SUMMARY OF *SWIFT* OBSERVATIONS OF GAMMA RAY BURSTS

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ABSTRACT

Swift is a NASA MIDEX mission with primary objective to study gamma-ray bursts (GRBs) and use them as probes of conditions in the high-redshift Universe. It is an international mission with hardware participation by the US, UK and Italy. The mission was launched on 20 November 2004 and is detecting $\sim$ 100 gamma-ray bursts (GRBs) each year. For almost every burst there is a prompt (within $\sim$ 90 s) spacecraft repointing to give X-ray and UV/optical observations of the afterglow. *Swift* has already collected an impressive database including prompt emission to higher sensitivities than BATSE, uniform monitoring of afterglows, and rapid follow-up by other observatories notified through the GCN. Significant progress has been made in our understanding of short GRBs. The detection of X-ray afterglows has led to accurate localizations and the conclusion that short GRBs can occur in non-star forming galaxies or regions, whereas long GRBs are strongly concentrated within star forming regions. This is consistent with the NS merger model. *Swift* has greatly increased the redshift range of GRB detection. The highest redshift GRBs, at $z \sim 5-6$, are approaching the era of reionization. Ground-based deep optical spectroscopy of high redshift bursts is giving metallicity measurements and other information on the source environment to greater distances than other techniques. The localization of GRB 060218 to a nearby galaxy, and association with SN 2006aj, added a valuable member to the class of GRBs with detected supernova. The prospects for future progress are excellent given the >10 year orbital lifetime of the *Swift* satellite.

Key words: Gamma Ray Bursts.

1. INTRODUCTION

GRBs are the most powerful explosions in the Universe and are thought to be the birth cries of black holes. They are a product of the space age, discovered [1] by Vela and observed by satellites for 40 years. Despite impressive advances over the past three decades, the study of bursts remains highly dependent on the capabilities of the observatories which carried out the measurements. The era of the *Compton Gamma Ray Observatory* (*CGRO*) led to the discovery of more than 2600 bursts in just 9 years. Analyses of these data produced the key result that GRBs are isotropic on the sky and occur at a frequency of roughly two per day all sky [2]. The hint from earlier instruments was confirmed that GRBs come in two distinct classes of short and long bursts, with distributions crossing at ~ 2 s duration [3]. The *BeppoSAX* mission made the critical discovery of X-ray afterglows of long bursts [4]. With the accompanying discoveries by ground-based telescopes of optical [5] and radio [6] afterglows, long GRBs were found to emanate from star forming regions in host galaxies at typical distance of $z = 1$. *BeppoSAX* and the following *HETE-2* mission also found evidence of associations of GRBs with Type Ic supernovae. This supported the growing evidence that long GRBs are caused by "collapsars" where the central core of a massive star collapses to a black hole [7].

The next chapter in our understanding of GRBs is being written by the *Swift* mission. In this paper we discuss the findings of *Swift* and their relevance to our understanding of GRBs. We also examine what is being learned about star formation, supernovae and the early Universe from the new results.

2. *SWIFT* GRB OPERATIONS & OBSERVATIONS

Swift [8] carries 3 instruments, a wide-field Burst Alert Telescope (BAT) [9] that detects GRBs and positions them to arcmin accuracy, and the narrow-field X-Ray Telescope (XRT) [10] and UV-Optical Telescope (UVOT) [11] that observe their afterglows and determine positions to arcsec accuracy, all within $\sim$ 100 seconds. The BAT detects the bursts in the $15-350$ keV band and determines a few-arc-min position onboard within 12 s. The position is provided to the spacecraft which is then re-pointed to the burst location in less than 2 minutes to allow XRT and UVOT observations of the afterglow. Alert data from all three instruments is sent to the ground via NASA's *TDRSS* relay satellite. The full data set is stored and dumped to the Italian Space Agency's equatorial Malindi Ground Station.

The *Swift* mission was built by an international team from the US, UK, and Italy. After five years of development it was launched from Kennedy Space Center on 20 November 2004. Full normal operations commenced on 5 April

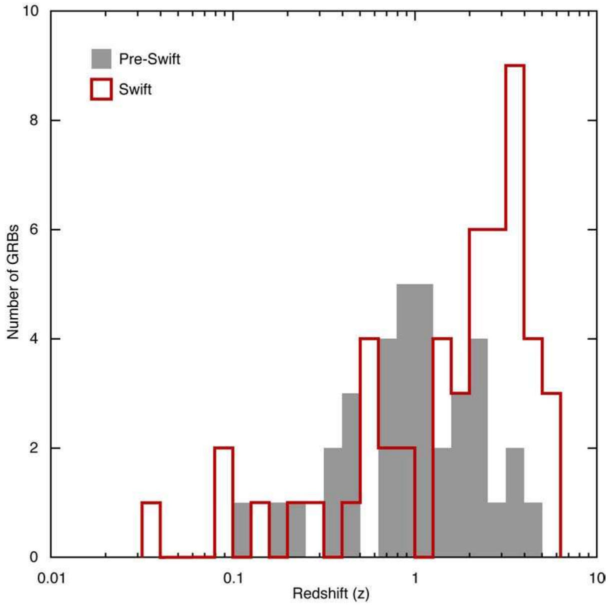

Figure 1. Redshift distribution of Swift detected bursts compared to the pre-Swift sample.

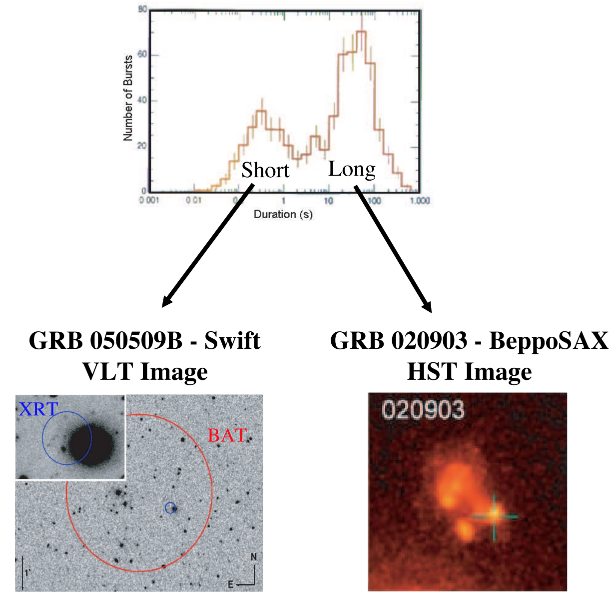

Figure 2. Comparison of the host galaxies of short and long bursts. The short burst GRB 050509B [20] is offset from a bright elliptical galaxy with low star formation rate. The long burst GRB 020903 [20] is located in a star forming region.

2005.

As of August 2006, BAT has detected 168 GRBs (annual average rate of $\sim$ 105 per year). Approximately 90% of the BAT-detected GRBs have repointings within 5 minutes (the remaining 10% have spacecraft constraints that prevent rapid slewing). Of those, virtually all bursts observed promptly have detected X-ray afterglow. The fraction of rapid-pointing GRBs that have UVOT detection is $\sim$ 30%. Combined with ground-based optical observations, about 50% of *Swift* GRBs have optical afterglow detection.

There are 57 *Swift* GRBs with redshifts. This total from the first 1.7 years of *Swift* operations is more than the number found from all previous observations since 1997. The distribution in redshift is given in Figure 1. It is seen that *Swift* is detecting GRBs at higher redshift than previous missions due to its higher sensitivity and rapid afterglow observations. The average redshift for the *Swift* GRBs is $< z >= 2.3$ compared to $< z >= 1.2$ for previous observations. Jakobsson et al. [12] find that the *Swift* redshift distribution is consistent with models where the GRB rate is proportional to the star formation rate in the Universe.

3. SHORT GRBS

At *Swift*'s launch, the greatest mystery of GRB astronomy was the nature of short-duration, hard-spectrum bursts. Although more than 50 long GRBs had afterglow detections, no afterglow had been found for any short burst. In May 2005 (GRB 050509B), *Swift* provided the first short GRB X-ray afterglow localization [13]. This burst plus the *HETE-2* GRB 050709 and *Swift* GRB 050724 led to a breakthrough in our understanding [20-24,13,25] of short bursts. BAT has now detected $\sim$ 13 short GRBs, most of which with XRT detections, and about half of which with host identifications or redshifts (an additional two have been detected by *HETE-2*).

In stark contrast to long bursts, the evidence to date on short bursts is that they can originate from regions with low star formation rate. GRB 050509B and 050724 were from elliptical galaxies with low current star formation rates while GRB 050709 was from a region of a star forming galaxy with no nebulosity or evidence of recent star formation activity in that location. The difference between host galaxies for short and long GRBs is illustrated in Figure 2. The data from the first 3 well-localized short bursts support the interpretation that short bursts are associated with an old stellar population, and may arise from mergers of compact binaries [i.e., double neutron star or neutron star - black hole (NS-BH) binaries].

There have been 18 short GRBs detected to date since GRB 050509B. This includes all bursts that researchers have discussed in the context of short events. Some, such as GRB 050911, 060505 and 060614 are uncertain as to their long or short classification.The 5 unambiguous short events with secure redshifts are concentrated near $z = 0.2$, but with some events as far away as $z = 2$, or possibly higher. It has been suggested [21] that there are separate populations of short bursts that are nearby ($z \lesssim 0.5$) and farther away ($z \gtrsim 1$). With the caveat that statistics are poor and the population appears diverse, the redshifts for short bursts are smaller on average by a fac-

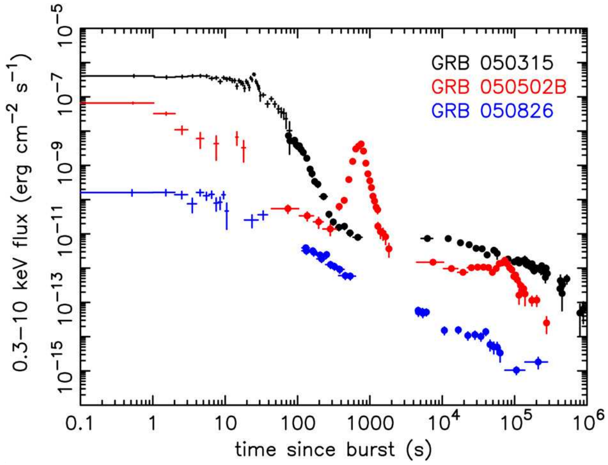

Figure 3. Example GRBs with steep-to-shallow transition (GRB 050315), large X-ray flare (GRB 050502B) and more gradually declining afterglow (GRB 050826; flux scale divided by 100 for clarity). Figure from K. L. Page and P. T. O'Brien.

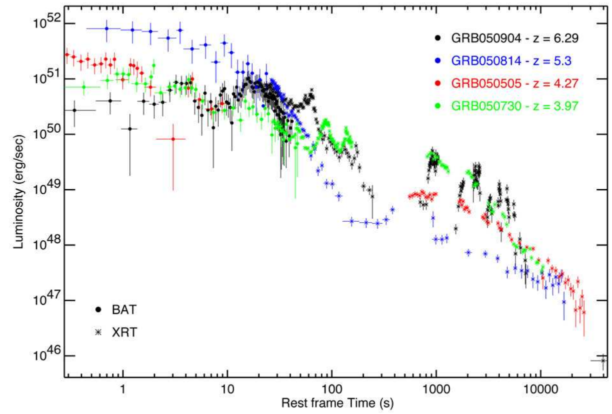

Figure 4. Lightcurves (BAT-XRT) of 4 high-z Swift bursts. Figure from G. Cusumano.

tor of ~ 4 than those of long bursts ($< z_{\rm short} >= 0.5$, $< z_{\rm long} >= 2.3$), and their isotropic energies are smaller by a factor of ~ 100.

4. AFTERGLOW PHYSICS

Swift was specifically designed to investigate GRB afterglows by filling the temporal gap between observations of the prompt emission and the afterglow [22]. The combined power of the BAT and XRT has revealed that in long GRBs the prompt X-ray emission smoothly transitions into the decaying afterglow (Figure 3). Often, a steep-to-shallow transition is found suggesting that prompt emission and the afterglow are distinct emission components. The early steep-decay phase seen in the majority of GRBs is a surprise. The current best explanation is that we are seeing high-latitude emission due to termination of central engine activity [23].

Swift has discovered erratic flaring behavior (Figure 3), lasting long after the prompt phase in $\sim 25\%$ of X-ray afterglows. The most extreme examples are flares with integrated power similar to or exceeding the initial burst [24]. The rapid rise and decay, multiple flares in the same burst, and cases of fluence comparable with the prompt emission, suggest that these flares are due to the central engine.

5. HIGH REDSHIFT GRBS AND COSMOLOGY

GRBs, as the most brilliant explosions we know of, offer us the potential to probe the early Universe into the epoch of reionization. They can trace the star formation, reionization, and metallicity histories of the Universe [25-28]. GRBs are $100 - 1000$ times brighter at early times than are high redshift QSOs (the near infrared afterglow of GRB 050904 was $J = 17.6$ at 3.5 hours). Also, they are expected to occur out to $z > 10$, whereas QSOs drop off beyond $z = 3$.

Six of the 8 highest redshift GRBs ever seen were discovered by *Swift*, including bursts at redshifts $z = 5.3$ and 6.3 [29-31]. Of the GRBs with measured redshift, we find that 4 out of 50 or $\sim 8\%$ of *Swift* GRBs lie at $z > 5$, consistent with model predictions [12, 32]. These same models predict that *Swift* can detect GRBs to redshifts of $z > 8$. A great deal of effort is currently being invested to rapidly recognize such bursts and obtain redshifts with large ground-based IR spectrographs.

Figure 4 shows the time evolution of gamma-ray and X-ray fluxes of 4 high-z GRBs. All of these bursts are quite luminous and long-lasting, and their evolution can be very complex.

6. THE GRB-SN CONNECTION

6.1. Observations of GRB 060218/SN 2006aj

On 18 February 2006 *Swift* detected the remarkable burst GRB 060218 that provided considerable new information on the connection between SNe and GRBs. It lasted longer than and was softer than any previous burst, and was associated with SN 2006aj at only $z = 0.033$. The BAT trigger enabled XRT and UVOT observations during the prompt phase of the GRB and initiated multiwavelength observations of the supernova from the time of the initial core collapse.

The spectral peak in prompt emission at ~ 5 keV places GRB 060218 in the X-ray flash category of GRBs [33], the first such association for a GRB-SN event. Combined BAT-XRT-UVOT observations provided the first direct observation of shock-breakout in a SN [33]. This is inferred from the evolution of a soft thermal component in the X-ray and UV spectra, and early-time luminosity variations. Concerning the supernova, SN 2006aj was dimmer by a factor ~ 2 than the previous SNe associated with GRBs, but still $\sim 2-3$ times brighter than normal SN Ic not associated with GRBs [34, 35].

GRB 060218 was an underluminous burst, as were 2 of the other 3 previous cases. Because of the low luminosity, these events are only detected when nearby and are therefore rare occurrences. However, they are actually ~ 10 times more common in the Universe than normal GRBs [36].

6.2. The Peculiar Case of GRB 060614

GRB 060614 was a low-redshift, long-duration burst with no detection of a coincident supernova to deep limits. It was a bright burst (fluence in $15-150$ keV band of 2.2×10^{-5} erg cm^{-2}) and well studied in the X-ray and optical. With a T90 duration of 102 s, it seemingly falls squarely in the long burst category. A host galaxy was found [30-32] at $z = 0.125$ and deep searches made for a coincident supernova. All other well-observed nearby GRBs have had supernovae detected, but this one did not to limits > 100 times fainter than previous detections [37-39].

We have found that GRB 060614 shares some characteristics with short bursts [40]. The BAT light curve shows a first short, hard-spectrum episode of emission (lasting 5 s) followed by an extended and somewhat softer episode (lasting $\sim$ 100 s). The total energy content of the second episode is five times that of the first. This light curve shape is similar in many respects to that of several recent *Swift* and *HETE-2* short-duration bursts (GRB 050709, 050724, 050911, 051227) and a subclass of BATSE short bursts [41]. There are differences in that the short episode of this burst is longer than the previous examples and the soft episode is relatively brighter.

Another similarity with short bursts comes from a lag analysis of GRB 060614 [40]. Figure 5 shows the peak luminosity ($L_{\rm peak}$) in *Swift* GRBs as a function of their spectral lag ($t_{\rm lag}$) between the $50-100$ keV and $15-25$ keV bands. For long bursts there is an anti-correlation between $t_{\rm lag}$ and $L_{\rm peak}$, whereas short bursts have small $t_{\rm lag}$ and small $L_{\rm peak}$ and occupy a separate area of parameter space. The lag for GRB 060614 for the first 5 s is 3 ± 6 ms which falls in the same region of the lag-luminosity plot as short bursts.

It is difficult to determine unambiguously which category of burst the well-observed GRB060614 falls into. It is a long event by the traditional definition, but it lacks an associated SN as had been seen in all other nearby long GRBs. It shares some similarities with *Swift* short bursts, but has important differences such as the brightness of the extended soft episode. If it is due to a collapsar, it is the first indication that some massive star collapses either fail as supernovae or highly underproduce ^{56}Ni. If it is due to a merger, then the bright long-lived soft episode is

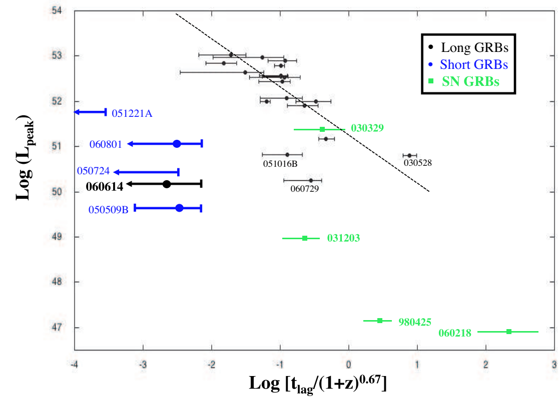

Figure 5. Spectral lag as a function of peak luminosity showing GRB 060614 in the region of short GRBs. The lags and peak luminosities are corrected to the source frame of the GRB. The data points labeled as long bursts are from Swift, with the exception of GRB 030528 which is a very long-lagged HETE-2 burst. The blue data points for short bursts are from Swift. In green are the 4 nearby long GRBs with associated SNe. Three of the four (980425, 031203 and 060218) fall below the long-burst correlation, while the only SN-associated GRB with normal luminosity (030329) falls near the long-burst line. From ref. [40].

hard to explain for a clean NS-NS merger where little accretion is expected at late time (but might fit in a NS-BH scenario). In any case, this peculiar burst is challenging our classifications of GRBs.

7. CONCLUSIONS

The study of GRBs has advanced greatly in the past 2 years. *Swift* is providing rapid and accurate localizations, which lead to intensive observing campaigns by *Swift* and ground-based observatories starting ~ 1 minute after the GRB trigger. Uniform multiwavelength afterglow light curves are available for the first time for a large number of bursts. The data have led to a break-through in our understanding of short GRBs, have extended our knowledge of the high redshift Universe, have elucidated the physics taking place in the highly relativistic GRB fireball outflows and have added significantly to the study of the connection between GRBs and SNe. The *Swift* mission has an orbital lifetime of > 10 years and no expendable resources on board, and so is likely to greatly expand on these results with detailed observations of > 1000 bursts.

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