

# On the GRB progenitors: possible consequences for supernovae connection with $\gamma$ -ray bursts

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**Abstract.** Unique data on *BVRI* light curves of the optical transient (OT) of GRB 970508 obtained with the 6 m telescope have been interpreted in the framework of the idea of a straightforward link between supernovae (SNe) and long duration gamma-ray bursts (GRBs). The effect must be maximum in the  $I_c$  band as for OT GRB 970228. The peak absolute ( $M_B$ ) magnitude of the suggested SN must be around  $-19.5$  for the OT of GRB 970508. So, in addition to the characteristic “shoulders” on the light curves of the OTs of GRB 970228, GRB 980326, 990712, 991208, more evidence of the link between GRBs and Type Ib/c SNe (or core-collapse SNe) was found, which could be an argument in favor of the idea of massive stars as progenitors of long duration GRBs. If all or the main part of long duration GRBs are associated with the SNe, GRB host galaxies (for ground-based observations, at least) must be dimmer than the peak magnitude of a SN. If some GRB/SN relation really exists, and if all or at least the main part of long duration GRBs are associated with SNe, then as a consequence we have a very strong  $\gamma$ -ray beaming with a solid angle of up to  $\Omega_{beam} \sim (10^{-5} - 10^{-6}) \cdot 4\pi$ . Besides, the observations of  $K_\alpha$  lines of iron in the X-ray afterglow spectra of GRBs (970508, 970828, 991216, 000214) and the observation of redshifted absorption feature of neutral iron (7.1 keV) simultaneously with GRB 990705 are also evidence in favor of massive stars — progenitors of GRBs.

**Key words:** gamma rays: bursts: gamma rays: observations — gamma ray: individual: GRB 970508

## 1. Introduction

The nature of  $\gamma$ -ray bursts is still a debated issue, but the consensus is growing on the association of GRBs with massive stars progenitors. The long duration GRBs are probably connected with the death of massive stars and hence with a supernova-like explosion (Paczinski, 1999; MacFadyen & Woosley, 1999, and references therein). Over the past three years this “hypernova” or “collapsar” model has gained strength, especially because long duration GRBs have been found to occur in star-forming regions of their galaxies — the only places where very massive stars live and die (Fruchter et al., 1999; Hogg & Fruchter, 1999; Bloom et al., 2000; Sokolov et al., 2001). The leading scenario now for long duration GRBs is a sudden collapse of a massive rapidly rotating star. May be merging neutron stars still remain a possibility for the short GRBs, but this model (Lattimer & Schramm, 1976) has lost favor as an explanation for long duration GRBs, those lasting more than 1 second.

This paper shows possible consequences for the scenario explaining GRBs if massive stars are GRB

progenitors actually. In particular, as a result of evolution the massive stars at a Wolf-Rayet phase (which is characterized by a strong stellar wind) can produce rather dense envelopes around them — an effect of the WR stellar wind interacting with the interstellar medium (Ramirez-Ruiz et al., 2001).

First we consider some features of *BVRI* light curves of such a well-studied object as the OT of GRB 970508 (Sokolov et al., 1998; Galama et al., 1998; Sokolov et al., 1999). We begin the analysis of these features of the *BVRI* light curves when the GRB host galaxy is observed. There is independent evidence in favor of the massive GRB progenitors: at least in some GRBs a SN may be the origin of a red component (or a shoulder) in the *BVRI* light curves of a GRB afterglow, detected several weeks after a GRB. A possible contribution of a SN in the *BVRI* light curves of GRB 970508 is considered. Then, on the basis of the light curve of the OT of GRB 970508 and other GRB transients with due regard for the observable magnitudes of GRB host galaxies, the possibility of the strong GRB beaming will be grounded.

The presence of a considerable component of the



X-ray emission in the radiation of BeppoSAX's GRBs which is observed simultaneously with the long duration GRBs (or a prompt GRB X-ray emission) is very essential. The Italian-Dutch X-ray mission BeppoSAX can provide not only arc minute localization of GRBs, but also measurements of their spectra in a broad (2 to 700 keV) energy band (Piro et al., 1998; Frontera et al., 2000). The iron line features (also detected in the X-ray afterglow with the ASCA and Chandra satellites) would strongly suggest a massive stellar GRB progenitor too, since these features can be direct evidence for the existence of these dense envelopes in the vicinity of a pre-GRB object. The account for a huge force of pressure on the environment around a GRB-progenitor produced by a huge and highly collimated flux of the prompt  $\gamma$ -ray and X-ray radiation can considerably change our understanding of a GRB afterglow.

## 2. The light curves: multiband photometry of the GRB970508 optical counterpart

The OT of GRB 970508 is a second optical source related to a  $\gamma$ -ray burst registered by the BeppoSAX satellite. The optical variable object was first reported by H. Bond as a possible optical counterpart of GRB 970508 (Bond, 1997) and was independently found in our data ( $R_c$  band, 1 m telescope) only about 0.5 day later. Observations of the GRB 970508 optical remnant were continued with the 6 m telescope in the standard  $BVR_cI_c$  bands till Aug. 1998. In Fig. 1 a,b the behavior of the OT light curves + host galaxy of GRB 970508 up to 470th day is shown; **a**) for the logarithmic time and **b**) for the linear time for days after the GRB. The  $BVR_cI_c$  magnitudes with their errors (joined by the broken heavy lines) are pictured. Four independent power laws (the smooth thin lines) determined by fitting the observed  $BVR_cI_c$  light curves with a two-component model, the sum of the OT GRB 970508, fading according to a power law (but after the brightness maximum in Fig. 1 **a**), and a constant brightness host galaxy ( $F = F_o \times t^\alpha + F_c$  with different  $\alpha$ ) are shown (for details see Sokolov et al., 1999).

The data obtained with the SAO RAS 1 m and 6 m telescopes allow us to divide the GRB OT brightness changes at least into 4 stages (Fig. 1 a,b): I) the increase of brightness on a time scale of about one day; II) (after the maximum) the exponential brightness fall from our observations during about 4 days with a stable broad-band spectrum; III) further brightness fading according to a rough power law; but note that from the 31–36th days after the GRB the object did not show any *smooth* further

power-law fall at least in the  $I_c$  filter. IV) after approximately 200 days any power-law decay ceased and the OT contribution to the host galaxy flux was already less than the observational errors.

At the first two stages — the increase of brightness and the OT brightness maximum — the behavior of the light curves has not been understood yet (see Panaitescu & Kumar, 2001). Nevertheless, at the OT brightness maximum and immediately after it, all  $BVRI$  fluxes were measured with the smallest errors, 0.03–0.07 mag. And any power law does not best fit for the brightness fading after the maximum (May 10.77 UT). We see the same exponential law in all  $BVRI$  bands (Sokolov et al., 1998), or an identical exponential brightness fading was observed in 4 bands simultaneously.

After the 5th day the light curves in the  $BVR_cI_c$  bands can be described by power laws (with different  $\alpha$ ). But starting with about the 31st day after the GRB, the OT did not show further fall of brightness in the  $I_c$  filter. This phenomenon lasted not less than 51 days. In that period the OT was stable around  $I_c = 23$ . After 87 days the deviation from the “average” power law was already as high as  $\simeq 1$  mag. ( $I_c$  was  $23.04 \pm 0.14$  for the 87.085th day after the GRB). The behavior we observed can also be explained by some intrinsic features of GRB 970508 OT. In this temporal and spectral behavior of the GRB OT there can be a hint of a similar behavior of supernovae (see below).

Late-time observations of the GRB 970508 optical counterpart in July–August 1998 show that the optical counterpart did not change during the last half-year, and we can conclude that we observe a pure GRB host galaxy with  $B = 25.77 \pm 0.19$ ,  $V = 25.25 \pm 0.22$ ,  $R_c = 24.99 \pm 0.17$ ,  $I_c = 24.07 \pm 0.25$ , already without the GRB optical remnant contribution. Comparison of the  $BVRI$  spectral energy distribution of the GRB host with local starburst galaxies leads to the best fits for Scd starburst H II galaxies (Sokolov et al., 1999; 2001).

The global best  $\chi^2$ -fits (see Fig. 1) with a single power law, for most of the filters used, are not acceptable (Sokolov et al., 1998). Some intrinsic variability of the GRB optical remnant fading is possible, which demands a more complex law presenting the largest multiband homogeneous data set from one telescope.

## 3. Supernovae and Gamma-ray beaming

The  $I_c$  band light curve of GRB 970508 afterglow exhibits a rebrightening phase, or a “shoulder” (Fig. 1 a,b). This spectral property lasts for not less than 51 days. Over across this period the color index ( $V -$



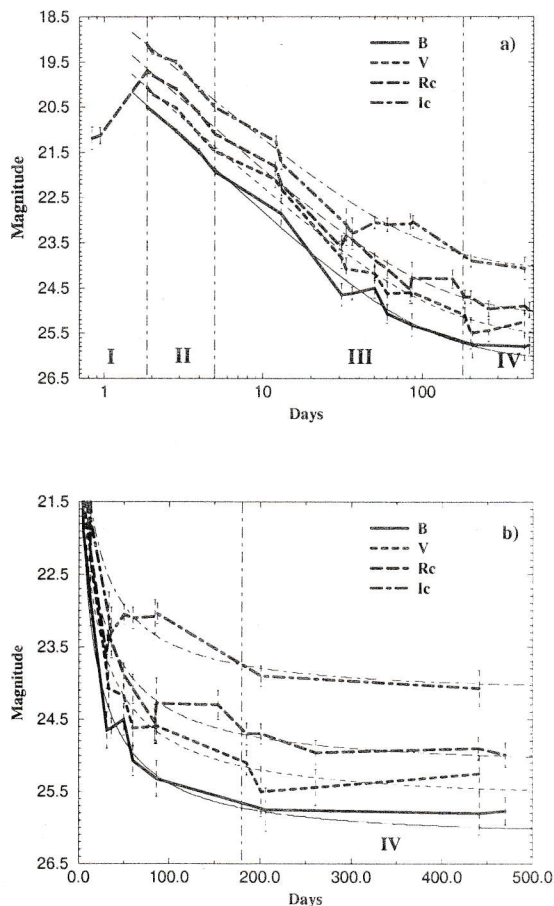


Figure 1: The behavior of  $BVR_cI_c$  light curves of the OT + host galaxy of GRB 970508 up to about 470th day from the time of the GRB. Four independent  $BVR_cI_c$  power-law fits with different  $\alpha$  (see text) are exhibited by the thin lines. The  $BVR_cI_c$  light curves are shown on logarithmic (a) and linear (b) scales.

$I$ ) increases up to  $\approx 1.6$  mag ( $I_c = 23.04 \pm 0.14$  for the OT). The deviation from the “average” power law with  $\langle \alpha \rangle = -1.25$  exceeds 1 magnitude. Recent investigations show that GRB optical afterglows have unusual temporal and  $VRI$  spectral properties: GRB 970228 (Galama et al., 2000), GRB 980326 (Bloom et al., 1999), GRB 990712 (Bjornsson et al., 2001), and GRB 991208 (Castro-Tirado et al., 2001). All these OTs have temporal and spectral characteristics similar to those of GRB 970508, for which the  $I_c$  band light curve is consistent with the assumption that the SN emission overtakes the OT flux at late times, i.e. nearly 31 days after the GRB. It should be noted that the emission of all Type I SNe shows a strong UV deficit owing to absorption lines below  $3900\text{\AA}$ . Thus, for the redshift  $z = 0.835$  a weak flux is expected from the suggested SN in the  $R_c$  band corresponding

to the  $U_{rest}$  ( $3652\text{\AA}$ ) in the rest frame.

In contrast, the SN brightness must be in the maximum at larger wavelengths (Fig.1), i.e. in the  $I_c$  band as observed for GRB 970508 (and for GRB 970228 with  $z = 0.695$  (Galama et al., 2000) plus time profile stretching for the light curve of the SN by a factor of  $(1+z)$ . One can see the effect from an “average” power-law fit  $F = F_o \times t^\alpha + F_c$  with  $\langle \alpha \rangle = -1.25$ . The deviations ( $\chi^2/\text{d.o.f}$ ) from the “average” power-law increase toward the red part of the OT  $BVR_cI_c$  spectrum:  $\chi^2/\text{d.o.f} = 1.57$  for the  $B$ -band, 2.41 for the  $V$ -band, 2.93 for the  $R_c$ -band, and 3.62 for the  $I_c$ -band (see Sokolov et al., 1999 for details).

As  $z = 0.835$ , the  $I_c$  band in the observer frame corresponds to the  $B_{rest}$  ( $4448\text{\AA}$ ) band in the rest frame, the observed  $I_c$  flux is thus used to derive the peak absolute magnitude ( $M_B$ ) of the assumed SN. At the  $I_c$  “shoulder” (Fig. 2) the brightness of GRB 970508 OT corresponds to the maximum luminosity of a peculiar SN with  $M_B$  around  $-19.5$  if for GRB 990708 host we have  $M_{B_{rest}}$  around  $-18.5$  (Sokolov et al., 1999). We can consider type-Ib/c SNe as a preliminary model of GRB/SN  $\gamma$ -ray bursters, but the peak magnitudes of type-Ib/c (or core collapse) SNe are not constant:  $M_B$  is from  $-16$  to  $-19.5$ . Thus, the GRB host galaxies (for ground-based observations, at least) must be dimmer than the peak magnitude of the SN (see Table 1 in Sokolov et al., 2001).

SN 1997ef has been recognized as a peculiar SN Ic from its light curve (Iwamoto et al., 2000). It shows a very broad/flat peak and a slow tail. (But the luminosity is lower than that of the well-known SN 1998bw.) However, for the purposes of this paper, the shape of SN Ic light curve is sufficient as an example of type-Ib/c SN. We do not know exactly the light curve (and the spectrum) of the true SN accompanying GRBs; may be in the OT GRB 970508 case it was a peculiar SN by its luminosity and by the shape of the light curve (Fig. 2).

So, we can expect GRBs to originate from massive stars which have lost their hydrogen envelope before a SN-like explosion. If GRBs arise from collapses of massive stars in starforming galaxies, it is an unavoidable consequence that emission from an underlying SN should be superimposed on the GRB afterglow. Economy of hypotheses leads us to suppose that all or at least the main part of long duration GRBs are associated with SNe (but not all SNe are associated with GRBs).

From the observations of 1997–2000 for known GRB host galaxies we have (see Fig. 3):

$$m_{HostGal} = \text{from } \sim 22 \text{ to } \sim 28 \text{ st.mag.}$$

Such faint (or fainter) galaxies are indeed expected from studies of the properties of the GRB host galaxies. It leads to the fact that the search for direct GRB-SN associations in galaxies close to us is a challenge,

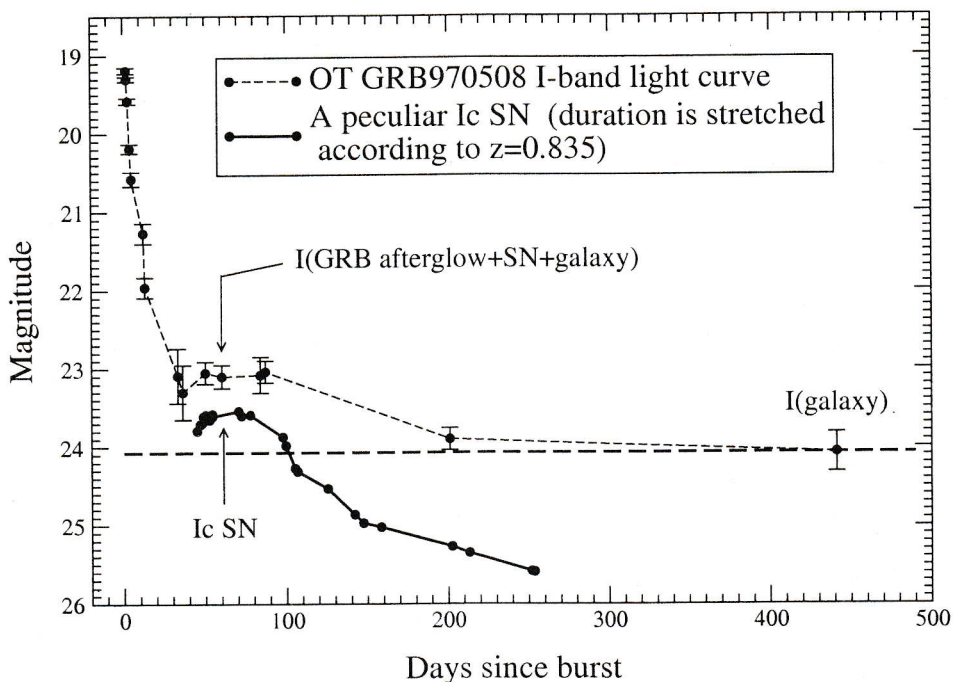


Figure 2: OT GRB 970508 I-band light curve plus a kind of a peculiar Ic SN similar to SN 1997ef by the shape of the light curve (but with the peak luminosity like SN 1998bw).

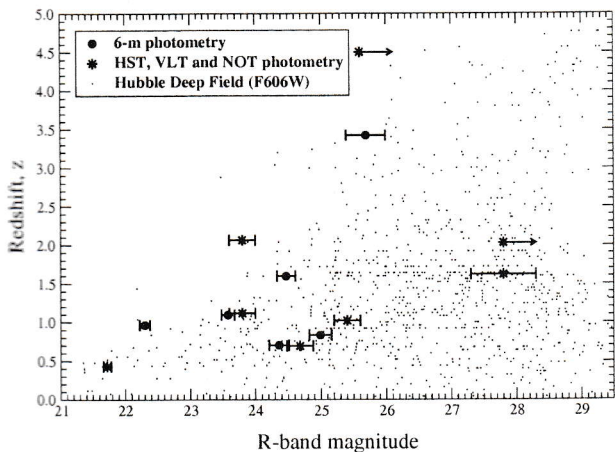


Figure 3: Observed R-band magnitude vs. redshift of the GRB host galaxies. The R-band magnitudes are corrected for the Galactic extinction. The BTA R-band magnitudes (from Sokolov et al., 2001) are marked with circles, while asterisks refer to the results of other authors. Also the HDF F606W magnitude vs. photometrical redshift distribution is plotted. Catalog of the F606W magnitudes and photometrical redshifts was used from Fernández-Soto et al., 1999.

because the majority of the SNe related to GRBs will be faint (22–26 mag) and also in very distant galaxies with  $z \geq 0.4 - 4.5$ .

Having established that the GRB hosts are faint, for a number of galaxies brighter than 26 mag in one

square degree of the sky we have  $N_{gal < 26 mag} \approx 2 \cdot 10^5 \cdot gal \cdot deg^{-2}$  (Casertano et al., 2000). Taking into account the observations with BATSE  $n_{GRB} \approx 0.01 \cdot deg^{-2} yr^{-1}$ , we conclude that the rate of GRB events is

$$N_{GRB} \approx 5 \cdot 10^{-8} \cdot yr^{-1} galaxy^{-1}.$$

For the SNe rate in the local starburst galaxies we have

$$N_{SN} \approx 0.02 \cdot yr^{-1} galaxy^{-1}$$

for all types of SNe combined. It should be kept in mind that GRBs are not observed in all galaxies and that not all types of SNe can be related to GRBs, but only type-Ib/c (Capellaro et al., 1999). So we have  $N_{SN} \approx 0.001 \cdot yr^{-1} galaxy^{-1}$ . But if one looks at the matter the other way round, we must remember: the massive star-forming in very distant (and dusty) GRB galaxies with  $z \sim > 1$  is more vigorous than in the local starburst galaxies or in galaxies like the Milky Way (Blain and Natarajan, 2000), giving rise SN bursts of 10 times and more.

Thus, with due regard for these reservations, an estimate for the number of GRBs which could be related to SNe is of order of

$$N_{GRB}/N_{SN} \approx 5 \cdot (10^{-5} - 10^{-6}).$$

So, if some GRB – SN relation really exists, then we have two possibilities:

1) either we deal with a very very rare type of SNe (or “hypernova”?) – GRBs related only to the



$10^{-5} - 10^{-6}$ -th part of all observed SNe in distant galaxies (up to 28th mag), or

2) we have a very strong  $\gamma$ -ray beaming with a solid angle up to

$$\Omega_{beam} \sim (10^{-5} - 10^{-6}) \cdot 4\pi,$$

if GRBs are associated with an **asymmetric** SN explosion, whereas the  $\gamma$ -ray beam (and narrow collimated jet) is directed towards the observer on the Earth. And if GRBs are so highly collimated, radiating only into a small fraction of the sky, the energy of each event may be much reduced, by several ( $\sim 5-6$ ) orders of magnitude:

$$E_{beam} = E_{\gamma} \Omega_{beam} / 4\pi \sim 10^{45} - 10^{47} \text{ ergs}$$

for the isotropic equivalent of the total GRB energy  $E_{\gamma} \sim 10^{51} - 10^{52}$  ergs.

Thus, if all or the main part of long GRBs are associated with SNe, we need more examples to test the GRB-SN link. But from the Earth we can see only peculiar SNe (by their luminosities and by light curves) connected with GRBs. The SNe must be brighter than their hosts. The luminosity of these dusty galaxies  $M_B$  is basically between  $-18.6$  and  $-21.3$  (Sokolov et al., 2001).

## 4. Discussion: still, what are the progenitors of Gamma-Ray Bursts?

### 4.1. X-ray spectra and close environment of GRB source

The BeppoSAX, ASCA and Chandra observations in X-rays confirm rather a link with the death of massive stars; the satellites found a spectral signature of iron from different GRBs. To date, four GRBs have shown evidence for an iron emission line during the X-ray afterglow, observed 8-40 hours after the burst event (GRB 970508, Piro et al., 1999; GRB 970828, Yoshida et al., 2001; GRB 991216, Piro et al., 2000; GRB 000214, Antonelli et al., 2000). SNe or SN-progenitors can be the most plausible source of such an iron. In any case, the new data are very important, because all spectral emission lines observed so far are produced by the GRB host galaxies rather than at the burst site.

Chandra's observation of the brightest GRB 991216 was started 37 hours after the BATSE/GRBM trigger (Piro et al., 2000). The spectrum of the X-ray afterglow shows the emission line at energy  $E = 3.49 \pm 0.06$  keV. The emission feature is associated with the rest energy of 6.97 keV of the emission of H-like ions of iron (FeXXVI) because at higher energies the Chandra/ACIS-S spectrum shows evidence of a recombination edge in the emission at  $E = 4.4 \pm 0.5$  keV. The identification of this feature with the iron

recombination edge (with the rest energy of 9.28 keV) gives  $z = 1.11 \pm 0.11$  consistent with  $z = 1.02$  found in optical spectroscopy of the OT GRB 991216 (Vreeswijk et al., 2000).

An iron recombination edge at 9.28 keV is, indeed, expected when the iron emission is driven by photoionization and the medium is heavily ionized by the radiation produced by X-rays from the GRB or its afterglow. If the medium lies in the line of sight, the edge is expected to be seen in absorption at early times, before the photoionization of the medium. (Evidence of such a feature has been found in another GRB, GRB 990705.) At later times, when the medium becomes heavily ionized and recombination takes place, the edge is seen in emission. In this condition X-ray lines are produced almost exclusively through recombination of electrons on H-like iron. From the Chandra observation of GRB 991216, the distance of the medium from the GRB source or the size of the region of the emission feature formation around the GRB site is  $R > 2 \cdot 10^{15}$  cm ( $R = c \cdot t$ ). The latter condition is derived from the presence of the line 1.5 days ( $> 37$  hours) after the GRB, which is shorter than the observed one by a factor of  $(1+z)^{-1}$ .

Different scenarios have been proposed to explain the lines in emission (see Lazzatti et al., 2001; Vietri et al., 2001; Rees and Meszaros, 2000; Weth et al., 2000). The observations by BeppoSAX, ASCA and Chandra seem to indicate large amount of iron close to the GRB site. One of the explanations emerging (Vietri et al., 2001) from all pieces of evidence is as follows: a massive progenitor — like a “hypernova” (Paczynski, 1998) or a “collapsar” (Woosley, 1993) — ejects, shortly (several months) before the GRB, a substantial fraction of its mass. But there is room for a lot of models so far and (for all that) other more simple scenarios invoking a simultaneous explosion of a GRB source and a progenitor star are possible — see below.

Unlike of GRB 991216 and others which showed evidence for the iron emission lines during the X-ray afterglow, GRB 990705 showed a prominent **absorption** feature at 3.8 keV and an equivalent hydrogen column density that disappeared 13 s after the burst onset (Amati et al., 2000). The absorption feature was interpreted as due to an edge produced by the neutral iron (i.e. at 7.1 keV), redshifted to 3.8 keV (corresponding to  $z = 0.86$ ). And what is the most important: the absorption feature seen during the first 13 seconds from the BeppoSAX/GRBM trigger, became undetectable afterwards. The straightforward (or a “simplest”) interpretation of the absorption feature reported by Amati et al. (2000) is that neutral iron is present along the line of sight to the burst. This iron is photoionized by the prompt GRB X-ray photons until all electrons are stripped from the iron ions, causing the disappearance of the edge. But in this case the



size of the region of the absorption feature formation around the GRB site is  $(l = c \cdot t) l \approx 4 \cdot 10^{11} \text{ cm} \approx 6R_{\odot}$ . It is quite immediate environment of the GRB site!

Emission and absorption features in the X-ray spectra of GRBs and their afterglows provide a fundamental new tool to study their close environment (or the circumburst) and thus their possible progenitors. Theoretical computations (Ramirez-Ruiz et al., 2001) show that only a **dense**, massive medium close to the GRB site — such as that expected in the case of a massive progenitor — could produce an iron emission line detectable with the current X-ray instrumentation. Ramirez-Ruiz et al. (2001) argued that high-density shells could be produced from a low-density and low-velocity wind if the massive progenitor or a massive star undergoes a Wolf-Rayet (WR) phase, which is characterized by a strong stellar wind that causes the star to lose enough of its outer layers for the surface hydrogen abundance to become minimal.

The radius of a WR star is sufficiently small before the internal engine ceases to operate. Because of the intrinsic variation of mass-loss rates in WR evolution, we have shells of varying gas density. The effects of the WR ejecta interacting with the interstellar medium (ISM) can be observed in the wind bubbles around some of these objects. The deceleration of a pre-SN wind by the pressure of the surrounding medium or the interaction of fast and slow winds could also create circumstellar shells. Moreover, massive stars tend to lie in associations, so there is the combined effect of the winds of many stars. Thus, the state of the ambient medium of a WR star **at the end of its life** is determined primarily by the time evolution (until core collapse) of the mass-loss rate. Here, by the paper of Ramirez-Ruiz et al. (2001), we emphasize some interesting contributions to the structure of the ambient medium that arise when the ejected winds interact with the ISM during the WR lifetime (about  $10^5$  yr).

From the inside (near WR site) and to the outside: the external medium particle density of the wind ejected by the progenitor is best modeled by a power law  $n = Ar^{-2}$ . A spherical shell with large column density arises when the ejected material accumulates at the radius  $r_{dec}$  at which the free expansion phase of the ejected wind terminates. So, we have set the density of the ambient material  $n_0$  before the WR phase to be  $1 \text{ cm}^{-3}$ . But if a neighbouring star is present, the density ( $n_0$ ) of the surrounding medium can be as large as  $10^6 \text{ cm}^{-3}$ , causing the ejected wind to slow rapidly at a much smaller radius,  $r_{dec}$ . Figs. 2b and 4b from the paper of Ramirez-Ruiz et al. (2001) show the effect of different initial masses on the structure of the ambient medium. The density can be fitted by the power law  $n(r) = Ar^{-2}$  for  $r < r_{dec}$ . The value of the constant  $A = 3.0 \cdot 10^{35} A_*$  as a function of  $M_0$  is shown in panels a. Figs. 2 and 4 show (panels b) also

the radial location ( $r_{dec}$ ) of the highest density shell as a function of initial main-sequence mass  $M_0$  for different values of  $n_0$  and for different metallicity (Fig. 4 in the Ramirez-Ruiz's et al. (2001) paper). The free expansion of the ejected wind is terminated when the swept-up mass becomes comparable to the mass of the wind. The ejected mass then accumulates at the radius  $r_{dec}$ . This overdense region lies closer to the progenitor for higher density  $n_0$  of the surrounding medium (or the density of ambient material before the WR phase) and for WR stars originating from low initial mass stars  $M_0$ . Panels c in Figs. 2 and 4 (Ramirez-Ruiz et al., 2001): all the evolved WR stars have lost their hydrogen envelope (Bisnovatyi-Kogan and Nadyozhin, 1972) and are left with a bare helium core prior to core collapse (or prior to GRB?).

An important result of these calculations for us is the fact that for the initial star masses of  $M_0 \approx 30M_{\odot}$  the region, in which almost all mass ( $\sim 10 - 20M_{\odot}$ ) released during the WR phase is concentrated, can really be of a typical dimension of  $\sim 10^{15} \text{ cm}$ , which is also the result of BeppoSAX, ASCA, and Chandra's X-ray observations of the GRBs (GRB 970508, GRB 970828, GRB 991216, GRB 000214). Whether there exists the overdense region ("bump") or not depends on the density of the ambient material  $n_0$  before the WR phase. (Note – it can be important for the OT GRB 970508 – many WR stars appear to be single; however, the fraction of visible close WR + OB binaries seems to be around 35 per cent.) The internal (or the inside) medium particle density near the GRB progenitor follows the power law  $n = Ar^{-2}$  where  $A = A_* \cdot 3 \cdot 10^{35} \text{ cm}^{-1}$  and  $0.1 < A_* < 10$  for WR stars at the end of their lives. Besides, there can exist a region of dimension of  $2r_{dec} \sim 10^{15} \text{ cm}$  or a more or less sharp boundary in which the released mass is stopped by the interaction between the WR winds and the ISM. Apparently, such a boundary around the WR star or the GRB progenitors should arise in typical star-forming regions with densities of at least and perhaps significantly exceeding  $10 - 100 \text{ cm}^{-3}$ , which is characteristic of large molecular clouds complexes if GRBs are associated with massive stars indeed.

#### 4.2. Optical and X-ray light curves of the OT of GRB 970508

Panaitescu & Kumar (2001) analyzed the afterglows of four **well-studied** GRBs (GRB 980703, GRB 990123, GRB 990510, GRB 991216), assuming that the emission is due to the interaction of a collimated relativistic shock with the ambient medium. They have shown from their particular afterglow shock model that the ambient density of some GRBs can be as low as  $\sim 10^{-1} - 10^{-4} \text{ cm}^{-3}$  by contrast with densities,  $10 - 100 \text{ cm}^{-3}$  (and perhaps even more), that



should be typical of the star-forming regions. But we have to note that the ascribed **paradoxical** densities are very model dependent. We have now the straightforward data from X-ray spectra: *e.g.* GRB 991216 just from their GRB list. (The search for spectral features is one of the primary objectives of Chandra and BeppoSAX's GRB observation programs.) In addition, it should be remarked that Panaitescu & Kumar (2001) in the analysis of multi-wavelength data of four GRBs leave out the **best-studied** OT of GRB 970508, whose optical light curve cannot be entirely explained within the framework of their GRB afterglow shock model, as the OT exhibited a re-brightening after 1 day, indicating a possible delayed energy injection or a strong fluctuation of the external density or the fluctuation of just the same ambient density (or  $n_0$  ?).

Piro et al. (1999) have searched the X-ray spectrum of GRB 970508's afterglow for an Fe line observed by BeppoSAX. They have found such a line but with a limited statistical significance (99.3 %) in the early part (first 16 h) of the afterglow. The line decreases in the later part of the observations ( $\sim 1$  day after the GRB) by at least a factor of 2, enough to make it undetectable with current apparatus. Simultaneously with the line disappearance, the X-ray flux both rises (see Fig. 5b) and hardens consistent with the appearance of a new shock (?). Then, at the end of the outburst, the spectrum steepens. It is most likely that the line of GRB 970508 is produced by fluorescence and recombination of Fe atoms ionized by the intense X-ray flux of the GRB. Judging by the X-ray and  $\gamma$ -ray peak fluxes (Frontera et al., 2000) the prompt X-ray radiation simultaneously detected with the BeppoSAX/GRBM (40–700 keV) and BeppoSAX/WFC (1.5–26 keV) can produce up to 10% of the total energy of GRBs. So, at the early phases of the GRB the radiation field is so high ( $F_X \sim 10^{17} - 10^{18} \text{ erg cm}^{-2} \text{ s}^{-1}$  for  $r = 3 \cdot 10^{15} \text{ cm}$ ) that iron atoms are completely (or nearly) stripped of their electrons. From the line variability for GRB 970508 one can deduce that this ambient medium should be located at the distance of  $c \cdot t \approx 3 \cdot 10^{15} \text{ cm}$  from the GRB source.

That is all at the moment what can be said about the interpretation of the X-ray observations, independently of one or another model adhered by the authors themselves (Piro et al., 1999; see also Vietri et al., 2001). In particular, the estimate of the Fe mass can be model-dependent. Note that the GRB beaming would introduce an additional geometrical factor. This would reduce the complete number of the X-ray's photons and hence reduce the mass of Fe required to produce the emission line. We can try to account for this circumstance after comparison of X-ray and optical data for OT GRB 970508. But we can agree at once with the authors (Piro et al., 1999;

Vietri et al., 2001) in one thing, independently of the model in which the mass of Fe is calculated: in contrast to the fairly clean environment expected in the merging of two neutron stars, the observed line properties would imply that the site of the GRB is embedded in a large mass of material, consistent with some pre-GRB-explosion ejecta arising from a massive star.

Besides, if the scenario "**a massive star**  $\rightarrow$  **WR**  $\rightarrow$  **pre-SN = pre-GRB**" with the formation of a shell around WR is true, then it could be supposed that the reason of the arising of relativistic jet is the powerful light pressure of the prompt X-ray radiation of a GRB source. For the force of the light pressure acting on the environment around the GRB source (WR-star ?) we have  $L_{GRB}/(4\pi r^2) \cdot (\sigma_T/c)$ , where  $L_{GRB}$  is an **isotropic equivalent** ( $\sim 10^{50-51} \text{ erg s}^{-1}$ ) of GRB luminosity,  $r$  is the distance from the center (near the GRB site),  $\sigma_T = 0.66 \cdot 10^{-24} \text{ cm}^2$  is the Thompson cross section,  $c$  – velocity of light. Even without detailed calculation it is clear that such a force can exceed the Eddington limit ( $\sim 10^{38} \text{ erg s}^{-1}$  for  $1 M_\odot$ ) by 12–13 orders. If we assume the GRB radiation (the prompt X-rays +  $\gamma$ -rays) to be collimated or if we have very strong beaming with the solid angle  $\Omega_{beam} \sim (10^{-5} - 10^{-6}) \cdot 4\pi$ , then the formation of an ultra-relativistic jet becomes inevitable. Now everything depends on the ionization, density, and temperature of matter in the immediate vicinity of the GRB source — an asymmetric collapsing nucleus of a massive star. But then the behavior of the X-ray and optical light curves for the afterglow of GRB 970508 (see Figs. 4 and 5), inexplicable within the framework of Panaitescu and Kumar's (2001) afterglow model, becomes quite natural.

From Fig. 4 we see some deviations from an average (or from a "standard") power law in all 4 bands. The broad-band optical spectrum of the OT did not change at all in that period of the exponential brightness fall. The exponential  $B, V, R, I$  behavior of the OT immediately after the maximum (Fig. 5 a) correlates with GRB 970508 X-ray transient light curve (Fig. 5 b) after the obvious minimum (Piro et al., 1998), and the subsequent X-ray flux fading deviates from the power law. The same, the OT decay does not follow any power law (Fig. 4). This is in favor of a common origin of the X-ray and optical events. More than 16%: 6% (in optical) + 10% (or  $\sim 10^{50}$  ergs in X-rays only) of energy of the GRB itself was released in that period. There was some activity which had rather high energy, comparable to that of the GRB burst. And it was on a time scale of ( $\sim 10^5 \text{ s}$ ) 10.000 times longer than the duration of the GRB itself.

This enigmatic re-brightening of the GRB 970508 afterglow could be a consequence of collision of the jet shock fronts with the high density spherical shell or a sharp boundary (or the overdense region) with a dimension of  $2r_{dec} \sim 10^{15} \text{ cm}$  in which the released



mass was stopped during the WR phase of the GRB progenitor. That dense outer shell with a dimension of  $\sim 10^{15}$  cm catches up the essential X-ray energy and we have a new X-ray source of 0.8 day after the GRB (Fig. 5 b). But we do not observe the jet itself. We see (especially in this maximum brightness of GRB 970508 afterglow) the manifestation of both these shocks and (as their effect) a powerful X-ray source arising as the jet moves through the density inhomogeneity ( $\sim 10^{10}$  cm $^{-3}$ ) around the pre-SN (= WR). Apparently, this is just the exponential decay lag of this shell (a spherical layer of a thickness of  $\sim 10^{15}$  cm too) against the background of synchrotron radiation of the shock wave in it that we observe during several days after the maximum (Figs. 4 and 5) for the GRB 970508 afterglow. After this a new X-ray source has flashed out (4–5 days after GRB), only synchrotron radiation of the shock wave remains at passage of the jet through the homogeneous ISM with a density of  $n_0$ , which existed around GRB progenitor or around the WR star. These are approximately the same mechanisms of radiation that are used by Panaitescu & Kumar (2001). But perhaps the strong deceleration due to the interaction of the relativistic shock with the ambient medium does not arise as in their model because the compact relativistic jet (or “bullet”) is decelerating but not the shock. This “bullet” moves at a relativistic speed and the shock (arising as it moves through ISM) only heats this medium.

It is not always that such an overdensity can arise around the GRB progenitors unlike the case of GRB 970508 progenitor. It depends on the value of  $n_0$  and other factors (see Ramirez-Ruiz et al., 2001). But apparently, a sphere of a size of  $\sim 10^{15}$  cm around WR stars often forms with a more or less sharp jump in density at its boundary. In connection with that I make bold to say here some “seditious” thought: the known breaks or steepening of some GRB afterglow light curves (have been interpreted as a collimation effect in GRB-models with fireball) can be explained in this scenario (with the acceleration of the relativistic jet by X-rays +  $\gamma$ -rays) by the same interaction between this jet (or “bullet”) and the inhomogeneous medium around WR. As the jet goes out of this sphere the medium density around the GRB source changes and the sphere flashes on. The breaks will appear at the light curves that are related only to inhomogeneities of  $n(r)$  near the GRB progenitor. (As to the breaks in the light curves see also Pian et al. (2000), Dai and Cheng (2001), and references therein.)

And where does the acceleration of the jet up to a relativistic velocity occur? Now we will try to answer this question. The photon flux producing the radiation pressure accelerating the matter at a distance of  $r$  from the center (near the GRB site) is  $L_{GRB}/(4\pi r^2)$ . It is inside this region and in the immediate vicinity of a GRB source the photon flux turns out to be huge

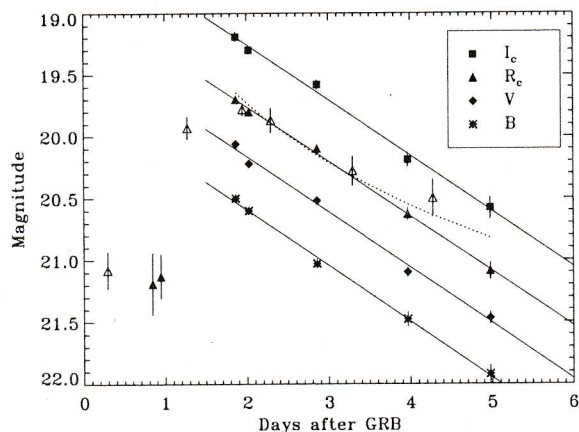


Figure 4: The light curves of GRB 970508 optical counterpart during 5 days after the burst. SAO RAS (filled symbols) and Palomar (open triangles) magnitudes with their errors are shown. The lines correspond to the exponential decline of brightness reported in (Sokolov et al., 1998). For  $R_c$  also the best fit power law is shown (dotted line).

and at least not less than Eddington’s flux. (From definition: if  $L_{Edd}$  is the Eddington limit  $\sim 10^{38}$  erg s $^{-1}$  for 1  $M_{\odot}$ , and  $R_*$  is the size of a compact object of  $\sim 10^6$  cm, then  $L_{Edd}/(4\pi R_*^2)$  is a flux stopping the accretion onto a compact source — the falling of matter on the source at a parabolic velocity.) From the condition that the photon flux  $L_{GRB}/(4\pi r^2)$  at a distance of  $r$  is equal to the  $L_{Edd}/(4\pi R_*^2)$  and taking into account that the luminosity of the GRB radiation is  $L_{GRB} \sim 10^{50-51}$  erg s $^{-1}$  (an isotropic equivalent), it is possible to obtain an estimate of the size ( $l$ ) of the region in which the light pressure accelerates the matter around the GRB source to relativistic and ultrarelativistic (for  $r < l$ ) velocities:  $l \sim 10^{12}$  cm  $\approx 14R_{\odot}$ . So, it can be near the region of a size of  $\approx 6R_{\odot}$ , which follows from the observation of the variable absorption feature in the prompt X-ray emission of GRB 990705 (Amati et al., 2000).

## 5. Summary

There is circumstantial evidence that GRBs are associated with the collapse of massive stars. The observations in optical (GRB host galaxies, OT light curves) and GRB X-rays (light curves and spectra) suggest that this is so. Nevertheless, does every long GRB begin with the core-collapse supernova explosion? It is still early to draw firm conclusions — new observations are needed — but in any case a link between GRBs and SNe seems to be convincingly confirmed. Weak emission line features 8–40 hours after the GRB may also result from the supernova GRB scenario. In all these cases significant X-ray absorption features,



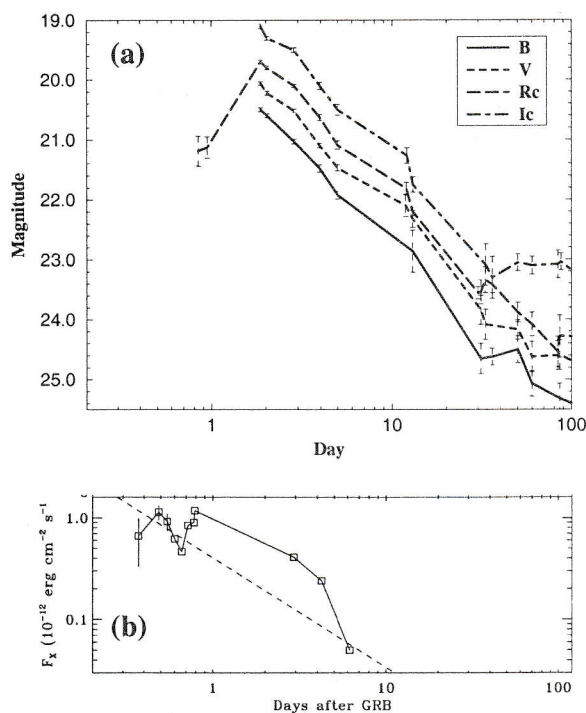


Figure 5: GRB 970508 light curves: (a)  $BVR_cI_c$  SAO RAS data; (b) 2–10 keV BeppoSAX MECS X-ray data (Piro et al., 1998), the power law with the slope of  $-1.1 \pm 0.1$  is shown (dashed line).

in particular during the prompt GRB phase, are expected. No significant X-ray spectral features should result from compact-object binary mergers.

Here an attempt is undertaken to understand the light curves (in X-ray and in optical) of the OT of GRB 970508 which have never been explained properly so far. The X-ray spectra and the light curves (like OT GRB 970508) some of GRB afterglows point to the existence of **the dense medium surrounding GRB sources**, which, combined with the data on GRB host galaxies and the manifestations of SNe on the light curves, agrees well with the scenarios where the GRB progenitor (or pre-SN) is a WR star.

If a GRB progenitor always coincides with a pre-SN progenitor (or GRB progenitors are actually WR stars), then the GRB radiation is always very collimated. Then the formation of relativistic jets becomes an inevitable consequence of huge radiational pressure owing to the huge flux during the GRB. We have not known so far how to produce such a narrow bunch of hard X-rays and  $\gamma$ -rays or what the mechanism of GRBs is. (The same as fireball GRB model makers do not know how to produce it — the fireball.) But in that scenario, with the **straightforward** link of the GRBs and core-collapse SNe and (as a result) with the strong  $\gamma$ -ray beaming, the energetics of the

GRB sources is substantially lower and the energy release is not higher than the bolometric luminosity of SNe. So, we can reduce the GRB problem to the old one — the problem of the SNe explosion mechanism. But this is a relief too — the number of hypotheses on the GRB sources does not increase at least.

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