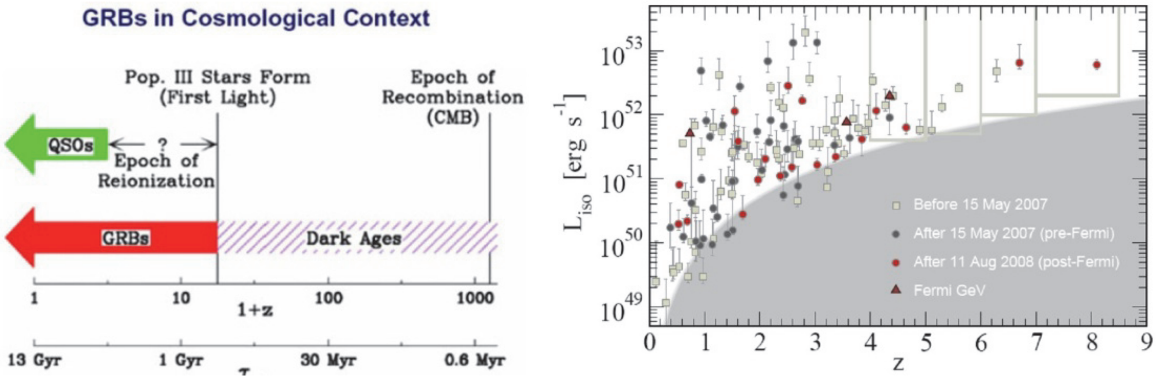


***Fig1**. **a)** GRBs in cosmological context, **b)** from [6] — The L_{iso} luminosity-redshift distribution of 119 Swift GRBs. Squares represent the 63 GRBs used in Y¨uksel et al. (2008), with 56 found subsequently: before (grey circles) and after (red circles) the start of Fermi. Three Fermi-LAT GeV bursts (triangles) are shown (but not used in our analysis).*

On localization of GRB sources: The search and localization of the counterparts for GRBs in all wavelengths (X, UV, opt, IR, radio) started since the launch of the *Swift* satellite more than ten years ago (see in [8]), with many ground-based optical telescopes with increasing sensitivity have accumulated a rich collection of optical afterglows. This international experiment (which still goes on) for detection and localization of GRBs is shown in Fig1a. The Gamma-ray burst Coordinates Network (GCN) was created especially for that. The GCN is a system that distributes information about the location of a GRB, called notices, when a burst is detected by various spacecraft. (This experience is now used in electromagnetic identification of GW sources.)

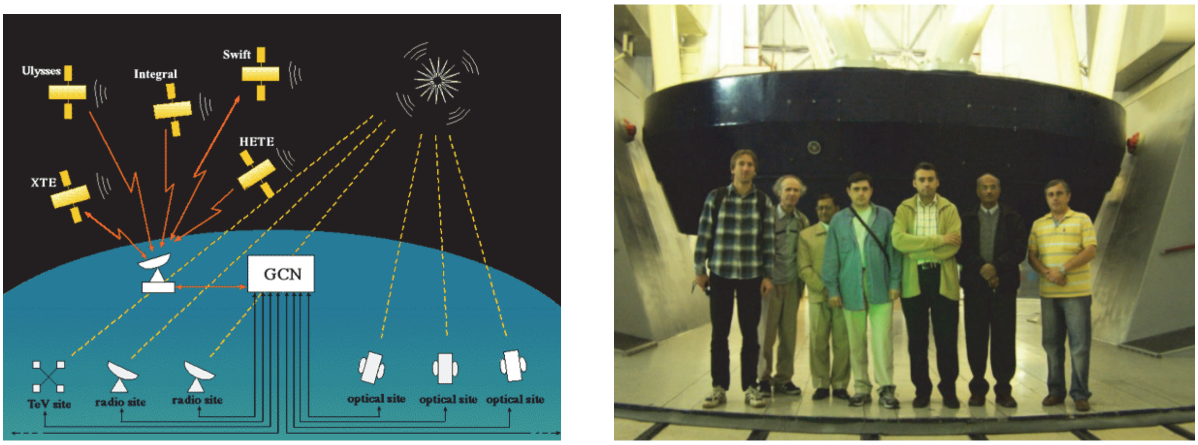


***Fig2. a)** Localization of GRBs in all accessible ranges. **b)** Participants of our international team for optical identification of RBs near BTA at the international workshop in SAO on July 11, 2006. From left to right: Petr Kubanek (Czechia, Prague, Observatory), V.V.Sokolov (SAO RAS), Ballabh Sanwal (India, Nainital, Manora Peak, ARIES), Alexander Bogdanov(Ukraine, Nikolaev Astronomical Observatory), Alberto Castro-Tirado (Instituto de Astrofisica de Andalucia, Granada, Spain), Ram Sagar (India, Nainital, Manora Peak, ARIES), Sergei Guzij(Ukraine, Nikolaev Astronomical Observatory)*

3. Optical identification of the GRBs in SAO RAS from 1997

On identification of gamma-ray burst in SAO, the optical identification of the first ten GRBs: from 1997, at last, the era of optical identification of new GRBs started – the *BeppoSAX* era [8]. Our BTA observations were continued in collaboration with other teams. Participants of joint observational programs met at international workshops in 2006 ("GRB mini-workshop 2006" on 9 - 11 July 2006, www.sao.ru/hq/grb/workshop/index.html, see Fig2b), the workshop in 2009 [9] and in 2011 at the Indo-Russian workshop "Gamma-Ray Bursts, Evolution of Massive Stars and Star Formation at High Red Shifts" in India [10].

In SAO the optical identification of the first ten started with GRB 970508 – the second GRB detected by *BeppoSAX*. In 1997 our BTA observations simultaneously in 5 photometric bands (*UBVRcIc*) resulted in the most detailed (at that time) light curve of an optical stellar-like source corresponding to a GRB of May 5, 1997 (GRB 970508) registered with the space satellite *BeppoSAX*, which made a breakthrough in the problem of identification existing from the moment of registration of first bursts in 1965. Now, more than 200 gamma-ray bursts have been identified already (see [7] and references therein).

In February 1997, the Dutch-Italian satellite *BeppoSAX* was able to trace GRB 970508 to a faint galaxy roughly 6 billion light years away [11]. From analyzing the spectroscopic data for both the burst and the galaxy, Bloom et al. concluded that a hypernova was the likely cause.

So, GRB-afterglow observations for long GRBs led to the discovery of the first optical afterglows [12] (see also [50]). Finally, this GRB 970508 at z = 0.8349 turned out to be a source of cosmological origin. In the maximum brightness of a variable optical object corresponding to GRB 970508 and after the maximum, the slope of continuum spectrum was measured with BTA. The change of object colors was traced up to the 200th day after GRB. Now this GRB 970508 is at the beginning of the above-mentioned new Large Catalogue of Multi-wavelength GRB Afterglows [7], or the sample of 70 GRBs with *multi-wavelength* optical transient data (see Table 1 in [7], "Properties of the GRB Sample with Multi-color Light Curves" and references therein).

During our multi-wavelength observations of the GRB 970508 optical transient the brightness weakening rate and color indexes were changing. Beside the temporal evolution

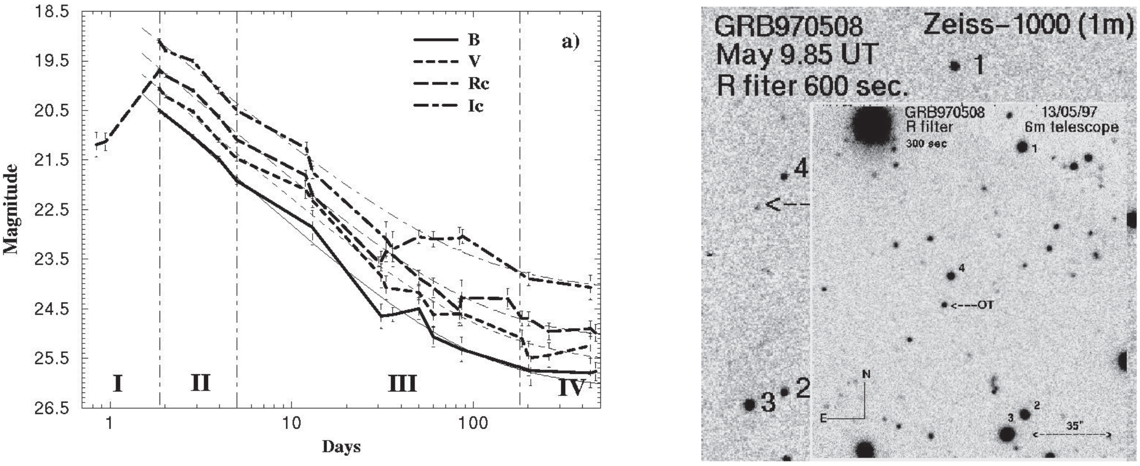


Fig3. a) *The combined light curve of the source GRB 970508 in the B, V, Rc, Ic bands obtained from data of the 1-m telescope Zeiss-1000 and the BTA telescope.* ***b)*** *Images of optical afterglow of the gamma-ray burst GRB 970508 obtained with the 1-meter telescope Zeiss-1000 at the moment of discovery and with the BTA telescope 5 days later (in the inset). Both images were obtained in the Rc band [13].*

of color indices, we noticed (with BTA) the effect of sharp slowdown of brightness weakening in infrared (~8000Å) in 36 days after the burst – the late GRB-SN bump (see below on the rebrightening effect). These new facts affected considerably the then-formed notions of the physical nature of GRBs.

The host galaxy of this GRB (an object of ~25 st.magn.) and other galaxies in the field of this GRB were also studied with BTA later. GRB 970508 was the second gamma-ray burst identified in optical, in observations of which SAO actively participated in collaboration with observers from other observatories and with the team of the famous specialized satellite *BeppoSAX*. The reddening of the optical transient (OT) of GRB 970508 in several weeks after the burst (as later in 7 other GRB OTs with z<1) was interpreted by us as the effect *directly confirming the relation between long GRBs and evolution of massive stars and SNe explosions.*

The next ***Fig3*** presents results of joint photometry of this transient source fulfilled at both telescopes: the brightest phase was studied at the 1-m telescope; the fainter stages were accessible, naturally, only for BTA [13]. Light curves of the optical transient of GRB 970508 in B, V, Rc and Ic bands were taken from [13]. The light curve (with a peak at about 2 days and slowdown in ~40 days) was observed in the R band by Garcia et al. [14] also.

So, from our data of ~40 days after the GRB, the flattening in Ic band (see in ***Fig3***) in late-time GRB 970508 optical afterglow (z = 0.835) was first detected, and then the host galaxy was also studied (see ***Fig4***).

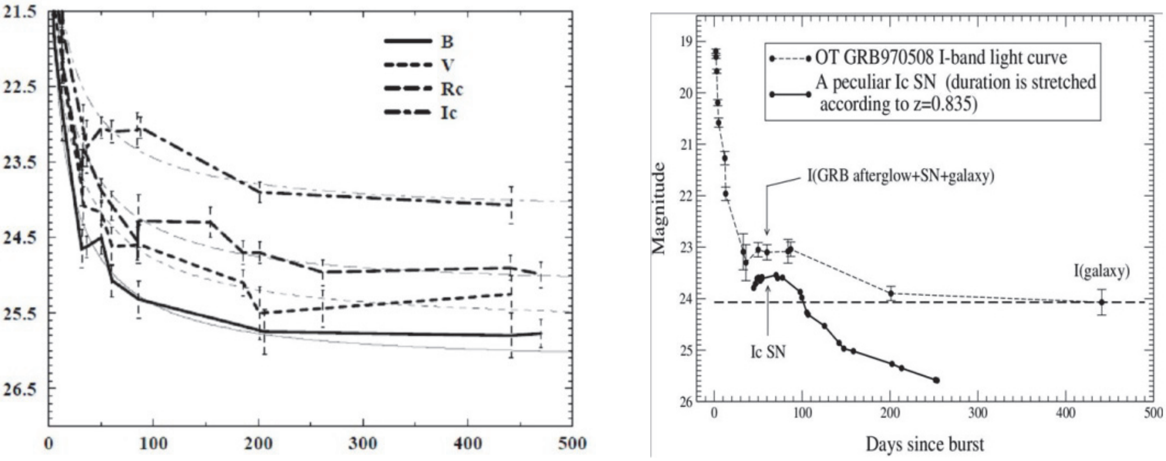


Fig 4. a) *The recent BVR_cI_c light-curve behavior of the OT + host galaxy of GRB 970508 up to ~470 days from the time of the GRB. Four independent BVR_cI_c power-law fits ($F = F_0 \times t^{\alpha} + F_c$, see Table 2) with different α are indicated by the thin lines.* ***b)*** *For comparison, the light curve of the Type Ic SN is shown.*

On the relation with CCSNe: Is the Type Ic core-collapse SN (CCSNe) in the light curve of the optical transient of GRB970508? ***Fig4b*** (without the very first point from ***Fig3a***) shows a typical light curve of such a CCSN. Thus, nonmonotonicities of type of the second burst (rebrightening) of GRB 970508 OT in 30-40 days after the GRB can be a direct consequence of the evolution scenario for a GRB source: “a massive star → a Wolf-Rayet star → a pre-supernova = a pre-GRB → GRB and explosion of a type Ib/c supernova”.

So, in February 1997, the Dutch-Italian satellite *BeppoSAX* was able to trace GRB 970508 to a faint galaxy roughly 6 billion light years away [15]. (See the last points in Figs4.) From analyzing the spectroscopic data for both the burst and the galaxy, Bloom et al. concluded that a hypernova was the likely cause.

4. GRBs & core-collapse SNe, on the rebrightening effect, the late GRB-SN bump, SN 1998bw and GRB 030329

The first hypernova observed was SN 1998bw, with a luminosity 100 times higher than a standard Type Ib [16]. But the first confirmed superluminous SN connected to GRB wasn't found until 2003, when GRB 030329 illuminated the Leo constellation [17].

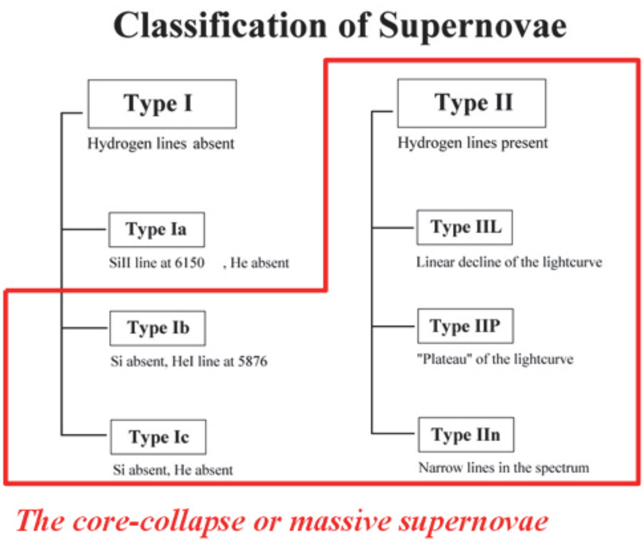


Fig 5. *SNe are the most violent explosions at the end of the star's life, and SNe are classified according to their spectra and light curve.*

Fig5 shows the Classification of SNe. Today, it is believed that stars with $M \geq 40M_\odot$ produce superluminous SNe [18]. *The core-collapse or massive supernovae:* according the (formal) definition, the Type Ic and Ib SNe don't have conspicuous lines of hydrogen in their optical spectra.

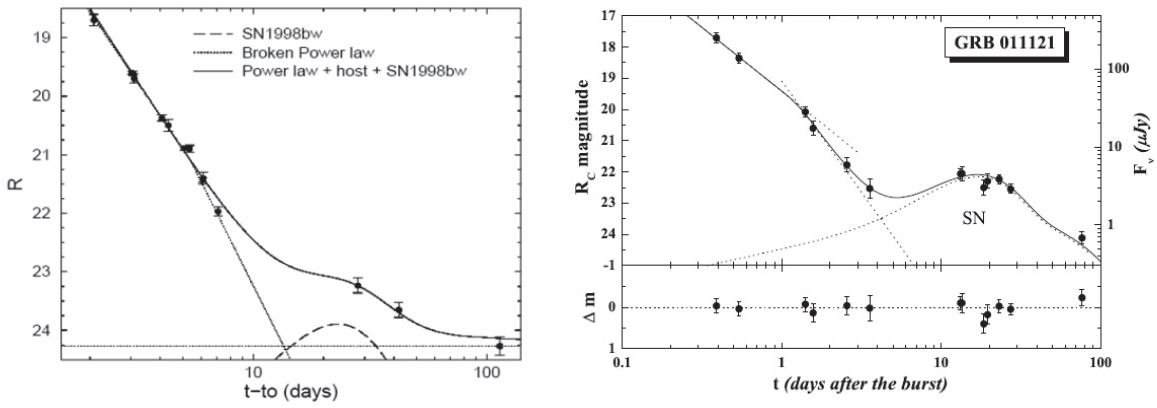


Fig6. *a) The GRB 991208 R-band light curve (the solid line) fitted with a SN1998bw-like component at z = 0.706 (the long dashed line) superposed to the broken power-law OA light curve displaying the second break at* t_{break} *~ 5 d (with* α_1 *= -2.3 and* α_2 *= -3.2, the short dotted lines) and the constant contribution of the host galaxy (R = 24.27 ± 0.15, the dotted line). b), from Zeh, Klose, Hartmann paper [21]: The afterglow of GRB 011121 (z = 0.362) showed a very clear signature of the SN 1998bw-like late-time bump rising some days after the GRB*

On the rebrightening effect in light curves: Some GRBs have shown the rebrightening effect (or the late GRB-SN bump) and flattening in their late optical afterglows, which have been interpreted as emergence of the underlying SN light curve. But a systematic study on the GRB afterglows with this approach made us supposing *that all long-duration GRBs are associated with CCSNe* [19]. Below other cases with identical rebrightening of afterglow (see Figs6), typical for such *hypernovas* [20](see also [50]) are shown. It is this rebrightening that was observed for GRB 970508 afterglows (see ***Figs 3*** and ***4***) and subsequently also for many other GRB afterglows [7].

See also in A.Zeh, S.Klose, D.Hartmann paper [21] and all references therein: **"**The key finding is photometric evidence of a late-time bump in *all* afterglows with a redshift </~ 0.7, including those of the year 2003 (GRBs 030329 and 031203) and 2004 (GRB 021006; [42]). For larger redshifts the data are usually not of sufficiently quality, or the SN is simply too faint, in order to search for such a feature in the late-time afterglow light curve. This extra light is modeled well by a SN component, peaking (1+*z*)(15…20) days after a burst. This, together with the spectral confirmation of SN light in the afterglows of GRB 021211, 030329 and 031203 further supports the view that in fact *all long-duration GRBs show SN bumps in their late-time optical afterglows*. Given the fact that a strong late-time bump was also found for XRF 030723 [10] and a less strong bump for XRF 020903 (but with spectroscopic confirmation of underlying SN light [39]) might indicate that this conclusion holds also for X-ray flashes (even though the finding of XRF-SNe might be more difficult; see [39])**"**.

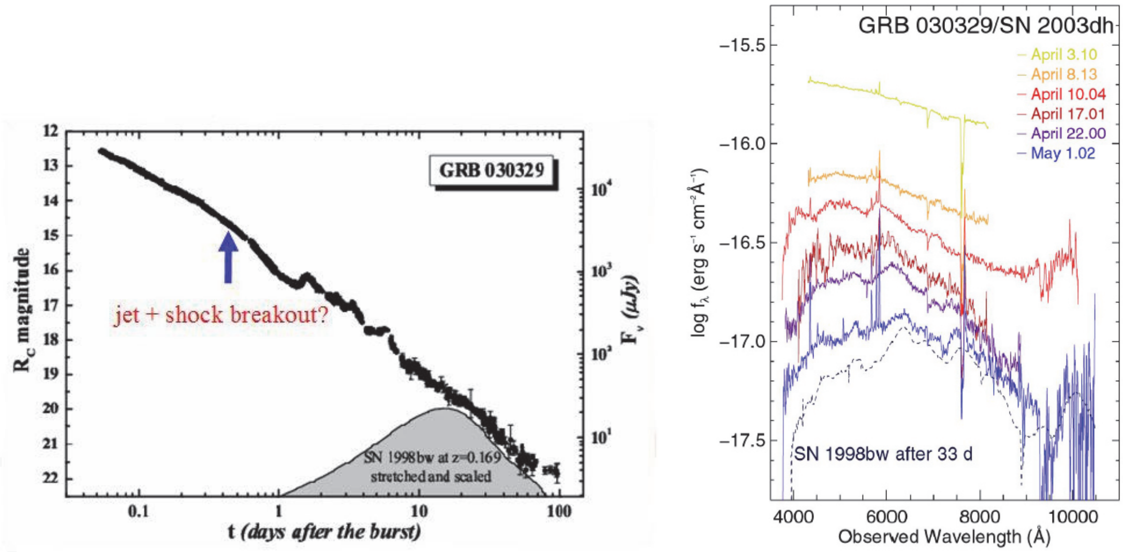


Fig7. a) *Presumably, if there were no spectroscopic evidences at hand, the SN had easily been missed in the data.* ***b)*** *Sketch of the hidden SN bump in the afterglow of GRB 030329. Various re-brightening episodes of the genuine afterglow, in combination with a relatively late break-time of the light curve, made the photometric signature for the underlying SN explosion very small.*

In particular, for the above-mentioned GRB 030329 (z=0,169), in 33 days a characteristic of the same spectrum of SN 1998bw was finally observed [22], see Figs7.

Fig7a shows interpretation of the light curve of GRB 030329/SN 2003dh with a blue arrow pointing to the на jet + shock breakout effects [19].

On early BTA spectroscopy of the GRB 030329 afterglow:

In 2003, the earliest spectra of Optical Transient were obtained for this burst with BTA (see Fig8). Characteristic broad details available already in these early spectra indicate the direct connection between the gamma-ray burst and CCSN explosion. Our spectra agree with the Nature-spectrum Hjorth, J., et al. [22].

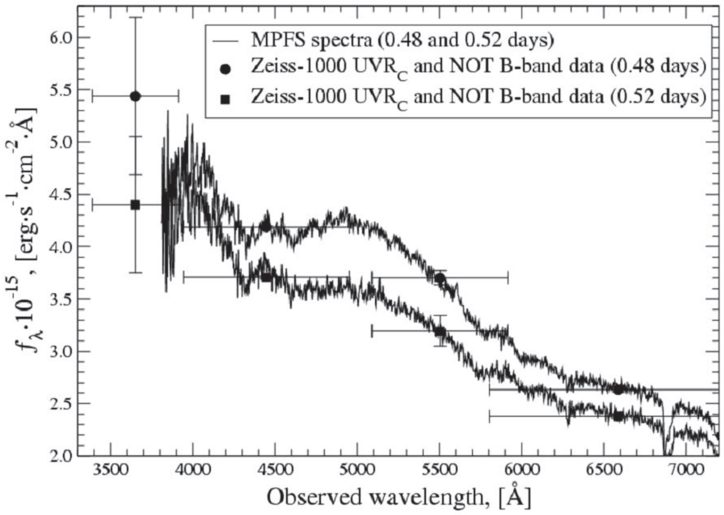


Fig8. *Early spectra and photometry of GRB 030329 OT from BTA & Zeiss-1000 & NOT [23].*

The spectrum of GRB 030329 OT in the first hours (see Fig8) can be a mixture of a GRB afterglow spectrum and early spectrum of type Ib/c CCSN. This can be a crucial argument in favor of the idea that, indeed, (long) cosmic GRBs can be the beginning of explosion of distant massive CCSNe and are observed during collapse of massive stellar cores at the end of their evolution (this result was accepted as one of the most important achievements of SAO RAS in 2003).

So, many people were speaking about a relation between GRBs and massive SNe (CCSNe), but a question of principle still remains: are long GRBs always related to this SNe type? That is why the obtaining of *the earliest spectra* of GRB OTs for (relatively!) close and rare (in comparison with other GRBs) events of type of GRB 030329 (z=0.1685) still remains topical.

5. GRB/XRF 060218/SN2006aj and interpretation of early spectra

In February 2006, the BTA spectra of GRB 060218/SN 2006aj afterglow were obtained under a joint program with the Institute of Astrophysics of Andalucia (Spain). As well as for the object GRB 030329/SN 2003dh (z = 0.1685), our observations turned out again to be among the earliest spectra of the two GRB/SN bursts.

The observational results showed that considerable changes in “standard”/popular scenarios describing both the GRB phenomenon itself and the explosion of a (massive) CCSN are inevitable. The observed UV excesses in these early spectra directly indicate to interaction between shock wave and stellar wind of a massive progenitor star (so-called “the SN Ic shock break-out effect”).

The results of SAO's observations of early spectra of these two GRBs, which are reliably identified with type Ib CCSNe, can considerably specify both the nature of a GRB source and the explosion mechanism of SNe of this type. This is an old problem, whose solution is reduced to the understanding of how the relativistic collapse of an evolving massive stellar cores occurs and what is the final result – a quark star of a singularity – black hole?

SN 2006aj UBVRIJ light curves [24]:

The light curve of GRB 060218 afterglow in Fig9 also showed the effects identical to ones described above – a peak with L_{max} ~/> 10^{45} erg/s and subsequent rebrightening [25]. So, the light curves showed non-monotonic behavior with the two maxima. The same first maximum was observed in SN1987A and SN1993J and attributed to shock break-out. The arrow in Fig9a points to the end of the shock break-out phase, as for SN1987A and SN1993J.

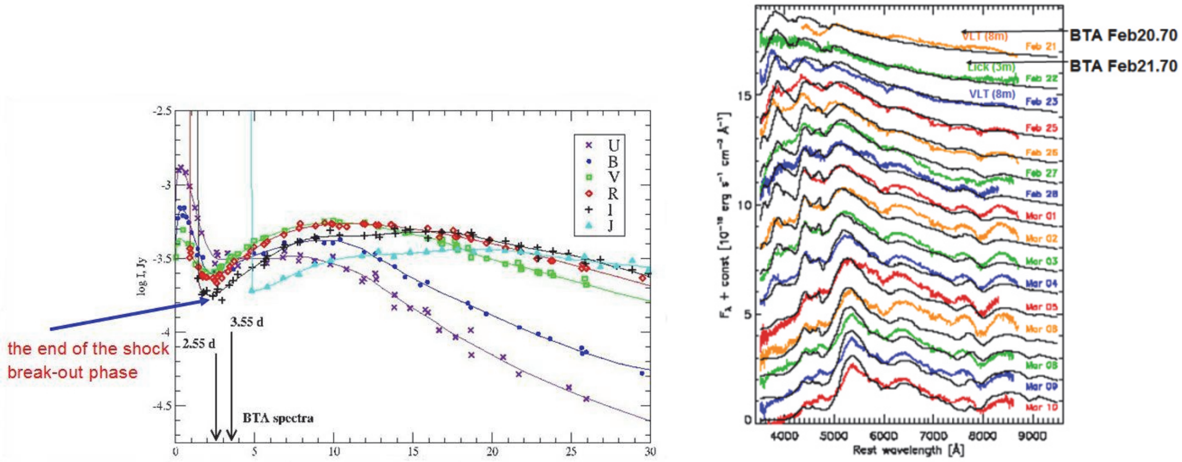


Fig9 a,b *– the light curve of GRB 060218 afterglow and spectra obtained with VLT (8 m) and Lick (3m). The arrows point also the BTA spectra. The black lines are for theoretical spectra, color lines denote real observations.*

In Fig9b and Table1 one can see also the spectra [25] obtained with BTA relative to other telescopes. Black lines are for theoretical spectra, color lines denote real observations.

Table1*. The early spectra of GRB 060218 OT before Feb 23.*

Telescope	Tfirst Sp	astro-ph
MDM (2.4m)	1.95 days (20.097 UT)	0603686 (Mirabal et al.)
BTA (6m)	**2.55 days (20.70 UT)**	
ESO VLT (8m)	**2.89 days (21.041 UT)**	0603530 (Pian et al.)
BTA (6m)	**3.55 days (21.70 UT)**	
NOT (2.56m)	3.78 days	0603495 (Sollerman et al.)
ESO Lick (3m)	4.01 days (22.159 UT)	0603530 (Pian et al.)
ESO VLT (8m)	**4.876 days (23.026 UT)**	0603530 (Pian et al.)

GRB/XRF 060218 and SN 2006aj : *Swift* (Feb. 18.149, 2006 UT) detected a peculiar GRB/XRF [28] X-ray emission was prevailing in the GRB spectrum, the GRB is also classified as XRF (X-Ray Flash) redshift z=0.0331 (can be compared to GRB 030329/SN 2003dh, z=0.1683, Ic SN).

In the Table1 Tfirst Sp is a time after GRB 060218. These are spectra with the high S/N ratio. The 6100A absorption reaches the maximal depth and width at the moment UT Feb ~ 23. (Here we do not take into account the early spectrum of their paper Modjaz et al. [27], obtained with the low S/N ratio at the FLWO 1.5m telescope 3.97 days after the burst.)

So, we managed [25] to obtain spectra between the peak and the phase of this rebrightening – see the BTA spectra in Fig10 (a,b): 2 broad absorption details (5900 - 6300A) in both spectra were interpreted as hydrogen lines (sign of stellar-wind envelope around a massive progenitor star of the γ-ray burst). The fitting [25] by synthetic SYNOW [29] spectra with the velocity of the photosphere (V_{phot}), all elements and their ions equal to 33,000 km s^{-1} is shown by smooth lines differing only in the blue range of the spectrum at $\lambda < 4000$ Å. HI denotes the Hα PCyg profile at V_{phot} = 33,000 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 Hα PCyg profile.

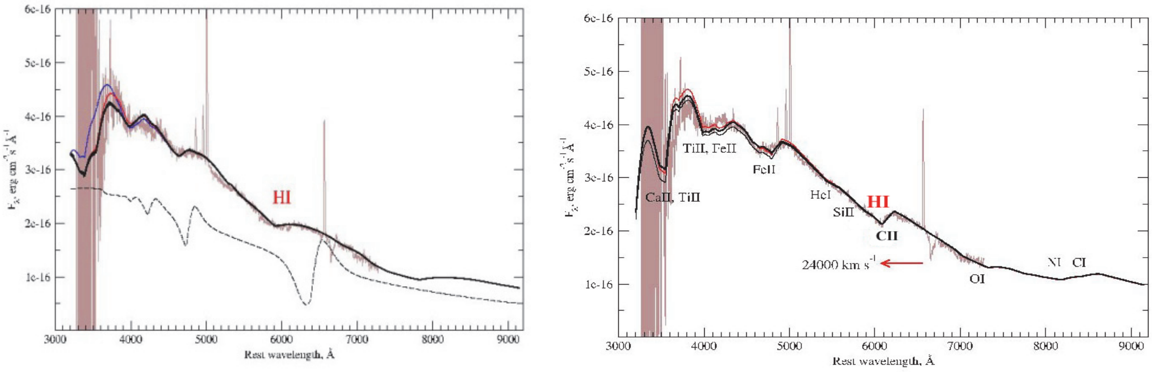


Fig. 10. *a), The SN 2006aj spectrum in rest wavelengths obtained with BTA in 2.55 days after XRF/GRB 060218. SN 2006aj/ GRB 060218, 2006 Feb. 20.7 UT, Δt = 2.55 d. The* ***undetached case****: v = 33,000 km s^{-1} (v ~ r).*
b) SN2006aj/GRB060218, 2006 Feb. 21.7UT, Δt = 3.55 d. The ***detached case****: 18000 km s^{-1} ≤ V ≤ 24000 km s^{-1} (v ~ r).*

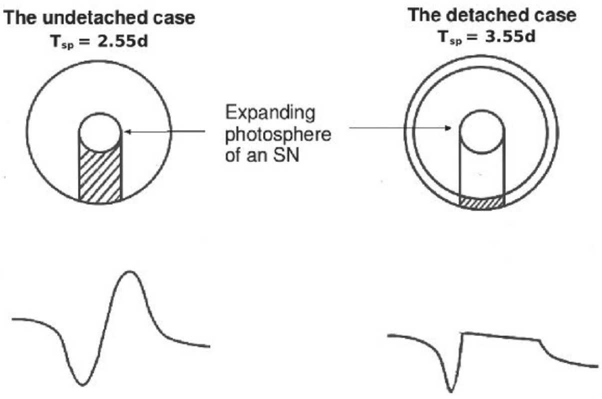


Fig. 11*. Line profiles corresponding to the cases when envelope layers (i.e. layers over the photosphere) detach or do not detach from the expanding photosphere, when the gas expansion velocity increases proportionally to distance to the center (v ~ r, see the text). The shaded regions form the absorption component of the PCyg profile. The time of BTA spectra is shown: Δt = 2.55 d and Δt = 3.55 d.*

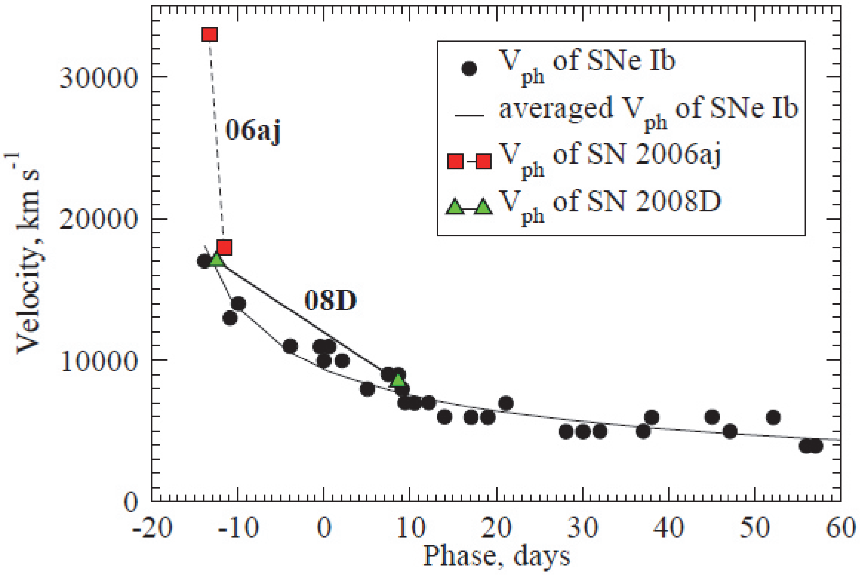


Fig12. *Velocity at the photosphere, the photosphere, as inferred from Fe II lines, is plotted against time after maximum light. The line is a power-law fit to the data, with SN 1998dt at 32 days (open circle) excluded Figure 22 from [29]. Squares (SN 2006aj) and diamonds (SN 2008D) are photosphere velocities, inferred from our spectra.*

In Fig11 the velocity of expansion is proportional to radius [25,29]. The expanding photosphere of an SN – the round in center for two cases is shown: the undetached case and the detached case (see details in [25]). In order to produce a peaked rather than a flat H-alpha emission component the hydrogen would have to be present down to the photosphere, rather than being confined to a detached high–velocity shell such as we have invoked for the absorption component.

What is "the Core-collapse SNe" in view of these results? See in Fig5 the scheme on the classification of SNe: SNe with the undetached hydrogen lines have obvious hydrogen lines and are classified as Type II. SNe with *detached* (see Fig11) hydrogen lines are classified as Type Ib because the presence of hydrogen is not immediately obvious. Type IIb SNe are those that have *undetached* hydrogen lines, when they are first observed. In some cases, whether an event is classified as Ib or IIb may depend on *how early the first spectrum is obtained*... Type Ic supernovae (SNe Ic) are very similar to SNe Ib, but they lack conspicuous He I lines.

Once more about Fig9 from [26]. The result is as follows: it is not surprising that at so huge expansion velocities as in our Fig10a (33000 km s^{-1}) nobody paid attention to broad details in the first observed spectra – see Fig8b where the smooth black lines denote the interpretation of spectra up to Feb 23 (the third spectrum), with no mention of hydrogen yet. Though by that time one could obviously see a wide absorption near 6100Å, which we interpreted [26] as the *detached* case with 18000 km s^{-1} – see our diagram velocity vs time in Fig12.

6. XRF 080109/SN2008D and others GRB/XRF/SNe

For XRF 080109/SN2008D (z=0.0065): two early BTA spectra with their SYNOW interpretation are shown in Fig13a and b. Fig12 presents location of the object (see the caption).

In total, in the period 1998-2010 in SAO RAS we investigated 6 such bursts – GRBs and SNe with spectroscopically confirmed connection:

GRB 980425/SN 1998bw	(z=0.0085),
GRB 030329/SN 2003dh	(z=0.1687),
GRB 031203/SN 2003lw	(z=0.1055),
GRB/XRF 060218/SN2006aj	(z=0.0335)
XRF 080109/SN2008D	(z=0.0065)
GRB 100316D/SN2010bh	(z=0.059)

+ the numerous phot. Confirmations

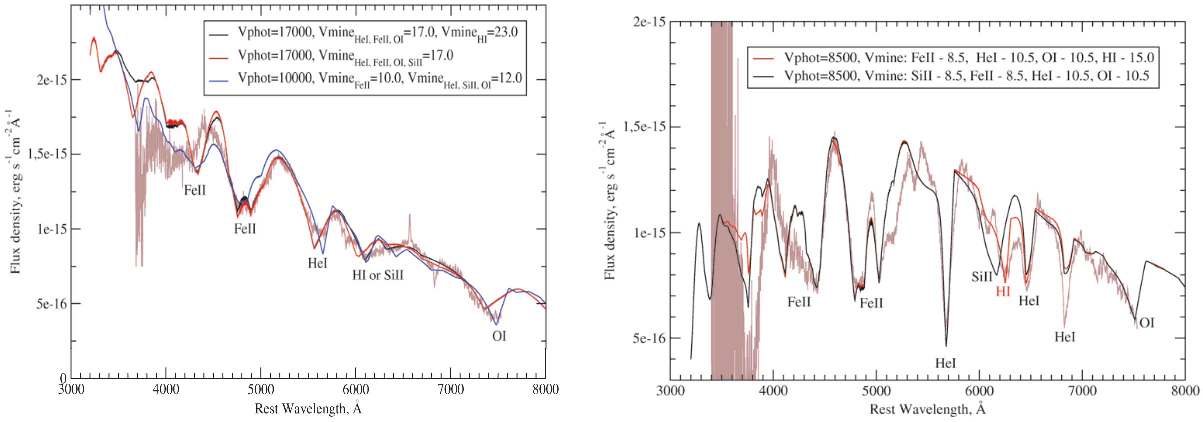


Fig13. a) *Spectrum of SN 2008D(XRF080109), Jan. 16. Physical conditions in the envelope of this SN were modeled with the SYNOW code.* ***b)*** *Spectrum of SN 2008D, Feb. 6, and SYNOW modeling.*

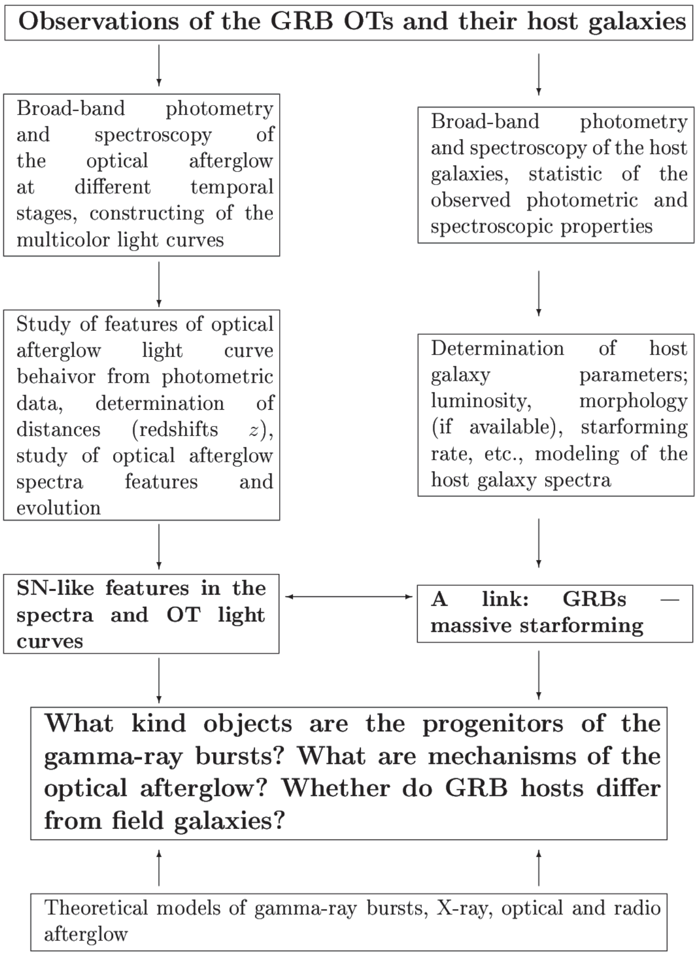
The searching for more spectrally confirmed pairs of GRBs (XRFs) and SNe in future observations is very important for understanding the nature of the GRB-SN connection, the nature of GRBs, and the mechanism of core-collapse SNe explosion.

The same is discussed in the paper "Gamma Ray Bursts in the *Swift-Fermi* Era" [30] and see references therein. Ibid. Table II (Nearby GRBs and Supernova Detections or Limit) gives one of the first lists of 24 cases of such coincidences GRB/SN up to z = 0.606 (for GRB 050525A). **"**On 19 February 2006 *Swift* detected the remarkable burst GRB 060218 that provided considerable new information on the connection between SNe and GRBs. It was longer (35 min) and softer than any previous burst, and was associated with SN2006aj at only z = 0.033. SN2006aj was a (core-collapse) SN Ib/c with an isotropic energy equivalent of a few 10^{49} erg, thus underluminous compared to the overall energy distribution for long GRBs. The spectral peak in prompt emission at ~5 keV places GRB 060218 in the X-ray flash category of GRBs [31], the first such association of a GRB-SN event. Combined BAT-XRT-UVOT observations provided the first direct observation of shock-breakout in a SN [28]. This is inferred from the evolution of a soft thermal component in the X-ray and UV spectra, and early-time luminosity variations. Concerning the SN, SN 2006aj was dimmer by a factor ~2 than the previous SNe associated with GRBs, but still ~2-3 times brighter than normal SN Ic not associated with GRBs [32, 26]. GRB060218 was an underluminous burst, as were two of the other three previous cases."

See also a new list of 70 GRBs with multi-wavelength optical transient data (and GRBs and Supernova Detections) in the above-mentioned paper by Liang et al. [7] dedicated to the study of the Properties of the GRB Sample with Multi-color Light Curves.

7. GRBs & CCSNe – the models

So, GRBs were identified with quite a definite class of supernovae – the core-collapse supernovae (CCSNe) or massive supernovae. It is a new era in the study of GRBs and CCSNe indeed. Thanks to GRBs, these SNe can be observed from the very beginning. Starting from the study of this SN1998bw, the astronomy of GRBs, their afterglows and host galaxies with the BTA telescope is now organized in the following way:



The closer GRB has the more features of SN (from 2000)... [46,25,30,7]**.** So, GRB may be the beginning of core-collapse SN explosion, and GRB is a signal allowing us to catch a SN at the very beginning of the exploding – right after collapse of a massive core.

The general belief is that core collapse supernovae connected with XRF/GRBs event can be naturally explained by the *aspherical axially-symmetrical* explosion of massive SNe. The common assumption is that in the case of an XRF type flash the observer is located outside the cone where for some reasons the bulk of gamma-ray radiation is concentrated. The asphericity is generally observed in a nebular phase. This nebular phase is shown in Fig15a from [34]. This figure explains why GRB and CCSNe cannot be observed always.

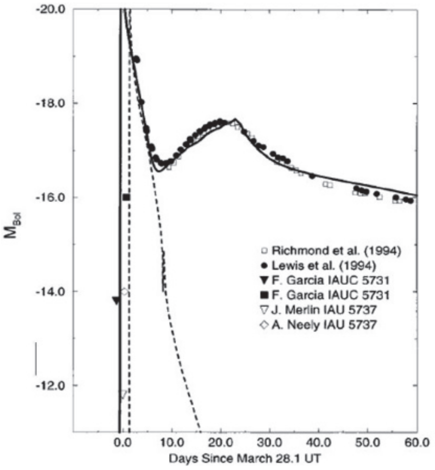


Fig14. *Earliest observations for SN1993J (II → I b) taken together with the bolometric light curve provide constrains on the initial radius of the progenitor stars. The model calculations have initial progenitor radii, R = 2.0 × 10*^{13} *cm (the dashed line) and R = 4.0 × 10*^{13} *cm (the solid line). The triangles are upper limits and no bolometric corrections have been applied to the early observations.*

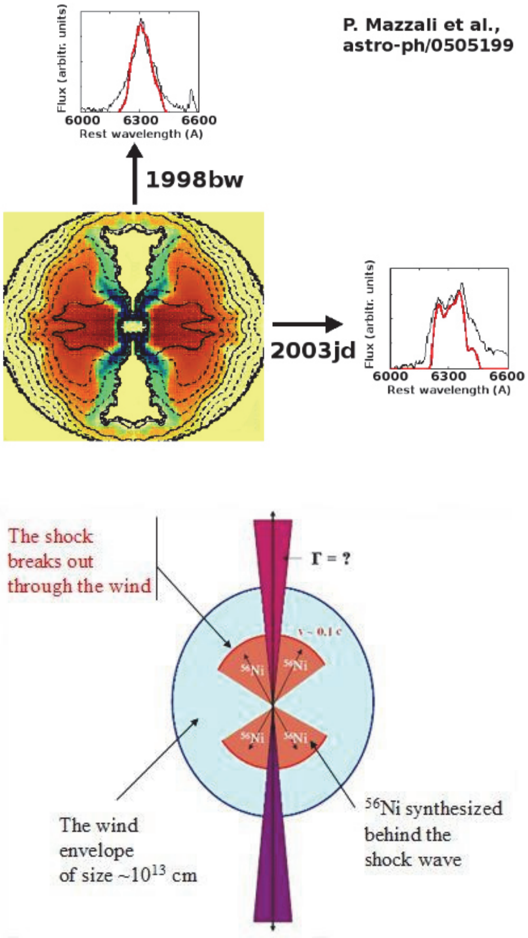


Figure 15.a) *The doubled peaked of [OI] emission must be observed for SNe which were not accompanied with GRBs, like SN2003jd e.g. And the single peak of the emission is observed in the nebular phase of SNe, which are accompanied with GRBs, like GRB 980425/SN 1998bw.* ***b)*** *Schematic model of asymmetric explosion of a GRB/SN progenitor.*

Why we cannot see any GRB event connected with SNe?

On close and distant GRBs and SNe:

Thus, the doubled peaked [OI] emission must be observed for SNe which were not accompanied with GRBs, like SN2003jd, SN2008D, and so on. And the single peak of [OI] emission is observed in the ***nebular phase*** of SNe which are accompanied with GRBs, as in the cases of GRB 980425/SN 1998bw, GRB060218/SN2006aj and others.

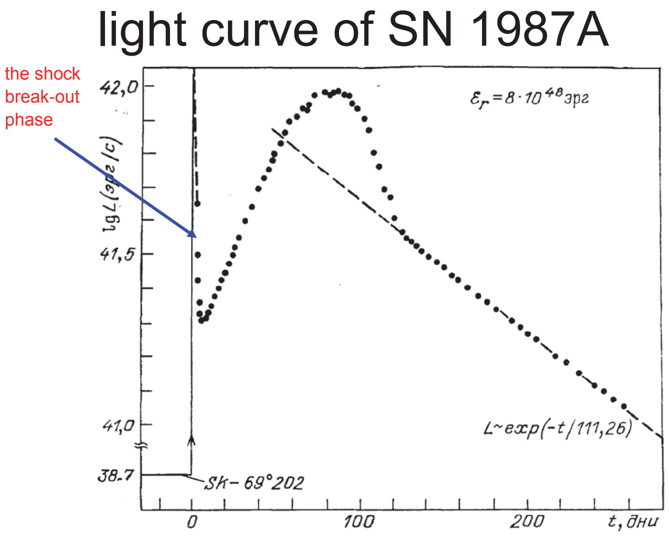
Fig15b shows the popular conception of the relation between long-duration GRBs and core-collapse SNe (the picture from [35]). One can see the shock breaks out through the wind envelope of size ~10^{13} cm, the characteristic expansion velocity of the shock wave and ^{56}Ni synthesized behind the shock.

A strongly non-spherical explosion may be a generic feature of CCSNe of all types. Though while it is not clear that the same mechanism that generates the GRB is also responsible for exploding the star [36]. Here it should be noticed that though the GRB phenomenon is unusual, but the object-source (SN) is not too unique. Another fact is that the more distant a GRB is, the less/smaller features of a SN are.

So, this is the second result of identification of GRBs:

Now long-duration GRBs are identified with (may be) ordinary massive CCSNe. The Core-collapse SNe explosions arise from the death of massive stars and hence are closely related to the cosmic star-formation rate and to massive-star evolution, and are responsible for the energy and baryonic feedback of the environment [37].

On the Core-collapse SN 1987A and GRBs:



Imshennik & Nadyozhiin, UFN, **156**, 261, (1988), fig.16

Fig. 16. *The bolometric light curve of SN 1987A from the review* [38].

This Fig16 should be compared with the above Fig14 для SN1993J II → Ib, where the maximum luminosity was $L_{max} \sim 10^{45}$ erg/s, and the same features in the light curve were observed (see Fig9a), as were observed also for GRB/XRF 060218/SN2006aj**.**

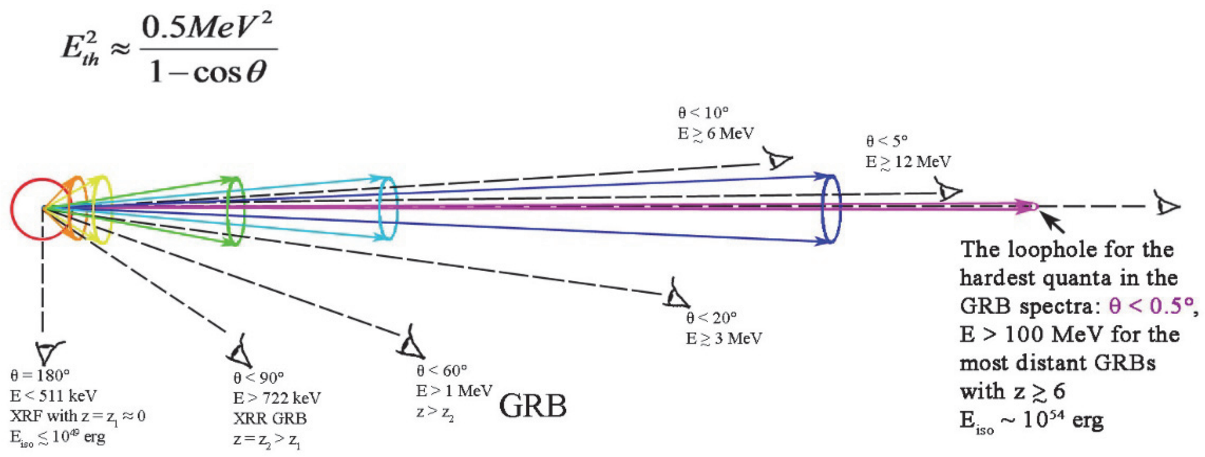


Fig17. *Collimated gamma-ray emission from GRBs – see the text.*

And on the GRBs, asymmetric explosion and so on:

If γ-rays are collimated *right in a GRB source* (with a size $c\ \delta T$ < 3000 km), then it is possible to interpret gamma-ray and X-ray emissions as is shown in Fig17. The cones (with the opening angle θ) contains the more and more hard radiation (as θ decreases) along some selected direction (or a selected axis in GRB source) with energy of quanta $E > E_{th}$. The length of arrows is proportional to the threshold energy E_{th}. The circle denotes the isotropic and the softest component of radiation with total energy of ~/<10^{49} erg. The hardest quanta of a GRB spectrum are concentrated in the *narrowest* cone, since the threshold of e^-e^+ pair creation E_{th} depends a lot on the angle θ. So, GRBs are observable only along the axis of a GRB/SN explosion, i.e. at sufficiently small θ.

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 GRB030329) and become X-ray Flashes [39, 23]. 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 SN1993J.

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). The 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 [40].

So, if all long GRBs are related to SNe explosions indeed, then a long burst is the collapse of a massive star core or the beginning of an axially symmetric explosion of SN, and the long GRBs must always be accompanied by an SN explosion (of Ib/c type or other types of core-collapse SNe). Then the total energy release of a burst source in gamma rays is in any case not higher that the total electromagnetic energy radiated by the SN (< or ~ 10^{49} erg). And the accumulated statistics of GRB + SN coincidences [7] will confirm the GRB compact model more and more.

8. Core-collapse SN 1987A and Conclusions

The Hubble Space Telescope was pointed at the SN 1987A remnant in 1994 (see Fig18b). Explanation: What's causing those odd rings in SN 1987A? In 1987, the brightest SN in recent history occurred in the Large Magellanic Clouds. In the center of the picture there is an object central to the remains of the violent stellar explosion. When the Hubble Space Telescope was pointed to the SN remnant in 1994, however, the existence of curious rings was confirmed. The origins of these rings still remains a mystery.

Speculation about the cause of the rings includes beamed jets emanating from a dense star left over from the SN, and a superposition of two stellar winds ionized by the SN explosion.

But see the model (in Fig17) of an asymmetric explosion of a GRB/SN progenitor…

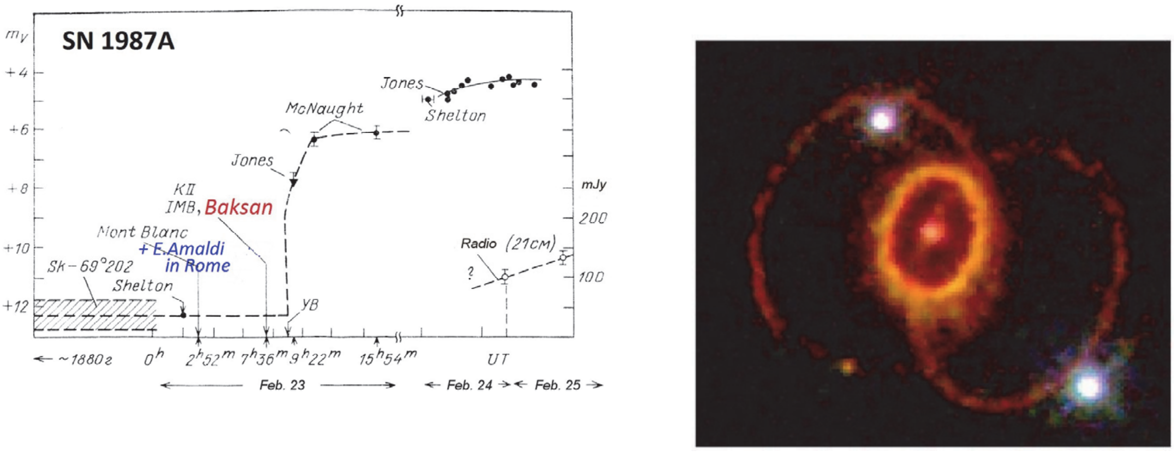


Fig18. a) *Observations of SN 1987A* ***before*** *and in the first days after its discovery (from [38]).*
b) *The SN 1987A remnant in 1994.*

So, GRBs and their afterglows are of great interest for studies related to stellar astrophysics, the interstellar and intergalactic medium, and most important, they reveal themselves as unique probes of the high redshift Universe.

Discovery of the relation between long-duration GRBs and CCSNe is the most important progress in this domain during recent 30 years. Now the search for SN signs in photometry and spectra of GRB afterglows became the main observational direction both for large ground-based telescopes and space platforms. In particular, in the process of study, a new branch of observational cosmology has arisen as a result of investigations of GRB host galaxies. The GRBs themselves are already considered as a tool for studying processes of star-forming at cosmological distances up to redshifts z~10.

Irrespective of specific models of this phenomenon, it might be said now that when observing GRBs we observe the most distant SN explosions which, probably, are *always* connected to the relativistic collapse of massive stellar cores in very distant galaxies. The connection is that GRBs may serve as a guideline to better understand the mechanism, and possibly solve the long-standing problem of the core-collapse SN explosion, since in the GRBs we have additional information related to the core-collapse.

On the quark-gluon plasma in the compact stars, GRBs, Neutrino signals, and Gravitational Wave emission:

Short GRBs can be connected with compact objects of stellar mass and a burst near (or on) their surface. The equation of state of these objects (maybe, quark stars) can be tested by studying them in all wavelength ranges. Professional astronomers and physicists investigating matter with supernuclear density understand well already that the modern science is standing at the threshold of discovery of quite a new state – quark-gluon plasma, quark stars (see in [41] a report of the Special Commission: The summary of the EMMI Rapid Reaction Task Force on "Quark Matter in Compact Stars", October 7-10, 2013, FIAS, Goethe University, Frankfurt, Germany).

Quark gluon plasma is now a new direction both in high energy physics and in the study of compact objects of neutron star type [45]. The phase transition to the quark-gluon plasma state is surely connected with the mechanism itself of core-collapse supernova explosion, and energy of such a transition can be a source of GRBs. Neutrinos which are observed with modern detectors (including Russian ones, e.g. Baksan Underground Neutrino Telescope) can serve as signals of the transition of matter to purely quark matter. Equipment of gravitational detectors (LIGO, VIRGO) is also developed for such signals.

Participation of astronomers in programs for the study of localization boxes of neutrino (and, possibly, gravitational) events is being discussed already in detail (see https://wikispaces.psu.edu/display/AMON). The recent measurement of 2Ꙩ pulsars has initiated an intense discussion on its impact on our understanding of the high-density matter in the cores of NSs. During this meeting, the recent observational astrophysical data were reviewed. The possibility of pure quark stars, hybrid stars and the nature of the QCD phase transition were discussed and their observational signals delineated + SNe & GRBs.

A task force meeting was held from October 7-10, 2013 at the Frankfurt Institute for Advanced Studies to address the presence of quark matter in these massive stars [41]. In this paper, in connection with observations of SN1987A ***before*** and in the first days after its discovery (see Fig18a) it was specially noted:

“The time-delay between the moment of SN explosion and the moment of the quark phase transition could explain a few observed features of Gamma-Ray Bursts, as e.g. the existence of very long quiescent times seen in a few bursts [43] and the possible existence of Gamma-Ray Bursts for which no associated SN explosion is observed [44].”

In connection with this remark, here it should be remembered also the first detection of GWs by the team of *Edoardo Amaldi* – see in Fig18a. The data recorded by the Rome room temperature gravitational-wave antenna during the Supernova SN 1987*a* [42] have been analyzed in connection with the Mont Blanc neutrino event. An energy innovation is observed which precedes by (1.4 ± 0.5) s the first observed neutrino arrival time with the probability of being accidental of 3 per cent. But an estimation of the energy emitted as GW *distributed over* 4π and a frequency bandwidth of 1 kHz gives the figure of 2400 $M_{\odot}$, which is abnormal according to standard views on GW…

Later on, the work on identification and studying the nature of GRBs has been fulfilled (up to the present time) in a wide international collaboration. The participants of the program, beside the SAO team, are the researchers from Spain (the 10.4-m GTC, the 4.2-m Calar Alto, etc.), France (the submm Observatory at Plateau de Bure), New Zealand, India (the 2.34-m VBT Kavalur, the 2.01-m HCT IAO, the 1.04-m ST Naini Tal).

At present, the software was elaborated in SAO which provides the on-line translation of alerts about GRBs and other transients discovered by the space missions *Swift*, *Fermi*, *MAXI*, *INTEGRAL*, etc., and with ground-based facilities. (See also [47] and references therein.) When there is an alert, an observer sees a dialog box in the monitor which, in case of the positive decision, permits to start immediate pointing to the object’s coordinates. So, the reaction time of the complex is reduced to minimum.

From the aforesaid, the *main result* of the many-year program on identification of GRBs in SAO can be formulated as follows:

Since (long) GRBs are the beginning of CCSNe explosion and, most probably, during the gamma-ray burst we do see (as V.F.. Shvartsman was guessing it in the old days) the relativistic collapse of a stellar core and the birth of a very dense compact object – a remnant of the SN explosion. (Judging from the new paper [7], many people already understand it...) But here new problems arise related with new cosmological tests.

Since GRBs are at very far cosmological distances (with redshifts more than 10) this poses additional questions which are of outmost importance for *observational* cosmology:

- What are redshifts at which the sky distribution of GRBs becomes homogeneous [48,49] ?
- What are the redshifts where such bursts (which are related now with collapse of compact objects of stellar mass) are unobservable already?
- And so on...

Acknowledgements

In conclusion we would like to thank all participants of identification of the first ten of gamma-ray bursts in SAO: S.V. Zharikov, S.N. Mitronova, T.A. Fatkhullin, V.L. Afanasiev, V.V. Vlasyuk, S.N. Dodonov, astronomers and administration of SAO and all colleagues who contributed to obtaining the above results with BTA and Zeiss-1000.

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