

Gamma-ray observations with Swift and their impact

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Abstract. The Swift gamma-ray burst explorer was launched on Nov. 20, 2004 from Cape Canaveral, Florida. The first instrument onboard became fully operational less than a month later. Since that time the Burst Alert Telescope (BAT) on Swift has detected more than 180 gamma-ray bursts (GRBs), most of which have also been observed within two minutes by the Swift narrow-field instruments: the X-Ray Telescope (XRT) and the Ultra-Violet and Optical Telescope (UVOT). Swift trigger notices are distributed worldwide within seconds of the trigger through the Gamma-ray burst Coordinates Network (GCN) and a substantial fraction of GRBs have been followed up by ground and space-based telescopes, ranging in wavelength from radio to TeV. Correlations of Swift bursts with neutrino and gravity wave detectors have promise of finding the first non-electromagnetic signature of a GRB. Swift is also a sensitive X-ray observatory with capabilities to monitor galactic and extragalactic transients on a daily basis, carry out the first all-sky hard X-ray survey since HEAO-1, and study in detail the spectra of X-ray transients as part of coordinated multi-wavelength observing campaigns.

1. Introduction

The Swift satellite[1] carries three astronomical instruments that work together to study all aspects of gamma-ray bursts (GRBs) over a wide range of energies. The instruments are the Burst Alert Telescope[2] (BAT), a coded aperture hard X-ray telescope that serves as the GRB trigger for Swift, the X-Ray Telescope[3] (XRT), a grazing incidence X-ray telescope, and the UltraViolet Optical Telescope[4] (UVOT), a Ritchey-Chrétien telescope that provides coverage into the optical band. For details of each instrument see the individual references. A significant feature of Swift (and the feature that gives the satellite its name) is the ability for Swift to swiftly and autonomously slew to a newly detected GRB within ~ 70 seconds to allow detailed multi-wavelength observations to be carried out with all three instruments.

Swift is also a sensitive instrument for the study of other X-ray and UV emitting objects. This includes the observations of > 100 AGN in the BAT hard X-ray survey and studies of galactic X-ray transient sources with the XRT. Since the BAT covers such a large (2 steradian) field of view, it is able to serve as a hard X-ray transient monitor for > 200 galactic and extra-galactic sources as well as a detector of new transient sources. Swift non-GRB studies are summarized in Section 3.

2. Gamma-Ray Bursts

Swift has detected 188 gamma-ray bursts between December 17, 2005 and October 25, 2006. Nearly all have been followed up with the Swift NFIs. GRB afterglows are observed starting

seconds after the burst and lasting for days to weeks in most cases. A large fraction of these bursts have also been observed by ground-based telescopes and other satellites.

2.1. Short GRBs

Among the most significant findings from Swift is the localization of 11 short gamma-ray bursts and the detailed studies of their afterglows. Localizations and subsequent host identifications and redshifts from ground-based observations have been obtained for five short bursts. It has been seen that short bursts are a nearer population than long bursts, with an average redshift one-sixth as large as long bursts and isotropic energies a factor of 100 smaller. Unlike long bursts, the host galaxies of short bursts have low star formation rates and are located in both elliptical and dwarf host galaxies. These findings combine to point to an old stellar population as progenitors and a likely origin as the coalescence of degenerate binaries (either a pair of neutron stars or a neutron star-black hole binary).

However, there are still unexplained mysteries about the short bursts studied with Swift. GRB 050724[5] is a good example of a short burst with unusual γ -ray and X-ray properties. The X-ray afterglow lies off the centre of an elliptical galaxy at a redshift of $z = 0.258$. The low level of star formation typical for elliptical galaxies makes it unlikely that the burst originated in a supernova explosion. The afterglow light curve showed evidence (such as late time X-ray flares) for continued energy injection for at least ~ 200 seconds after the burst, a finding inconsistent with most current neutron star- neutron star merger models, but a possibility for a neutron star-black hole merger.[6]

2.2. Implications for TeV, neutrino and gravity wave astronomy

Gravity waves and neutrinos are the only way to probe the actual merger since the fireball itself is too dense for electromagnetic radiation to escape. Using calculations derived from [7] and [8], one can derive an expected detection rate of GRBs with the Advanced Laser Interferometer Gravitational Wave Observatory (ALIGO). Based on Swift and BATSE results, the rate for short GRBs is $10 - 50 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Using the beaming angles derived for GRB 050709 [9] and GRB 050724[2] we derive a beaming factor $1/f_b \sim 10 - 30$. Assuming all short GRBs are due to mergers, the merger rate for neutron-star/neutron-star (NS/NS) and neutron-star/black-hole (NS/BH) mergers is between 100 and $> 1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$. The expected distance to which ALIGO is sensitive to mergers is 300 Mpc ($0.1 \text{ Gpc}^{-3}, \sim 10^6$ galaxies). Thus the expected ALIGO detection rate is ~ 10 to $> 100 \text{ yr}^{-1}$. If NS/BH mergers are responsible, there will be a coincidence rate of $\sim 2 \text{ yr}^{-1}$ between Swift and ALIGO.

The fireball model for GRBs includes relativistic hadron acceleration which can produce high energy neutrinos through a Δ^+ resonance[10, 11]:

$$\text{If } E_{cm}^{p\gamma} > E_{\Delta^+}^{Th} \implies p^+ + \gamma \rightarrow \Delta^+ \rightarrow (n) + \pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu$$

Since E_γ decreases as the burst progresses, to meet the threshold for the Δ^+ resonance, E_p must increase and $E_\nu \propto E_p$. Thus one expects neutrino energy to increase with time during a burst from $\sim 10^7$ eV in the actual collapse, up to $\sim 10^{14} - 10^{15}$ eV in the internal shock (prompt emission) and as much as $\sim 10^{17} - 10^{18}$ eV in the external shock (afterglow).

Stamatikos *et al.* have developed a method for searching for correlations between neutrino events in a detector such as AMANDA-II or IceCube and GRB events detected by Swift. This method[12] uses time and position cuts to reject $> 99\%$ of the background and improves the sensitivity of the search by modelling particular parameters of each burst instead of generic burst parameters.

There is also a good possibility that GRBs will be detected in the TeV energy range. The EGRET instrument on the Compton Gamma-Ray Observatory detected GeV emission from

some bursts and theories suggest that GRBs could produce very high energy (VHE) cosmic rays, which in turn would produce hadronic showers containing VHE γ -rays. Such high energy photons will be severely attenuated through interaction with the cosmic background radiation. This limits the range of a detectable TeV GRB, but a detection would give insight into flux attenuation by cosmological pair production. The search for GRBs at TeV energies is part of the plan of all of the major TeV observatories.

3. Non-GRB science

Although the predominant science of Swift is gamma-ray burst studies, there have also been significant discoveries in numerous other areas. These include the BAT hard X-ray survey and transient monitor and multiwavelength studies of blazars.

3.1. BAT hard X-ray survey

The BAT hard X-ray survey is carried out simultaneously with the search for GRBs. For each Swift pointing sky images are made in four energy bands. Since the observation schedule for Swift is driven by the follow-up of randomly occurring GRBs, the survey covers $\sim 50\%$ to 80% of the sky each day. The individual sky images are joined in a mosaic to produce a hard X-ray map of the entire sky. Since a given region of the sky is observed multiple times throughout the survey, the survey also provides temporal variability coverage for bright sources. The first three months of the BAT hard X-ray survey have been presented by Markwardt *et al* [13]. The survey reaches a flux of $\sim 10^{-11}$ ergs cm $^{-2}$ s $^{-1}$ and has $\sim 2.7'$ (90% confidence) positional uncertainties for the faintest sources. These data confirm the conjectures that a high-energy-selected active galactic nucleus (AGN) sample represents a true sample of the AGN population. Most of the high-latitude sources are AGN with a median redshift (excluding blazars) of 0.012.

3.2. Transient monitor

The large field of view and extensive sky coverage of the BAT make it ideal as a monitor in the hard X-ray energy range. The BAT transient monitor program is complementary to the BAT hard X-ray survey. The transient monitor is designed to monitor changes in source output on time scales of < 1 day. In the transient monitor program, sky images are processed to detect astrophysical sources in a single energy band covering 15-50 keV. The detected flux or upper limit in each energy band is calculated for > 200 objects on time scales ranging from 64 seconds up to one day. In addition, the monitor is sensitive to an outburst from a new or unknown source. The daily integrated exposure for a typical source is $\sim 1500 - 3000$ seconds, with a 3σ sensitivity of ~ 6 mCrab. In October 2006, the BAT team made the results of the transient monitor public to the astrophysical community through the Swift mission web page[14]. Figure 1 is shown as an illustration of the power of the transient monitor to detect variations in the galactic black hole candidate Cygnus X-3.

3.3. Multi-wavelength AGN campaigns

Swift is very well suited for multi-wavelength studies of astrophysical objects. It has a large energy range (0.3 to 150 keV) plus ultra-violet and optical coverage and the ability to rapidly repoint through target of opportunity observations. A particularly promising field of study is the study of blazars with Swift and atmospheric Cherenkov telescopes. The unified picture of the spectral energy distribution (SED) of blazars[15] shows that X-ray selected blazars with low radio luminosity have their twin peaks of emission in the hard X-ray and TeV energy ranges. Successful coordinated blazar observations include 3C 454.3 during its 2005 flare[16] and campaigns are being planned for coordinated observations with Swift and TeV telescopes such as VERITAS, MAGIC and HESS.

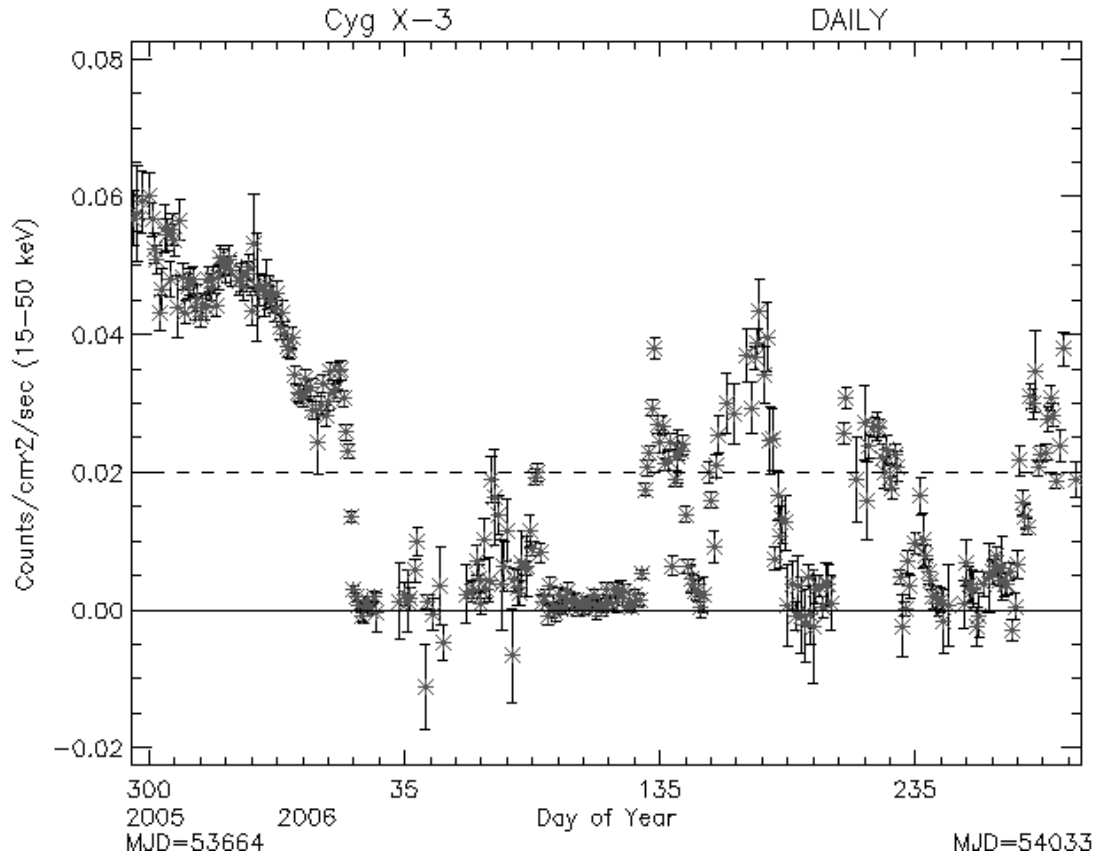


Figure 1. Light curve for Cygnus X-3 taken from the BAT hard X-ray transient monitor.

4. Acknowledgements

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5. References

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