Non-GRB Sources Observed with Swift

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Abstract

The Swift mission has great synergy with MAXI. Operating together, the two missions will provide sensitive sky monitoring in both the soft and hard X-ray bands. Swift will also provide follow-up observations for sources detected by MAXI. This paper describes the non-GRB capabilities and science of Swift. The mission is made up of the BAT wide-field hard X-ray instrument and the XRT and UVOT focusing narrow-field X-ray and UV-optical telescopes. The BAT continuously observes the hard X-ray sky performing a sensitive survey in the 15 - 350 keV range. It is nearly uniform across the sky and is not affected by absorption for Compton-thin sources. At a sensitivity of 10^{-11} ergs cm^{-2} s^{-1}, it is has detected $\sim$580 sources in 22 months. The XRT performs observations in the 0.2 - 10 keV range of select source fields during GRB and non-GRB pointings. Sensitivities achieved are in the 10^{-15} to 10^{-14} erg cm^{-2} range. The UVOT observes UV and optical fields to a sensitivity of $\sim$23 magnitude. Valuable data are obtained from Target of Opportunity observations of transients. To date more that 500 such TOOs have been performed. This paper summarizes the non-GRB capabilities and science of Swift.

Key words: Swift

1. Introduction

Swift (Gehrels et al. 2004) is a first-of-its-kind autonomous spacecraft with on-board constraint checking and a 3-instruments multiwavelength payload. The wide-field Burst Alert Telescope (BAT) instrument (Barthelmy et al. 2005) surveys the sky for persistent and transient sources in the 15 - 350 keV band and positions them to arcmin accuracy (20 arcmin PSF). The narrow-field X-Ray Telescope (XRT) (Burrows et al. 2005) covers the 0.2 - 10 keV band in a 24 arcmin $\times$ 24 arcmin field of view. It has CCD spectroscopy and positions sources to few arcsec accuracy (18 arcsec PSF). The UV-Optical Telescope (UVOT) (Roming et al. 2005) covers the 170 - 600 nm optical/UV band in a 17 arcmin $\times$ 17 arcmin field of view. It has a filter wheel with 6 colors and 2 grisms (resolving power of 200 and 400) and position sources to subarcsec accuracy (1.9 arcsec PSF).

Gamma-ray bursts and other short transients are detected by the BAT which determines their position using on-board software. The position is provided to the spacecraft, built by General Dynamics, which then repoints to the burst location in less than 2 minutes to allow XRT and UVOT observations. Alert data from all three instruments are 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. Source positions can also be sent up to the spacecraft for rapid (<1 hour turn around) target of opportunity (TOO) observations.

The Swift mission was built by an international team from the US, UK, and Italy. After five years of development it was launched form Kennedy Space Center on 20 November 2004. Full normal operations commenced on 5 April 2005.

2. Non-GRB Science

The Swift observing strategies have been changing as the mission matures with the fraction of time spent on non-GRB science increasing. This is shown in Figure 1 comparing 2005 and 2007. The time spent on TOOs observations of transient sources has increased from 8% to 20% and on scheduled "fill-in" observations of persistent sources from 18% to 25% (8 Ms per year). The reason for the change is both an increased interest in the non-GRB capabilities in the user community and a new strategy for GRBs where follow-up observations are terminate earlier for less interesting bursts.

Another indication of change in Swift is in the rate of TOO observations per year. Figure 2 shows the number of TOOs performed per year. It is seen to rise continuously since launch and is now at a rate of more than one

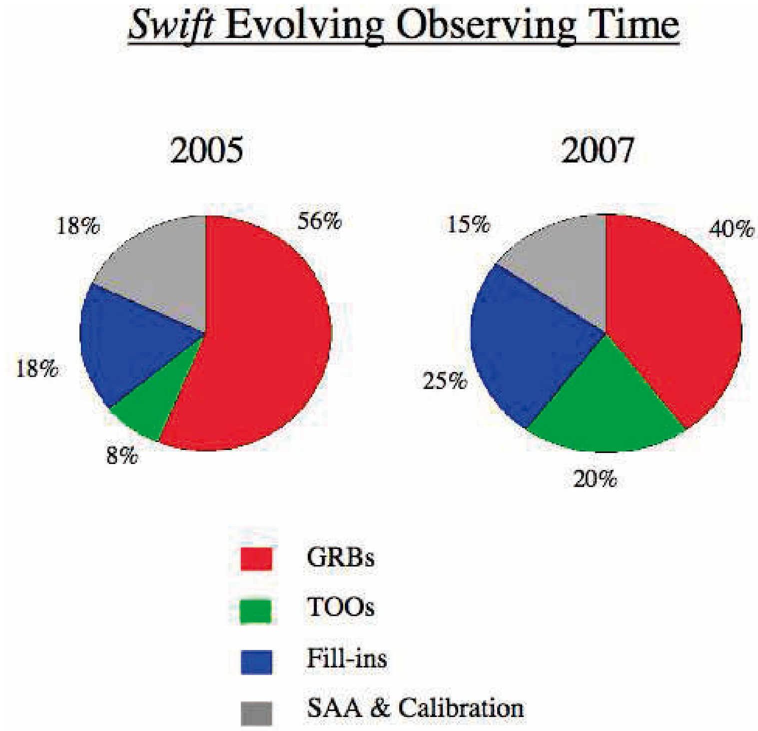

Fig. 1. Evolution of the Swift observing time fractions. More time is being spent on TOOs and fill-in observations than GRBs in 2007 than in 2005.

per day.

Key areas of Swift non-GRB science are BAT sky survey, transient monitoring, AGN studies, supernovae, and CVs/novae. These topics will now be addressed individually.

3. Hard X-ray Survey

Swift/BAT is performing the most sensitive hard X-ray (15 - 150 keV) all-sky survey ever (Markwardt et al. 2005). In its first 22 months, the BAT survey has reached a sensitivity of 0.8 mCrab over 80% of the sky (Figure 3), >15 times deeper than the 1978 HEAO-1 survey (Rothschild et al. 1983). It has detected ∼583 sources across the sky including 235 AGN (Tueller et al. 2008). Since hard X-rays are highly penetrating, this spectral band is unique in its complete coverage of AGN including the long-sought obscured population (Ueda et al. 2007). It is found in the BAT survey that ∼50% of the AGN are heavily absorbed ($N_H > 10^{22}$ cm^{-2}).

The BAT survey sensitivity is becoming more sensitive as the square root of observing time with no indication yet of limitation from systematic errors. The predict sensitivity for 4 years of data collection is 0.5 mCrab. The survey is complementary to that of INTEGRAL (Bird et al. 2007) which concentrates on the galactic plane. It will also complement of that of MAXI which will be in the X-ray band at comparable sensitivity to BAT.

4. Transient Monitoring

Swift's flexible observing schedule and the large BAT field of view make it an ideal monitor of high energy sources. The BAT observes ∼80% of the sky each day. The BAT Transient Monitor software autonomously searches for outbursts in known and new sources. Additional BAT transient detection is now being provided by the recently implemented BAT Slew Survey (Grindlay et al. 2008).

BAT light curves for over 500 galactic and extragalactic sources are available on a public web site (http://swift.gsfc.nasa.gov/docs/swift/results/transients). The daily exposure for a typical source is ∼9000 seconds, with a 1-sigma sensitivity of ∼7 mCrab. Of these, 65 are detectable in a day's observations or are periodic, and another 49 are transient. Through the transient monitoring the 8th known transient accretion-powered ms pulsar, SWIFT J1756.9-2508, was found with one of the lowest mass companions yet identified (Krimm et al. 2007).

5. AGN Observations

Due to its multiwavelength capacity and flexible observing schedule, Swift has become an important observatory for studies of Active Galactic Nuclei (AGN). Swift covers the critical optical/UV to X-ray range where most of the accretion power in an AGN is released. AGN are

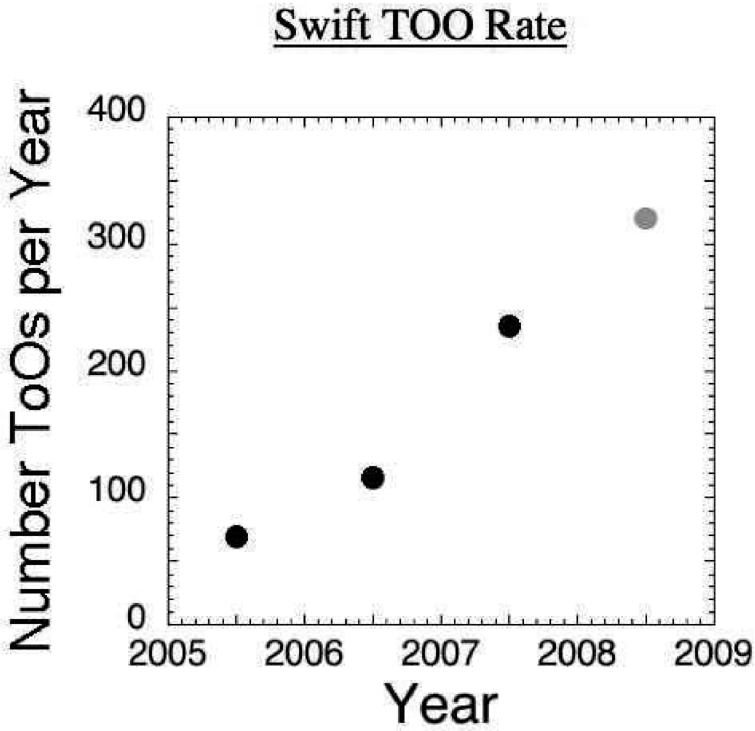

Fig. 2. The number of TOO observations per year is growing rapidly. The point for 2008 is an extrapolation to the full year from the TOOs observed in the first months.

highly variable, changing in their X-ray intensity by factors of 2-5 within a day and in the UV on time scales of days to weeks. Simultaneous observations at UV and X-ray energies are required to infer the physical conditions. The flexible schedule allows easy coordination with other observatories.

Swift studies of Big-Blue-Bump emission in 70 AGN clearly shows that UV and X-ray spectral slopes are correlated. Swift caught Mkn 335 in a historic low state (Grupe et al. 2007a) and detected hard X-ray photons in WPVS 007 (Grupe et al. 2007b), previously the softest X-ray AGN known.

Swift regularly monitors blazars in coordination with the Fermi and AGILE high energy gamma-ray telescopes and with the MAGIC, HESS, VERITAS and MILAGO TeV telescopes. These observations determine the flux and spectral slope of jet emission and constrain models for inverse Compton boosting of X-ray photons into the TeV range (Foschini et al. 2007). Swift observations of the blazar 3C454.3 in outburst coordinated with AGILE have sampled the broad-band spectrum during this historically brightest MeV-GeV emission state (Ghisellini et al. 2007).

6. Supernovae

The rapid response and flexible scheduling, and multi-wavelength capability of Swift provide unique observations of supernovae. Swift has now observed more than 60 SNe (Brown et al. 2008).

The interaction of outgoing SN shocks with material in their environments can create copious amounts of UV and X-radiation. Over the past 2 years, Swift has discovered X-ray emission from 8 core collapse SNe. Perhaps the most interesting case is SN 2006jc, a Type Ib SN whose progenitor ejected a shell of He-rich material in a Luminous Blue Variable eruption two years before the SN explosion. The X-ray data record the interaction of the SN blast wave with this dense shell of material, resulting in a brightening in X-rays over a period of 120 days, followed by a steep decline as the shock moved out of this shell (Immler et al. 2007a). Multi-epoch UVOT grism observations further showed the presence of a resonance MgII 2800 $\AA$ emission line as one of the main coolants in the SN 2006jc shell.

Utilizing the fast response of Swift, SN 2006bp (Type IIP) was observed less than two days after shock breakout. The observations showed that the SN was bright in X-rays even at such an early epoch, caused by the presence of substantial amounts of dense ($>10^6$ cm^{-3}) material from the progenitor's strong stellar wind (Immler et al. 2007b). Additional Swift XRT observations led to the detections of the two brightest SNe discovered in X-rays over the past three decades, SNe 2005kd and 2006jd (both Type IIn, $L_x > 10^{41}$ erg s^{-1}). UV obser-

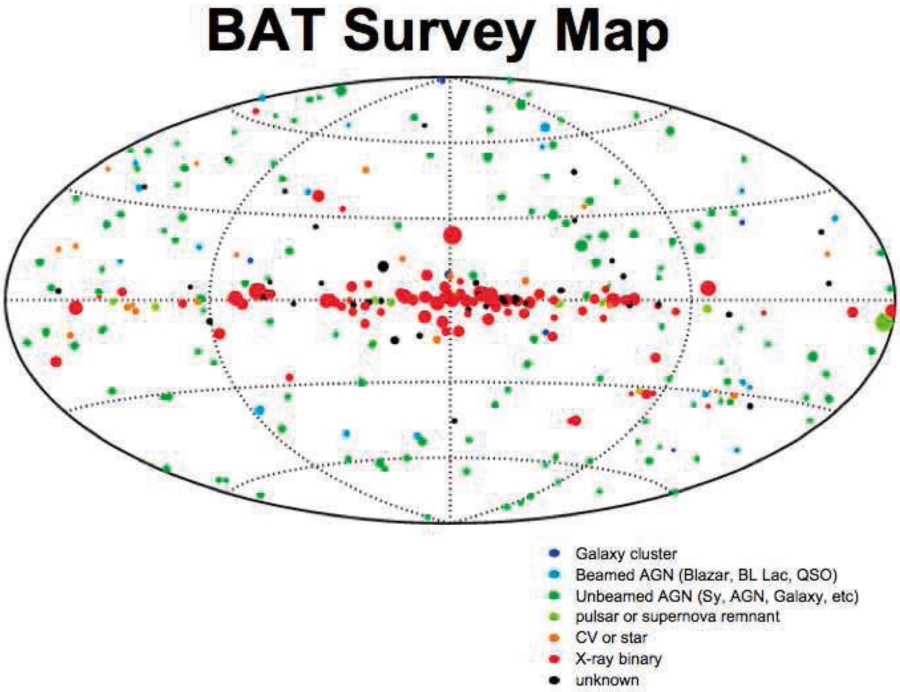

Fig. 3. Sources detected in the BAT all-sky hard X-ray survey. Based on 22 months of data. Color of dot shows sources type as indicated in the key and size of dot shows intensity.

vations of SN 2006bp and 2005cs (Type IIP; Brown et al. 2007), demonstrated the critical importance of these types of observations for constraining the extinction and evolving temperature/ionization structure in the photosphere of SNe II (Dessart et al. 2008). This greatly improves our ability to model Type II spectra and use them as independent distance indicators.

UVOT and XRT observations of thermonuclear (Type Ia) SNe permit a systematic study of SNe Ia in the UV and X-ray wavelength ranges. Beginning with observations of SN 2005am (Brown et al. 2005), the UV light curves of 13 SNe Ia observed to date have highly homogeneous light curve shapes, with peak dates similar to the peak dates in the U band. From these light curves a mean template has been generated. This template permits the peak date and magnitude to be determined with minimal dependence on sampling (Milne et al. 2007). These findings are important for cosmological utilization of SNe Ia as standard candles, and they afford insight into the thermonuclear explosion mechanism.

XRT observed an X-ray outburst signaling the shock breakout from the surface of a normal Type Ibc supernova (Soderberg et al. 2008). The object was discovered serendipitously on 9 January 2008 during scheduled observations of SN2007uy in NGC2770. This discovery raises the possibility that all core collapse supernovae have X-ray outburst from shock breakout.

7. Accreting White Dwarfs

Swift's rapid-response ToO capability has resulted in significant discoveries about the X-ray evolution of Cataclysmic Variables (CVs) in general, and Classical (CN) and Recurrent Novae (RN) in particular. X-ray observations are the best means to follow the evolution of the central nuclear-burning white dwarf during the outburst. Such observations constrain the mass, radius and composition of the white dwarf through model atmosphere fitting of the X-ray spectrum, determine the ejecta energy budget by measuring the hard X-ray shock temperature, and reveal the evolution of the later stages of the thermonuclear runaway by observing the flux variations.

These aspects were spectacularly demonstrated by Swift's high-density campaign on the 2006 outburst of the recurrent nova RS Oph (Figure 4, Osborne et al. 2007). There are two key results from the observations: 1) RS Oph was detected by the BAT showing unique hard X-ray emission, and 2) XRT observed turn-on of super soft emission 30 days after the optical turn-on, rare for such RNe and important for understanding the population and mix of supersoft sources in the Galaxy. There are other such RNe, with quiescent X-ray behavior different from RS Oph that are overdue for explosion and will be exciting targets for Swift. We have already made observations of over 20 other novae to date (Ness et al. 2007).

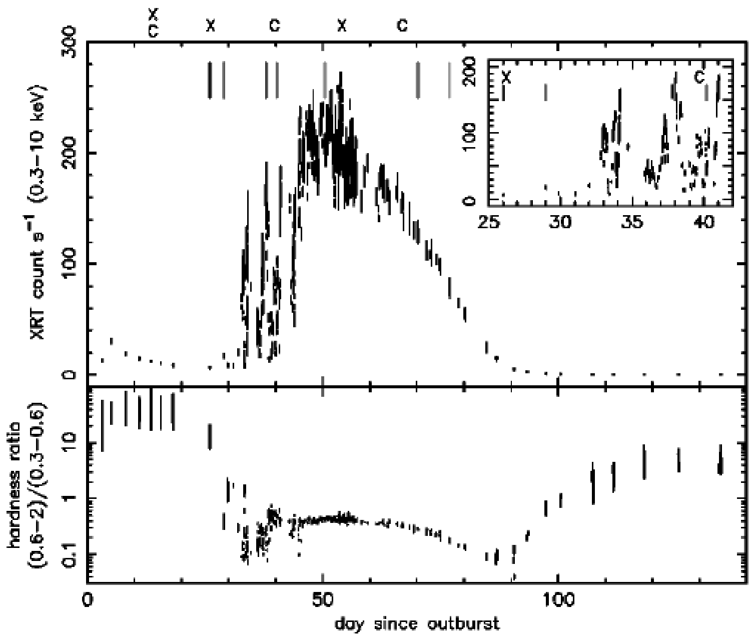

Fig. 4. Swift XRT light curve of RS Oph (Osborne et al. 2007). The dramatic flaring during the onset of the supersoft phase may be related to highly variable absorption. Note the marked change of hardness on day 35 indicating the onset of the super soft phase.

8. Conclusions

Swift is a versatile satellite with increasing observing time spent on non-GRB science areas. It is an excellent joint mission with MAXI, having complementary sky survey capabilities and the ability to perform TOO follow-up observations of source bound by MAXI.

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