Gamma-Ray Bursts in the SALT/Swift Era: GRB/SN Connection

Krzysztof Z. Stanek

kstanek@cfa.harvard.edu
Harvard-Smithsonian Center for Astrophysics
60 Garden St., MS20
Cambridge, MA 02138

Abstract. Invited talk at the First International Workshop on “Stellar Astrophysics with the World Largest Telescopes”, Toruń, Poland, 7-10 September 2004. I discuss the Gamma Ray Burst research in the era of SALT and Swift, concentrating on the GRB/SN connection.

INTRODUCTION

The mechanism that produces gamma-ray bursts (GRBs) has been the subject of considerable speculation during the three decades since their discovery (Klebesadel, Strong & Olson 1973). The CGRO and BATSE observations demonstrated that GRBs are isotropically distributed on the sky (Meegan et al. 1992), which could have been explained with either a Galactic (Lamb 1995) or a cosmological (Paczyński 1995) spatial distribution. The BeppoSAX satellite (Boella et al. 1997) contributed the breakthrough in this field by providing rapid and accurate localizations of X-ray afterglows of GRBs. Such precision allowed for quick optical (Groot et al. 1997; van Paradijs et al. 1997) and radio (Frail et al. 1997) identifications of transients associated with individual GRBs. The identification of the optical transient (OT) associated with GRB 970508 led to the first optical spectroscopic redshift determination for a GRB, placing it at $z \geq 0.835$ (Metzger et al. 1997), and thus firmly at a cosmological distance. However, despite the great progress made in GRB science since 1997, many problems remain open. I discuss some of them, concentrating on the GRB/SN connection. I also discuss some of the exciting GRB science that could be done with the SALT telescope.

GRB SCIENCE WITH LARGE TELESCOPES

Large telescopes played a very significant role in the GRB science since the discovery of first GRB afterglows in 1997. Obviously, large telescopes can do things that smaller telescopes cannot do, such as obtaining spectroscopy of very faint sources (such as faint afterglows or GRB host galaxies) or high-resolution spectroscopy of fairly faint objects. Perhaps more importantly, given the unpredictable timing of GRBs, large telescopes allow us to obtain very significant results in relatively short telescope time, defined as "how much telescope time can I ask for from a random (even if friendly) observer on
a remote telescope who has her/his own important program to do, before he/she gets annoyed with me”? It is my experience that up to one hour per night is doable. It is important to realize that most large telescope users do not sit around waiting for a GRB worker to call them and tell them what to do, so common sense should be applied. Common Polish heritage and passion for pierogies helps in some cases. Of course, with a queue-scheduled telescope like SALT, the life of a GRB researcher becomes a bit easier, but not boring.

Below I list several areas of important GRB science explored with the largest telescopes:

- **Redshifts of the GRBs**: This can be measured via absorption lines in an intervening galaxy or galaxies (as was done for the first GRB redshift by Metzger et al. 1997 using Keck 10-m telescope), via emission lines of the host galaxy superimposed on the featureless power-law spectrum of the afterglow (as was done for example for GRB 011121 by Garnavich et al. 2003a using Magellan 6.5-m telescope), or via absorption lines in the spectrum of the host galaxy. For a review on the hosts of GRBs, their redshifts and properties see Djorgovski et al. (2003) The first method, in principle, does not require large telescopes, given a bright enough afterglow and the presence of absorption lines (indeed, Jha et al. 2001 were able to measure three different absorption systems in the afterglow of GRB 010222 using our FLWO 1.5-m telescope!), but large aperture helps, given that most afterglows decay quickly.

- **High-resolution spectroscopy of GRB afterglows**: High-resolution spectra have now been obtained for several afterglows (see for example Schaefer et al. 2003). In a number of cases a complicated line structure with multiple components has been observed (see for example a nice paper by Mirabal et al. 2003 on “GRB 021004: A Possible Shell Nebula around a Wolf-Rayet Star Gamma-Ray Burst Progenitor”), allowing us to probe the environment of the GRB.

- **Optical polarization of the GRB afterglows**: This is truly the domain of the largest telescopes, given the photon-starved nature of polarization research (i.e. trying to measure a very small effect in the light of fairly faint objects). Despite this challenge, polarization has been now successfully measured in a number of afterglows. The first detection was accomplished using imaging polarimetry of a fairly bright afterglow of GRB 990510 with the 8-m VLT (Covino et al. 1999; Wijers et al. 1999). Spectropolarimetry has been obtained for several afterglows now as well, starting with GRB 020813 (Barth et al. 2003), using Keck 10-m telescope. The level of optical polarization is usually low, 1-2%, except in the case of GRB 020405, where 9.9% polarization has been measured 1.3 days after the burst (Bersier et al. 2003a) with the 6.5-m MMT.

The above was not intended as a review, but rather as a brief illustration of some of the many interesting results obtained for the GRBs with the largest telescopes. Needless to say, many exciting results for the GRBs were obtained with mid-sized or in some cases truly small telescopes (9th magnitude optical flash from the GRB 990123, observed with a 10-cm robotic ROTSE telescope, comes to mind: Akerlof et al. 1999). For an interested reader, there are many excellent reviews out there to learn more about GRBs. I found the recent review by Piran (2004) to be very useful.
FIGURE 1. $UBVRIJ$ light curves of GRB 011121. Included are three $HST$ F702W epochs converted to the standard $R$-band. Dotted lines show the OT power-law decay and the dashed line is the light curve of hypernova SN 1998bw redshifted to $z = 0.36$, converted to the $R$-band, corrected for extinction and scaled by 0.1 mag. The solid line shows the combination of the OA and SN 1998bw (from Garnavich et al. 2003a).

GAMMA-RAY BURST/SUPERNOVA CONNECTION

The measured redshift of a typical GRB is $z \approx 1$, implying that a supernova component underlying an optical afterglow would be difficult to detect. At $z \approx 1$, even a bright core-collapse event would peak at $R > 23$ mag. Nevertheless, late-time deviations from the power-law decline typically observed for optical afterglows have been seen and these bumps in the light curves have been interpreted as evidence for supernovae (for a recent summary, see Bloom 2003). GRB 980425 was likely associated with “hypernova” 1998bw (Galama et al. 1998), but the isotropic energy of that burst was $10^{-3}$ to $10^{-4}$
times weaker than classical cosmological GRBs which placed it in a unique class. Before March 2003, the best evidence that classical, long-duration gamma-ray bursts are generated by core-collapse supernovae was provided by GRB 011121. It was at $z = 0.36$, so the supernova component would have been relatively bright. A bump in the light curve was observed both from the ground and with HST (Garnavich et al. 2003; Bloom et al. 2002). The color changes in the light curve of GRB 011121 were also consistent with a supernova (designated SN 2001ke), but a spectrum obtained by Garnavich et al. (2003) during the time that the bump was apparent did not show any features that could be definitively identified as originating from a supernova.

While SN 1998bw was a strong hint of the GRB-SN association, no optical afterglow was observed. Without that direct association, the link between GRBs and SNe was still in question. The ‘monster burst’ of 2003, GRB 030329 provided that link. The burst was extremely bright in gamma-rays, implying that it was relatively close, as was quickly confirmed by the VLT spectroscopy of the afterglow, which yielded $z = 0.168$ (Greiner et al. 2003). As the afterglow faded, subtle features appeared in the normally flat power-law spectrum of the afterglow. By subtracting a continuum based upon the early shape of the spectrum, this structure was revealed as the spectrum of an unusual Type Ic SN similar to SN 1998bw, designated SN 2003dh (Matheson et al. 2003a; Garnavich et al. 2003b; Stanek et al. 2003). Within a few days, the SN became the dominant component in the spectrum (Stanek et al. 2003; Kawabata et al. 2003; Hjorth et al. 2003w).

Using the early power-law continuum spectrum as a model, one could decompose the observed spectra at later times into two separate components: GRB afterglow and SN spectrum. Using a least-squares technique, the best match for the SN among the low-redshift sample was SN 1998bw (Matheson et al. 2003b). In fact, taking into account cosmological time dilation, the spectroscopic evolution of SN 2003dh almost exactly matched SN 1998bw. Models of these spectra are presented by Mazzali et al. (2003).

An important point about the appearance of the SN was that the light curve did not show the bump that is characteristic of a rebrightening caused by the SN (see Matheson et al. 2003b and Lipkin et al. 2004 for a discussion of the light curve, which actually showed many bumps). Without the spectroscopic confirmation, the presence of SN in GRB 030329 would still be argued about.

Nebular-phase spectra of SN 2003dh show a spectrum similar to a typical Type Ic SN. Kosugi et al. (2004) present a spectrum at an age of $\sim 3$ months. A spectrum obtained with the Keck telescope by Filippenko, Chornock, & Foley (2004) in December of 2003 is much like a normal Type Ic SN (Bersier et al. 2005, in preparation).

Following the discovery of SN 2003dh, reexamination of spectra of an earlier burst yielded some evidence for a SN component. Della Valle et al. (2003) found that a spectrum of the very faint afterglow of GRB 021211 had structure similar to an SN. In this case, however, the SN did not match SN 1998bw or any other peculiar Type Ic SN, but it was most similar to SN 1994I, a relatively normal Type Ic.

Another example of the GRB/SN connection came with GRB 031203. Despite high foreground reddening, spectroscopy with the VLT revealed an SN component, designated SN 2003lw (Malesani et al. 2004). For this SN, SN 1998bw was again a good match. Of the four SNe with clear GRB associations, three show remarkably similar spectra.
\[ -2.5\log(f_\lambda) + \text{Constant} \]

FIGURE 2. Evolution of the GRB 030329/SN 2003dh spectrum, from March 30.23 UT (0.75 days after the burst), to April 10.14 UT (11.66 days after the burst). The early spectra consist of a power-law continuum with narrow emission lines originating from H II regions in the host galaxy at \( z = 0.1685 \). Spectra taken after \( \Delta T = 6.66 \) days show the development of broad peaks characteristic of a supernova (from Matheson et al. 2003b).

FUTURE DIRECTIONS OF THE GRB/SN CONNECTION

There is now indisputable evidence that some classical (long duration/soft spectrum) GRBs come from core-collapse supernovae. But there are only two classical bursts (GRB 030329 and GRB 031203) where the progenitor supernovae have been definitively classified. SN 2003dh and SN 2003lw were type Ic events similar to the progenitor of the underluminous GRB 980425. Some theorists have concluded that all supernovae that
FIGURE 3. MMT spectrum of GRB 030329 from April 8 with the smoothed MMT spectrum of April 1 scaled and subtracted. The residual spectrum shows broad bumps at approximately 5000Å and 4200Å (rest frame), which is similar to the spectrum of the peculiar type Ic SN 1998bw a week before maximum light. The match is not as good for SN 1998bw at maximum light (from Stanek et al. 2003).

produce GRB are type Ic. The bias toward type Ic is partly due to the perceived difficulty in getting the jet to escape from a star with a massive envelope. But this prejudice may not be justified; after all, it was recently believed that no supernova could possibly be a GRB source because of the large baryon content of supernovae. I feel that the range of SN types that are responsible for GRBs is an unsolved observational problem.

There are hints of a diversity in the supernova progenitors of GRB. SN1997cy was a powerful type II supernova that may have been associated with a classical GRB (Germany et al. 2000), though connection to a particular GRB has not been strongly established. A better indication comes from GRB 011121 and its associated supernova 2001ke. Garnavich et al. (2003a) found the color near maximum of SN 2001ke was very
blue which is more consistent with a type II event than a type Ic. Unfortunately, there was no spectrum of the event with sufficient quality to establish the supernova type.

The small number of supernovae directly associated with GRB also leaves the question of the energetics unanswered. The supernovae that produced GRB 980425 and 030329 were two of the most energetic core-collapse events recorded. But the supernova that produced GRB 011121 was somewhat fainter and faded quickly. What is the range of supernova luminosities? Is there a connection between the energy of core col-

FIGURE 4. Evolution of the GRB 030329/SN 2003dh spectrum, from April 24.28 UT (25.8 days after the burst), to May 24.38 (55.9 days after the burst). The power-law contribution decreases and the spectra become more red as the SN component begins to dominate. The upturn at blue wavelengths may still be the power law. The broad features of a supernova are readily apparent, and the overall spectrum continues to resemble that of SN 1998bw several days after maximum (from Matheson et al. 2003b).
FIGURE 5. Relative contribution of a supernova spectrum to the GRB 030329/SN 2003dh afterglow as a function of time in the $B$ (open circles) and $R$ (filled squares) bands. We derived a best fit to the afterglow spectrum at each epoch with the fiducial power-law continuum and the closest match from our set of peculiar SNe Ic. We then synthesize the relative $B$-band and $R$-band contributions. There is some scatter for the early epochs due to noise in the spectra, but a clear deviation is evident starting at $\Delta T = 7.67$ days, with a subsequent rapid increase in the fraction of the overall spectrum contributed by the SN. Errors are estimated from the scatter when the SN component is close to zero ($\Delta T < 6$ days) and from the scale of the error in the least-squares minimization (from Matheson et al. 2003b).

Frail et al. (2001) corrected the observed GRB energy for the beam opening angle and found that most bursts produce a total energy of $10^{51}$ erg. While this is a very large amount of energy, it is still an order of magnitude less than the total energy in a typical core-collapse supernova. Clearly, there is sufficient energy in a core-collapse to allow a wide range of supernovae to produce high-energy beams. The greatly improved sensitivity of Swift will allow low-energy bursts to be detectable out to a large volume of space. This will be an important test of the single-energy reservoir theory as well as the ability of supernovae with a range of properties to create GRB.

The few supernovae associated with GRBs also lead theorists to conclude that GRB are produced promptly by the core-collapse of massive stars. But this could be an observational bias. It is possible that GRBs occur within a wide range of times following...
core-collapse, and we only detected those few bursts that occurred less than a few days after the supernova. In support of this possibility, a number of GRB have not been seen with accompanying supernovae (e.g. Price et al. 2003). The ‘supranova’ model predicts that the final collapse of a neutron star into a black hole can be delayed by seconds to years after the initial core-collapse. While it would be difficult to show a supernova went off years before a burst using optical wavelengths, supernovae that exploded weeks to a month before the GRB could be detected with careful observation.

Obtaining magnitudes, colors and spectra of more GRB supernovae is clearly a top priority in understanding the origin of long/soft bursts. Since the typical GRB has a redshift of $z \sim 1$, this work requires large telescopes such as SALT.
A MODEST PROPOSAL FOR SALT IN THE SWIFT ERA

The Swift satellite (Gehrels et al. 2004) will push the GRB research into an even higher gear, with > 100 GRBs per year rapidly and accurately localized. SALT is very well positioned to take full advantage of Swift, due to a number of factors:

- Unique position on the globe;
- Queue schedule;
- Stable instrumentation for several years;

For the description of SALT and its capabilities, see Buckley 2004 (this volume). The first item on the list is obvious, i.e. despite limitations on pointing, due to its location in South Africa SALT will be able to access some of the GRBs not possible to observe from the North or to observe them earlier than possible from Chile, where other large southern telescopes are located. Queue scheduling is even more important, allowing certain programs to be executed which would not be possible otherwise, for example to observe an object each night for a month or a year. Stability of the instrumentation (PFIS\(^1\)—The Prime Focus Imaging Spectrograph—will be always available for the first several years), combined with the queue schedule, will allow one to obtain very uniform data sets over long periods of time, which is very hard to do on other large telescopes.

Here are several GRB projects to consider over the first several years of the SALT operation:

- GRBs-SNe connection: observe every \( z < 0.5 \) GRB afterglow (several a year) at 15-20 epochs during the first month after the burst and during 5-10 epochs later. This will answer the questions posed above: what are the GRB progenitors, do they form a uniform class?
- Physics of the afterglow: obtain polarization light curves of several bright afterglows per year for 3-7 days each. This will be important to understand the physics of the GRB emission and to test the jet model of the afterglow.
- Very short timescale variability of GRB afterglows. We have reported short-timescale afterglow variability in two cases (GRB 011211: Holland et al. 2002; GRB 021004: Bersier at al. 2003b). In some cases the afterglows are very smooth (GRB 990510: Stanek et al. 1999; short-timescale variability <0.5% for GRB 020813: Laursen & Stanek 2003). Again, the ability of SALT to perform very rapid photometry (Charles 2004, this volume) is unique among the largest telescopes.

Many other projects can be proposed, here I tried to concentrate on areas where the strengths of SALT would be well utilized. Earlier during the conference, we were encouraged to think about truly large projects (“what would you do with infinite time on SALT”) to be done with SALT during the first few years. Being a reasonable person, I decided not to use “infinite time”, just 10% of it, to spend one hour every night to obtain various kinds of data (depending on the brightness) for any GRB afterglow that is

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\(^1\) http://www.sal.wisc.edu/pfis/
observable from SALT that night. Such a project would be a major undertaking, but with the expected Swift GRB rate the sample of well observed afterglows would easily double in just several months, and there would be many surprises and new exciting results.

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