Bohdan’s Impact on Our Understanding of Gamma-ray Bursts

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**Abstract.** Bohdan Paczyński was one of the pioneers of the cosmological GRB model. His ideas on how GRBs operate and what are their progenitors have dominated the field of GRBs in the hectic nineties during which the distances and the origin of GRBs were revealed. I discuss here Bohdan’s contributions in some historical perspective.

1. Prologue

I first met Bohdan in the summer of 1977 at the IOA. I don’t remember the exact date, but I remember the time. It was between 3am and 4am. Several of us were trying to open the last remaining bottle of wine at the traditional IOA summer (Argentinean) barbecue. Something did not work out. Bohdan approached us and succinctly pointed out that the process will be much easier if we remove first the plastic warp that covered the cork. We did. It worked. This was a simple demonstration of Bohdan’s ability to see the obvious simple fact that everyone else around stared at - but no one sees.

Our next meeting took place several years later at Princeton. Bohdan and his family moved to the Institute housing, where I lived as well. I have spent many pleasant evenings visiting them. We enjoyed many discussions. When we did not discuss life in America versus life in Europe those conversations turned naturally to Gamma-Ray Bursts (GRBs) - a subject that fascinated both of us.

2. Introduction - GRBs as we understand them today

I begin with a brief description of the present picture of GRBs and their models. This section is not intended to be a comprehensive review (see Piran 1999; Mészáros 2002; Piran 2005; Mészáros 2006; Woosley & Bloom 2006; Zhang, 2007 for recent reviews and Fishman & Meegan, 1995; Piran 1995 for a historical perspective). My objective is to outline our current understanding so that Bohdan’s contributions and impact can be put into the right perspective and be appreciated.

GRBs are short and intense ($\sim 10^{-7} – 10^{-5}\text{ergs/cm}^2$) bursts of soft (10 keV - 2 MeV) gamma rays coming from random directions in the sky. GRBs were discovered accidentally in the late sixties by the Vela satellites - defense satellites that were sent to monitor the outer space treaty. The discovery was reported only in 1973 (Klebesadel et al.). In the early nineties the BATSE detector on-board of the COMPTON-GRO satellite indicated that GRBs are cosmological
Towards the late nineties the BeppoSAX satellite discovered X-ray afterglows (Costa et al., 1997). Optical (van Paradijs et al., 1997) and Radio (Frail et al., 1997) afterglows followed shortly. Direct redshift measurement of the optical afterglow of GRB 970508 (Matzger et al., 1997) established the cosmological origin of GRBs. Radio scintillation (Goodman, 1997) and later VLBI observations (Taylor et al., 2004) confirmed the relativistic bulk motion, predicted earlier by the fireball model. In the following years afterglow observations revealed a wealth of information on host galaxies (Djorgovski et al. 2003) and the positions of GRBs within host galaxies, which was always within star forming regions (Paczyński 1998, Fruchter, 2006).

GRB belong to two groups (Kouveliotou et al. 1993) according to their durations $T_{90}$: Long GRBs ($T_{90} > 2$ sec) and short ($T_{90} < 2$). Short bursts are also typically harder and hence they are called at times short hard bursts (SHBs). The association of several long GRBs with supernovae (Galama et al. 1998; Bloom et al. 1999; Stanek et al. 2003; Hjorth, et al. 2003) confirmed the Collapsar model (Woosley 1993; Paczyński 1998; Mészáros & Rees, 1992, Rees & Mészáros, 1994) according to which (long duration) GRBs arise during the collapse of massive stars. The origin of short GRBs is less certain. Unlike long GRBs, short ones do not arise in star forming regions. They arise in both elliptical and spiral galaxies (see e.g. Nakar 2007 for a review). The redshift distributions shows that the observed short bursts are much nearer than the observed long ones (Guetta & Piran, 2006; Nakar et al., 2006). These observations are consistent with earlier suggestions that short GRBs arise from neutron star mergers (Paczyński, 1986; Eichler et al., 1999). Within this model the delay corresponds to the gravitational radiation spiral in time. The delay is crucial also in positioning the progenitors away from their birth places, possible even outside the original galaxy.

The internal-external shocks model (also called the fireball model) (Goodman 1986; Paczyński, 1986; Shemi & Piran, 1990; Mészáros & Rees 1992, Rees & Mészáros, 1994, Narayan, Paczyński & Piran, 1992; Sari & Piran 1997, Wijers, Rees & Mészáros, 1997) is depicted in Fig. 1. It suggests that GRBs involve ultrarelativisitic (baryonic or Poynting flux) jets that emerge from compact objects, most likely black holes. Internal collisionless shocks or instabilities within the relativistic outflow, that take place at $10^{14} - 10^{16}$ cm from the central engine, accelerate particles to relativistic velocities and generate strong magnetic field. Synchrotron or SSC emission of these particles produce the prompt emission. The outflow interacts later with the surrounding medium producing a relativistic blast wave - a relativistic analogue of a Supernova remnant. This long lasting blast wave accelerates particles and generates magnetic fields that produce the multiwavelength afterglow. The predictions (Sari, Narayan & Piran, 1998; Sari, Halpern & Piran, 1999) of this “standard model” agreed nicely the observed light curves and spectra of GRB afterglows (Wijers & Galama, 1999; Kulkarni et al., 1999; Panaitescu & Kumar 2002; Yost S.A., et al., 2003). Recent Swift observations indicate that the picture is somewhat more complicated than what is described here. Still for the purpose of this review this description is sufficient.
The Internal-External Fireball Model

Figure 1. The standard internal-external shocks model of GRBs (see e.g. Piran 1999; Mészáros 2002; Zhang and Mészáros 2004; Piran 2005; Mészáros 2006 for reviews). 1. Central engine and acceleration of the flow. 2. Coasting phase; terminal Lorentz factor $\Gamma > 100$. 3. Internal shocks; prompt gamma-ray emission. 4. The interaction of the outflow with the surrounding matter produces the external shocks system with a blast wave propagating outwards producing the afterglow.

3. Prehistory - GRBs before BATSE

The history of GRBs should be divided to two period. Pre and post BATSE. At the pre-BATSE era (up to the late eighties and very early nineties) a consensus formed that GRBs originate in magnetic instabilities on galactic neutron stars. What was considered as a strong evidence for this model was the detection of 20 and 40 keV lines which were interpreted as cyclotron lines of a $\sim 10^{12}$ Gauss field - a magnetic field expected in neutron stars.

Bohdan was skeptical. He never believed the observed 20 and 40 keV lines e.g.(see Narayan, Paczyński & Piran, 1992) - insisting that there was never the case that the same line was observed simultaneously from the same burst by two different detectors. With no lines there was no compelling case for galactic neutron stars and the road to cosmological sources was open. If the bursts are cosmological they release much more energy $\sim 10^{51}$ergs or more. A basic problem with any cosmological model was that GRBs have non-thermal spectra indicating that they are optically thin. However, the temporal variability (less
than a fraction of a second) indicated that the emission region is small (less than $10^9$ cm). If $10^{51}$ ergs of soft gamma-rays (with numerous photons above 500 keV) are released from such a source there would be copious pair production that will lead to an optically thick source. This is the so called "Compactness problem".

Figure 2. The “Compactness problem”. Left: light curves for different bursts. Variability on very short time scales is clearly seen. Right: The spectrum of GRB 910601. The nonthermal spectrum is clearly seen. If $10^{51}$ ergs of radiation with many photons above $m_e c^2$ (as seen in this spectrum) are released within a small region (as indicated by the temporal variability) numerous pairs will form and the radiation-pairs plasma will be optically thin.

The breakthrough concerning the resolution of the "Compactness problem" came in 1986 when two back to back papers where published in the Astrophysical Journal Letters by Jeremy Goodman (1986) and Bohdan Paczyński (1986). Both papers describe an idealized problem in which a hot radiation, a fireball, with $T_0 \gg m_e c^2$ is released within a small region. They argues that the radiation will form a radiation-pair plasma fluid that will expand rapidly. As the fireball accelerates it cools (in its local frame). When the local temperature drops below $m_e c^2$ the pair begin to annihilate. There are enough pairs to keep the fireball optically thick until the local temperature drops to $\sim 20$ keV when the fireball become optically thin. By this time the fireball has reached a relativistic motion with $\Gamma \sim T_0/(20 \text{ keV})$. The photons escape freely now. Because of the relativistic motion the escaping photons will be seen by an observer at rest with
approximately the original temperature $T_0$. Jeremy solved the problem in the impulse approximation, considering the case of an “explosion”. Bohdan, on the other hand, considered a steady state approximation in which the evolution was approximated as a steady wind. The results were more or less similar. The papers were the first to suggest that GRBs involve relativistic motion. A concept that was verified more than ten years later first using radio scintillations (Goodman, 1997) and later with direct VLBI measurements (Taylor et al., 2004). While the two papers are closely related, they are not similar. Goodman focuses on the physics and is very concerned with the fact that at the end the resulting photons have a thermal like spectrum. Bohdan, on the other hand, is not so worried about this issue and he uses this model to put forward his idea that GRBs are in fact cosmological. He even goes on to suggest, in the discussion section of his work, that some reoccurring sources arise because of gravitational lensing of cosmological events.

At that time we spent many hours discussing what could drive such events. Our discussions focused on neutron star mergers. Objects that at the time became popular among relativists as it was realized that they are prime candidates for detection as sources of gravitational radiation. Our discussions evolved around the final stages in which tidal interaction between the two stars will tear them apart, and Bohdan borrowed here a lot from his work on binaries. Still Bohdan was reluctant to publish a paper with a model describing mergers as GRB sources. My guess was that what he really cared most at the time was to "win the cosmological war" on the distances to the bursts. He was probably worried that linking the cosmological idea to the very speculative merger model (Neutron star mergers were considered as somewhat esoteric events in those days), might weaken his cosmological case. Bohdan speculated on this merger possibility very briefly in two or three sentences in his 1986 paper and returned to it (actually to a variant - black hole neutron star merger (Paczyński, 1991)) only in the early nineties. I went on and published these ideas, with a detailed model on how a merger can produce a GRB, in 1989 (Eichler, Livio, Piran & Schramm 1989). We wrote our joint paper on this subject only in 1992 (Narayan, Paczyński & Piran, 1992). I will return to this paper later in this talk.

4. BATSE, the Cosmological-Galactic War and the Great Debate

The Burst and Transient Source Experiment, BATSE, on board of the Compton-GRO satellite, was expected to demonstrate that GRBs are galactic. BATSE’s spectrograph was supposed to detect the lines and its ability to localize the bursts within a few degrees was sufficient to demonstrate that the bursts are within the galactic disk. It is difficult to imagine the shock when BATSE’s first results were announced in the fall of 1991: No lines, Isotropic distribution with no dipole moment (corresponding to our position relative to the galactic center), and last but not least a paucity of weak bursts (Meegan et al., 1992). The results were accepted with disbelief and at first were sort of ignored. Most of the talks, at least most of the theoretical talks, given at the first Huntsville symposium, that took place in October 1991, dealt with various aspects of the galactic neutron star model. A whole session was devoted to magnetospheric
instabilities on neutron stars. One speaker, J. P. Lasota, withdrew his talk on
a galactic model and stated that it became irrelevant in view of the new data.
Bohdan (Paczyński, 1992) and me (Piran, Narayan & Shemi 1992) were the only
speakers that dealt with cosmological models in that meeting.

Both Bohdan (Mau & Paczyński, 1992) and me (Piran 1992) rushed to
publish letters on the essential cosmological interpretation of BATSE’s result.
We stressed that the combination of an isotropic distribution, that at that stage
was demonstrated by upper limits on the dipole moment of the distribution (see
e.g. Fishman et al.1994; Hakkila et al.1994) and the paucity of weak bursts,
which at that stage was not demonstrated by a full log $N – \log S$ distribution
(see Fig. 3) but by the very low $(V/V_{max}) = 0.32$ value (see e.g Fishman et
al.1994; Hakkila et al.1994) forced a cosmological distribution. The argument
was surprisingly simple. If the sources are galactic their angular distribution
must show a significant dipole moment, unless (i) Their radial distribution is
extremely local (and we don’t see the galactic structure) or (ii) The radial dis-
tances are very large so that the typical distance compared to our distance from
the galactic center is large. Possibility (i) is ruled out by the $(V/V_{max})$ value.
A small industry begum by proponents of the galactic models that threw GRB
sources to larger and larger distances in the galactic halo (e.g. Podsiadlowski
et al.1995). As the limits on the dipole moment become tighter and tighter
the average distance needed for the sources continuously increased. I vividly re-
member Bohdan joking that with a typical distance of 200kpc one might call the
model cosmological... Additionally, as the distances increased so did the energy
budget until even the galactic models suffered from the Compactness problem
(Shemi & Piran, 1993).

Bohdan was very excited during this period. He enjoyed the lively (at
times too lively) debate that went on. He told me that in order to prevent
misunderstanding or misrepresentations of his ideas he was signing, at that time,
all GRB referee reports that we wrote. He was most amused when Nature
published a galactic origin paper (Lingenfelter & Higdon 1992) and refused to
publish his rebuttal because “our readers will be confused if we published two
contradicting opinions”. Both of us had a great time making fun of some of
the models. Surprisingly the fight went on for quite some time. At the second
Huntsville meeting that took place at the fall of 1993 more than half of the
audience still believed in galactic origin and this situation persisted even in the
“Great Debate” that took place in 1995.

The debate culminated in the “Great Debate” that too place in April 1995
at the Smithsonian in Washington, D.C., between Bohdan (Paczyński, 1995) and
Don Lamb (Lamb 1995). Bohdan’s abstract presents his argument best: “The
positions of over 1000 gamma-ray bursts detected with the BATSE experiment
on board of the Compton Gamma Ray Observatory are uniformly and randomly
distributed in the sky, with no significant concentration to the galactic plane or
to the galactic center. The strong gamma-ray bursts have an intensity distrib-
ution consistent with a number density independent of distance in Euclidean
space. Weak gamma-ray bursts are relatively rare, indicating that either their
number density is reduced at large distances or that the space in which they are
distributed is non-Euclidean. In other words, we appear to be at the center of
a spherical and bounded distribution of bursters. This is consistent with the
Figure 3. Right: The distribution of BATSE bursts on the sky, in galactic coordinates. The isotropy is self evident now. Left: the log($N$) − log($S$) plot. The number of bursts with $N$ with a peak flux larger than $S$. In a homogenous distribution we should see a straight line with a slope of $-3/2$.

distribution of all objects that are known to be at cosmological distances (like galaxies and quasars), but inconsistent with the distribution of any objects which are known to be in our galaxy (like stars and globular clusters). If the bursters are at cosmological distances then the weakest bursts should be redshifted, i.e., on average their durations should be longer and their spectra should be softer than the corresponding quantities for the strong bursts. There is some evidence for both effects in the BATSE data. At this time, the cosmological distance scale is strongly favored over the galactic one, but is not proven. A definite proof (or dis-proof) could be provided with the results of a search for very weak bursts in the Andromeda galaxy (M31) with an instrument 10 times more sensitive than BATSE. If the bursters are indeed at cosmological distances then they are the most luminous sources of electromagnetic radiation known in the universe. At this time we have no clue as to their nature, even though well over a hundred suggestions were published in the scientific journals. An experiment providing 1 arc second positions would greatly improve the likelihood that counterparts of gamma-ray bursters are finally found. A new interplanetary network would offer the best opportunity.”
It was the 75th anniversary of the Curtis and Shapley 'Great Debate' (where the size of the Universe was contested just three years before Edwin Hubble made his seminal discovery about its expansion and thus the size of the Universe). The parallel of the Curtis/Shapley and GRB debates could not be more poignant: just as few changed their minds about the size of the Universe after the 1920 debate as have changed their mind about the distances of GRBs after this one. The audience was split roughly 50% 50% at the end of this discussion. I must say that when I heard the results of the vote at this debate I was shocked. To me at that time the question what are the distances of GRBs was not an open question (Piran 1995).

Bohdan was very happy about this work. In a report of his achievements in a NASA grant that he posts (in a very unusual manner) on astro-ph (Paczyński, 1996) he writes: “The research project: 'Models and Scenarios for Gamma-Ray Bursts' resulted in a total of 20 published research papers. The central issue was the distance scale to gamma-ray bursters, the issue brought up by the remarkable discovery of the distribution properties of gamma-ray bursts by the BATSE on Compton GRO. The last paper on the reference list is the PI’s contribution to the debate on the distance scale to gamma-ray bursts held in Washington DC on 22 Apr. 22 1995. When this project got started, right after the announcement of the BATSE results at the conference in Annapolis in the fall of 1991, only a small fraction of astrophysicists seriously considered the possibility that gamma-ray bursts are at cosmological distances. By now the cosmological distance scale has become a majority view, to a large extent because of the publications listed in this final report. PI considers this to be the most important and lasting result from the research supported by this grant.”

The debate ended with the measurement of the redshift of the optical afterglow of GRB 970508 (Metzger et al., 1997). It is amusing to recall that even after this observation “conspiracy theories” suggesting coincidence between this GRB and the observed afterglow was put forwards for a while.

5. Building a theoretical model - how GRBs work

In 1986 Bohdan contributed to the early ideas on a thermal fireball. However, it was clear that this idea is rather preliminary. The resulting emission from this simple fireball has a quasi-thermal spectrum, quite unlike what is observed. Additionally, it was clear that this picture of a pure radiation (and pairs) fireball was too idealized.

5.1. From Radiation and Baryons to Ultra relativistic Baryonic outflow

The next question was what would be the effects of baryons on such a pure radiation fireball. Here, once more we have worked in parallel on the same problem and the results were published more or less simultaneously (Abramowicz, Novikov & Paczyński, 1990; Shemi & Piran, 1990). Both works have shown that the addition of even a small baryonic load would change drastically the outcome. The baryons will be dragged along and accelerated by the radiation field. If the total baryonic load is not too small eventually all the initial thermal energy will be transferred to the kinetic energy of the baryons. If the baryonic load is not
too large, that is $m < E_0/c^2$ the final outcome will be a relativistic baryonic outflow with $\Gamma = E_0/M$ ($E_0$ being the total energy and $M$ the baryonic mass). This was a step in the right direction but it was not good enough. Relativistic baryons can serve as a source of cosmic rays. But what we have to find a way to convert their kinetic bulk energy back to radiation.

5.2. Astro-ph/9204001

In the spring of 1992 Bohdan gave a colloquium, on the cosmological origin of GRBs at Harvard. I was amused by the fact that talk was on March 5th - the anniversary of the famous 1979 March 5th GRB. This was the only well localized GRB at that time, and it was in the LMC - giving credence to the Galactic origin. By now we know that it was not a regular GRB but a soft Gamma repeater (SGR) but this is another story. Bohdan stayed for a whole week during which we wrote, together with Ramesh Narayan, “Gamma-Ray Bursts as the death throes of massive binary stars” (Narayan, Paczyński & Piran, 1992- NPP92).

This paper, astro-ph/9204001, is the first astro-ph. It is a well known, highly cited (more than 400 citations) paper. Most remember it because of the serious attempt to build a consistent merger model for GRBs. However, in addition to discussing neutron star mergers that it contained several new ideas that helped shape our theoretical understanding of GRBs:

- Internal shocks

- GRBs are powered by accretion onto a newborn black holes.

- The duration of the GRB is determined by the activity of the inner engine (accretion onto the black hole) while the duration of the pulses is determined by the dynamical time scale of the source

- GRBs should be followed by a long lasting Afterglow

- Binary neutron stars has a long spiraling-in phase before they merge. As they receive a large kick when the binary is born they can escape during this phase from their host galaxy.

- $10^{15}$Gauss magnetic fields may exist at GRBs’ inner engines.

Somewhat surprising, or maybe not, the paper was not easily accepted. The first referee simply rejected it as (i) too speculative and (ii) irrelevant because GRBs are galactic. The second one accepted it reluctantly stating: “It three well respected well known scientists what to make fools of themselves who am I to stop them. I was very happy to be referred to as a “respectable and well known scientist” but I suspected that I gained this title because of my co-authors. I was even happier that the paper was accepted. In retrospect given the “anti-cosmological” atmosphere at that time we should have been grateful to have had such a broad minded referee.
5.3. From Matter to Light  Internal Shocks

The most urgent question was how to convert the relativistic baryonic outflow to radiation. The solution proposed in NPP92 was internal shocks: “These ejecta should, through collisions with one another at large radii and low optical depth, give a non Planckian spectrum by various nonthermal mechanisms. For instance given the strong magnetic fields, synchrotron processes might naturally produce the observed power-law spectrum.”. This was of course just a short exposition of the idea and Bohdan continues to elaborate on it later in 1993 together with Ghuohong Xu (Paczyński & Xu 1993). The basic idea is that the source is irregular and it emits a wind with a variable Lorentz factor. An idealized picture of such a wind is a situation when the outflow is in the form of shells that moves with different Lorentz factors. Faster shells collide with slower ones. Paczyński & Xu (1993) consider within this context proton proton collisions that produce pions that decay producing Gamma-Rays. However this won’t be very efficient. Later on Rees & Mészáros (1994)suggested the picture accepted now according to which the collisionless shocks that form accelerate particles to very high energies and possibly also generate strong magnetic fields. These shocks are the source of the observed prompt emission. The schematic picture is depicted as a central part of Fig. 1 and in Fig. 4. It is central now to our current model. However at the time the simpler external shocks picture proposed a few years earlier by Mészáros and Rees (1992) - namely interaction of the outflow with the surrounding matter- was considered as the source of the prompt emission. Only in 1997 we (Sari & Piran, 1997) have shown that external shocks cannot produced the observed variable light curves and as of today internal shocks are the only known viable way to convert the kinetic energy of the outflow to radiation and produce a highly variable light curve!

It should be stressed that the same ideas hold for Poynting flux dominated outflow, a possibility that is considered seriously now as an alternative to the baryonic outflow. The kinematic arguments that require internal process within the outflow are applicable regardless of the exact nature of the outflow. The main difference of course is that in the Poynting flux case instabilities such as reconnection replace the collisionless shocks. But the basic feature that external interaction cannot produce the variable light curves remains.

The idea of internal shocks is linked directly to another important issue. In internal shocks the temporal structure of the burst is determined by the inner engine. The duration is determined by the time that the source is active while the dynamical time scale of the source dictates the short term fluctuations time scale seen in the individual pulses. The need of a prolonged activity of the inner has pointed out towards accretion onto a newborn black hole as the main candidate for the activity

5.4. From Matter to Light  Afterglow

Clearly, not all the kinetic energy can be dissipated in internal shocks. Only the relative kinetic energy can be dissipated there. The bulk center of mass kinetic will remain. This leads immediately to the idea of an afterglow: “The ejecta should much later also produce something similar to a supernova remnant.” (NPP92). With James Rhodas, (Paczyński & Rhodas, 1993) Bohdan continues to elaborate on this idea. They use the analogy with supernova to es-
Bohdan's GRBs

Figure 4. Internal shocks are produced from a variably flow (schematically depicted as shells). The faster shells catch up with the slower ones and produce the shocks. The system is, most likely, powered by an accretion disk and $10^{15}\text{ Gauss field could arise in this disk.}$

timate that GRBs will be followed by a radio transients. More detailed models focusing on higher energies were suggested later by numerous authors, (Mészáros & Rees, 1997; Wijers, Rees & Mészáros, 1997; Waxman, 1997; Sari, Piran & Narayan, 1998). Still this was the first suggestion that GRBs will be followed by a long duration afterglow.

The afterglow prediction was verified in 1997 with the discovery of X-ray afterglow by BeppoSAX (Costa et al., 1997). This discovery was followed by detection of optical (van Paradijs et al., 1997) and radio (Frail et al., 1997) afterglows as well.

6. GRB progenitors - mergers and hypernovae

The question what makes GRBs is of course the central one for the whole problem. Once it was realized that the bursts are cosmological and the energy budget was set to be around $10^{51} - 10^{52}\text{ergs it was clear that the sources involve a compact object. Most likely the formation of the object and the release of its binding energy, and if not that at least a significant catastrophic event. The neutron star merger model, which is currently the most likely to work for short GRBs,
was proposed already in the eighties (Paczyński, 1986; Eichler et al., 1999). For a while it was thought that this is the model for all GRBs.

However, when BeppoSAX begun detecting X-ray afterglows and host galaxies were revealed, it turned out that GRBs (actually long GRBs, as BeppoSAX detected afterglow only from long GRBs) are located within small irregular star forming galaxies. Now we know that within these galaxies GRBs are located in the highest star forming regions and that the rate of GRBs is roughly proportional to the square of the rate of star formation (Fruchter et al., 2006). Bohdan did not need much data to make a far reaching conclusion. At the fall of 1997 he concluded on the basis of just three well localized GRBs, 970228, 0970508 and 980828 that GRBs arise in the vicinity of star forming regions (Paczyński, 1998). He concludes that the merger model must be abandoned and GRBs must be linked to death of massive stars. “There is tentative evidence that the GRBs 970228, 970508, and 970828 were close to star-forming regions. If this case is strengthened with future afterglows, then the popular model in which GRBs are caused by merging neutron stars will have to be abandoned, and a model linking GRBs to cataclysmic deaths of massive stars will be favored.”

In a typical manner Bohdan ignored the theoretical prejudice against this idea. At the time baryonic contamination was a major concern. Within the fireball model discussed above it was clear that a significant baryonic load will result in a non-relativistic outflow which won’t be able to drive a GRB. Collapsing stars have large envelopes that could be a strong source of contamination. However, observations are more important than theory and if the bursts are near star forming regions they must involve stellar death. Bohdan outlines a model based on Woosley’s (1993) “failed supernova” on accretion and Blandford-Znajek mechanism (1976) and suggests that GRBs operate like microquasars.

Once again Bohdan’s ability to grasp the basic point from a dismal amount of data leads to a great success. A few month later Galama et al., (1998) discovered that a very powerful type Ic SN 1998bw is associated with GRB 980425! At the same time MacFadyen & Woosley (1999) demonstrate that a sufficiently powerful jet can punch a hole in a stellar atmosphere, (provided that the later is sufficient small as would be the case if the Hydrogen envelope has escaped). As more and more SN like bumps were discovered on GRB afterglow light curves (Bloom et al., 1999) the model gained credibility. It was eventually proven with GBR 030339/SN 2003dh where an 98bw like SN spectrum arose just as expected from the GRB optical light curve (Staneck et al., 2003; Hjorth, J., et al. 2003).

In the process Bohdan coined the name Hypernovae (Paczyński, 1998). Bohdan anticipated that GRB associated collapse events are more powerful than a regular supernovae and hence they should be given a name indicating that. Hyper is clearly more powerful than Super. It turned out that the first GRB associated supernova SN 1998bw was indeed much more powerful than average and indeed GRB associated supernovae do show higher velocity ejecta and are more powerful than other type Ic SNe.
7. Some ideas for the future: Neutrinos, GRB remnants and optical flashes preceding GRBs

Bohdan has left many ideas to be tested in the future.

7.1. GRB neutrinos

Already in 1994 Bohdan noticed (Paczyński & Xu, 1993) that internal shocks within GRBs can produce high energy neutrinos. In this specific model proton-proton collisions between protons from different shells produce pions, which in turn produce the observed gamma-rays as well as 30 GeV neutrinos. In fact, more energy is released in this case in neutrinos than in gamma-rays.

Proton-proton collisions are not very efficient and they can produce only a weak GRB signal. To overcome this problem Paczyński and Xu proposed that the bursts are very narrow beamed. As far as we understand GRBs today both ideas are invalid. GRBs are beamed but the jets are much wider. Proton-proton collisions are indeed not efficient enough to produce the observed prompt emission. However, what we do take from this paper today is first the basic concept of internal shocks within the outflows and second the idea that GRBs are prime candidates for being sources of high energy neutrinos - an idea that is generally accepted today (see e.g. Achterberg et al. (2007) for a description of a recent search using AMANDA).

7.2. GRB remnants

Several times we have worked in parallel on related idea. The last one was in the early 2000. It was realized at that time that GRBs are beamed (Rhodas, 1999; Sari et al., 1999; Kulkarni et al., 1999). It was also realized that the afterglow, in which the Lorentz factor is much lower is essentially less beamed. One expects therefore, orphan afterglows. Afterglows whose GRB prompt emission does not points towards us. An intriguing question was how to search for such orphan afterglows. The late radio phase is naturally the longest one. But this phase is the weakest. Additionally, if one waits too long the afterglow becomes spherical and indistinguishable from a regular Supernova remnant.

However, for a period of 5000 years it is possible to see within the GRB remnant a bipolar structure that is induced by the original nonspherical GRB jets (Ayal & Piran, 2001). This will enable us to distinguish GRB remnants from SNRs. Bohdan (Paczyński, 2001a) build on these ideas and estimated that at any time there should be several dozen relatively nearby GRB radio remnants which can be resolved with VLBA as being bipolar rather than spherical. He suggested to combine this idea with other methods to detect imprints of GRBs such as the effect of the original gamma-rays on the interstellar medium (Draine, 2000) and perform a systematic search for GRB remnants. Such a search was not done yet. It is something that Bohdan has left for the future.

7.3. Optical Flashes

In recent years Bohdan was fascinated with the transient Universe (Paczyński, 2001). This was not surprising. After all both microlensing events and GRBs to whom he devoted his research in recent years are transient phenomenon. He kept constantly looking for new possible “flashes” that will shine in the night sky.
Along this line Bohdan noticed an exciting idea of Beloborodov (2002) that the prompt emission can cause a cascade of pairs at a distance of $\sim 10^{18}$ cm from the origin. The idea is simple. Some gamma-rays will interact with the surrounding matter and will be reflected backwards. Each photon that is reflected backwards will certainly interact with the outgoing radiation and produce a pair. The produced pairs will increase the number of back scattered photons and will accelerate the process causing a possible runaway. Bohdan suggested that with the right conditions (Kumar & Panaitescu, 2004) a cloud of pairs will form and this cloud will be opaque to gamma-rays. Until this cloud is cleared away only lower energy photons will be seen. Bohdan suggested, therefore, that an optical flash will appear in such a case and that this flash will precede the gamma-rays (Paczyński, 2001). He was worried, however, that such flashes might be missed, as they appear before the GRB trigger, and he searched for method to detect them.

8. Epilogue

Bohdan was dominant in convincing the community that GRBs are cosmological. However, he also had far reaching contributions that shaped our current
understanding of how GRBs operate. The scope of these contributions is best realized by presenting once again Fig. 1, that describes the basic theory of GRBs, but now with Bohdan’s contributions superimposed on it. His ideas on hypernova, links with star formation, internal shocks, afterglow that looks like a SNR, and above all the cosmological origin of GRBs all paved the ways to the present “standard” model.

Figure 6. Bohdan’s major contributions to the current GRB model.

The fast response satellite Swift that was launched three years ago have changed to a large extend the simple picture that we had before. It turns out that, like in other cases in Astronomy, the afterglow picture is more complicated than what was originally thought. In particular the early X-ray light curve, as seen by Swift is rather different from the previous expectations, showing unexpected rapid decline that is followed by a shallow phase before joining the more familiar light curve at about $10^4$ sec (Nousek et al., 2006). At present it is not clear what are the processes that control this light curve. One widely discussed possibility is that energy is added to the blast wave during the shallow phase. It is interesting to note that already in 1993 Bohdan discussed the possibility that a significant amount of energy can come out from the inner engine in a low Lorentz factor material (Paczynski & Xu, 1993). “The slower material with a low Lorentz factor will be gradually added to the blast wave”. This kind of “energy injection” is in fact the leading interpretation today of this phase (see e.g. Zhang et al., 2006; Granot, Konigl & Piran, 2006).

Another interesting issue is the fact that Swift has observed bursts that are further out than what is expected if the bursts simply follow the SFR (Natarajan et al., 2005, Daigne et al., 2006; Guetta & Piran, 2007). There are more distance bursts than the simple model suggests. This result is consistent with the fact
that in space GRBs are more concentrated in high SFR regions, as if they follow a higher power of the SFR. It could be that the relevant factor is low metalicity (Fynbo, 2003) but the possibility of evolution of the luminosity function or another unexpected factor cannot be ignored.

Other long standing open questions have existed before Swift and are still with us: What is the exact working of the inner engine, what is the nature of the relativistic outflow and how do collisionless shock accelerate particles and generate magnetic fields? It is illuminating to read what were Bohdan’s thoughts about all that: “It is not likely that the concept of a GRB as a microquasar powered by the Blandford & Znajek (1977) mechanism can be proven or disproven on purely theoretical grounds. It is useful to realize, that while we have plenty of sound evidence that Type II supernovae explode as a result of some ‘bounce’, or whatever process following the formation of a hot neutron star, there is no generally accepted physical process which would be efficient enough to make this happen. The theoretical problem with the SN II explosions persists in spite of 2 or 3 decades of intense effort by a large number researchers. The problem is vastly worse with the GRBs as they are $10^4 - 10^5$ times less common than supernovae. This might imply that a very special set of circumstances is necessary to generate the suitable energetic explosion”.

Bohdan was probably right. It will take time, a lot of detailed observations and ingenious theoretical insight to figure out all those details. However, regardless of the different variants of the current model and the current observational puzzles I am sure that Bohdan’s basic ideas on how GRBs work will be with us forever to stay.

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