

High Energy Transients

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We present an overview of high energy transients in astrophysics, highlighting important advances over the past 50 years. We begin with early discoveries of γ -ray transients, and then delve into physical details associated with a variety of phenomena. We discuss some of the unexpected transients found by *Fermi* and *Swift*, many of which are not easily classifiable or in some way challenge conventional wisdom. These objects are important insofar as they underscore the necessity of future, more detailed studies.

Key words: Gamma rays: general - telescopes - bursts - blazars - Galactic transients.

1. Early Discoveries in γ -ray Astronomy: GRBs, Solar Flares, and Supernovae

Some of the early discoveries in γ -ray astronomy were unexpected for different reasons. Some unveiled entirely new phenomena, whereas others showed that γ -rays could accompany previously known phenomena that had not been suspected to have a high energy component. The discovery of γ -ray bursts (GRBs) in the 1960's was serendipitous, and falls into the first category. The *Vela* satellites were launched to verify the 1963 Partial Test Ban Treaty governing the testing of nuclear weapons. They contained γ -ray and X-ray detectors. On July 2, 1967 a flash of γ -radiation unlike that expected from nuclear testing was observed by a team led by Ray Klebesadel. Years later when the puzzling results were fully analyzed and understood they became the basis of the discovery paper for GRBs (Klebesadel et al. 1973). For many years the distance scale to GRBs was unknown, prompting theories ranging from local (i.e., solar system) to extragalactic. The next breakthrough came with the *Compton Gamma Ray Observatory* (CGRO) which discovered more than 2600 bursts in just 9 years (1991-2000) and provided localizations of $\sim 3^\circ - 20^\circ$ for individual bursts. Their isotropy over the sky hinted at a cosmological origin. In 1997 the first ~ 1 arcmin localizations (done by *BeppoSAX*) led to the identifications of galaxies within which GRBs had occurred, and subsequent redshift determinations showed them to lie at cosmological distances (van Paradijs et al. 1997; Bloom et al. 2001).

The discovery of γ -rays in solar flares falls into the latter category: energetic radiation from an unexpected source. A solar flare is an explosion in the solar atmosphere due to the sudden release of magnetic energy in the corona. Flares occur in active regions around sunspots where strong magnetic field lines penetrate the photosphere and connect the corona to the solar interior. Solar flares can be

quite energetic, up to $\sim 0.16L_{\odot}$, releasing energy across the full electromagnetic spectrum from the radio waves to high energy γ -rays. The first detection of γ -radiation from a solar flare was August 4, 1972 by *OSO-7* using a $3'' \times 3''$ NaI crystal detector (Chupp et al. 1973).

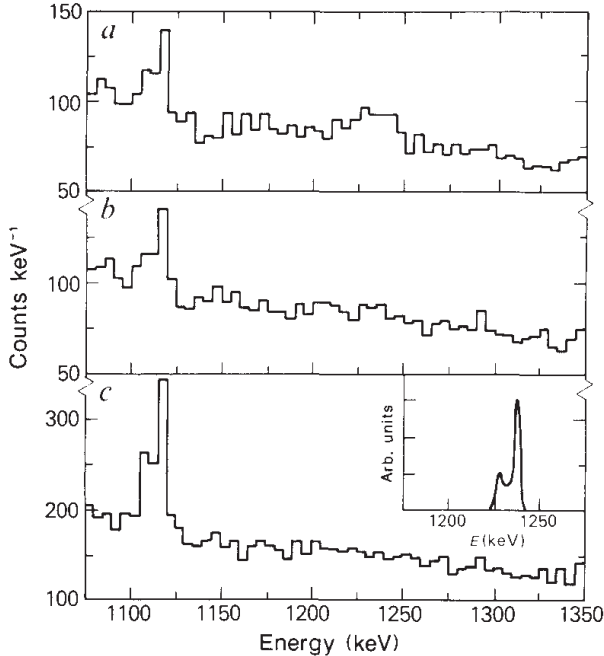


Figure 1. GRIS spectra of 1987A (Teegarden et al. 1989).

The discovery of γ -rays in supernovae (SNe) was not unexpected, but the early arrival after the initial SN blast was. High energy photons had been predicted as a result of the shock breakout from the stellar interior. The discovery of SN 1987A in the LMC on Feb 24, 1987 gave astronomers a ringside seat to the nearest SN in 400 yrs. The detection of a γ -ray signal in SN 1987A by *SMM* (Matz et al. 1988) and the GRIS balloon flight from Alice Springs, Australia on 1 May 1988 (Teegarden et al. 1989) at a little over one year after the SN, was much sooner than expected and prompted theorists to propose that “fingers” of ejecta from the exploding core are able to penetrate the overlying, expanding stellar layers more rapidly than the earlier, spherically symmetric estimates had indicated¹. The GRIS observations were made on day 433 after the SN, whereas a spherically symmetric

¹ The detection of a hard X-ray continuum in Aug 1987 (Dotani et al. 1987, Sunyaev et al. 1987) led to a revision in the theoretical prediction for the time of appearance of the γ -ray signal (Pinto & Woosley 1988ab).

shock breakout was not expected by theorists for several years. Teegarden et al. observed line emission at 1.238 MeV with a full width at half maximum of 16.3 ± 6 keV (Figure 1). The optical light curve of SN1987A indicated a production of $0.075 M_{\odot}$ of radioactive ^{56}Ni in the initial explosion. Comparison of the radioactive output of the daughter product ^{56}Co with the measured GRIS 1.238 MeV line flux indicates only $\sim 13\%$ of the 1.238 MeV γ -rays escaping – under the assumption of spherical symmetry.

2. The Modern Era

(a) Missions

Currently operating satellites carrying γ -ray detectors benefit from decades of experience plus technological advances. Three of the mainstays in present day γ -ray astronomy are *INTEGRAL*, *Swift*, and *Fermi*.

INTEGRAL (*INTErnational Gamma-Ray Astrophysics Laboratory* – Winkler et al. 2003) was launched in 2002 into a 72 hr orbit with a perigee of 10,000 km and an apogee of 153,000 km. It was four coaligned instruments: (1) The IBIS (Imager on-Board the *INTEGRAL* Satellite) observes between ~ 15 keV and ~ 10 MeV, and an angular resolution of ~ 12 arcmin. It consists of a 95×95 mass of rectangular tungsten tiles 3.2 m above a detector consisting of 128×128 CaTe tiles backed by 64×64 CsI tiles. The detectors are surround by tungsten/lead shielding. (2) The main spectrometer, the SPI (SPECTrometer for *INTEGRAL*) is sensitive from ~ 20 keV to ~ 8 MeV and comprises a coded mask of hexagonal tungsten tiles overlying a detector plane of 19 Ge crystals. The resolution is ~ 2 keV at 1 MeV. (3) The ACS (AntiCoincidence Shield) is composed of a mask shield of plastic scintillator behind a detector shield of tungsten tiles and BGO scintillator tiles. The all-sky coverage of the ACS make it a valuable GRB detector, and one of the components of the IPN (InterPlanetary Network) for localizing GRBs. (4) There are dual JEM-X units that observe from 3 to 35 keV using gas scintillation detectors in a microstrip layout.

Swift (Gehrels et al. 2004) was launched in 2004 into a standard low Earth orbit (600 km). It carries three science instruments: (1) The BAT (Burst Alert Telescope) is a coded-aperture mask of 52,000 randomly placed 5 mm Pb tiles situated 1 m above a detector plane of 32,768 4 mm CdZnTe tiles. It covers > 1 sr fully-coded (~ 3 sr partially coded) and detects and localizes GRBs to $\sim 1 - 4$ arcmin within 15 s. Its energy range is 15 – 150 keV. (2) The XRT (X-ray Telescope) is one of two co-pointed NFI (narrow field instruments) that are trained on a GRB after the spacecraft has slewed to the BAT determined localization. The XRT uses a Wolter Type I X-ray telescope with 12 nested mirrors focused onto a single MOS CCD. It has sensitivity in the range 0.2 – 10 keV. (3) the UVOT (Ultraviolet/Optical Telescope) is the other NFI which is used to study GRB afterglow. It can obtain positions to less than one arcsec, and provides optical and UV photometry and low resolution spectra in the range 170 – 650 nm.

Fermi (formerly the *Gamma-ray Large Area Space Telescope* – *GLAST* – Atwood et al. 2009) was launched 2008 into a standard low Earth orbit (550 km). It has two instruments: (1) The LAT (Large Area Telescope), an imaging γ -ray detector has a FoV (field of view) of ~ 2.4 sr and sensitivity between ~ 30 MeV and

~ 300 GeV. It is a natural successor to the EGRET instrument on the *Compton Gamma-Ray Observatory*. (2) The GBM (Gamma-ray Burst Monitor) can detect GRBs over the entire non-Earth occulted sky and has sensitivity from ~ 8 keV to ~ 30 MeV. It consists of 14 scintillation detectors – 12 NaI crystals with energy range ~ 8 keV – ~ 1 MeV and two BGO crystals with energy range ~ 150 keV – ~ 30 MeV.

Table 1. High Energy Transients

Source	typical duration	Energy Source	$E(\gamma\text{-ray})$
TGF	msec	E field	10^{10} erg
GRB	msec – mins	gravity	10^{51} erg
SGR	msec – sec	B field	10^{44} erg
TDE	day - yrs	gravity	10^{52} erg
solar flare	mins	B field	10^{32} erg
SN/nova	mins – yrs	nuclear	10^{49} erg
accreting BH/NS	secs – days (variable)	gravity	10^{36} erg s $^{-1}$
AGN	hrs – days (variable)	gravity	10^{43} erg s $^{-1}$

(b) *Science*

Table 1 indicates the panoply of high energy transients, with their associated timescales and energies.

Terrestrial γ -ray flashes (TGFs) were first seen the the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-Ray Observatory*. They are thought to be due to decaying electric fields above thunderclouds after a lightning discharge. Relativistic electrons interact with nuclei of atoms in the atmosphere and produce γ -rays via bremsstrahlung. A process known as runaway electron avalanche is thought to be relevant, but the details are uncertain (Gurevich et al. 1992, Dwyer 2003). Subsequent observations by the *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)* have revealed TGFs with much higher energies, and show that ~ 500 TGFs occur per day (Figure 2, from Smith et al. 2005), which is a small fraction of the total number of daily lightning strikes on Earth ($\sim 3 - 4 \times 10^6$). This estimate excludes effects relating to beaming and atmospheric obscuration of low altitude TGFs. The *Fermi*/GBM is currently detecting TGFs at a rate of ~ 10 yr $^{-1}$; some are even detected by *Fermi*/LAT during special Earth-pointed observations.

Gamma-ray bursts (GRBs) are intense flashes of radiation produced at cosmological distances $z \simeq 2$. GRBs come in two primary flavors, long and short, with the dividing point being roughly 2 s (Kouveliotou et al. 1993). A further division can be made spectrally according to their hardness ratio (i.e., ratio of high to low energies). The redshift range is from about 0.2 to 2 for short GRBs (sGRBs), with a mean of about 0.4. For long GRBs (lGRBs) the range is between about 0.009 and 8.2, with a mean of about 2.3. The typical energy release is $\sim 10^{49} - 10^{50}$ erg for sGRBs and $\sim 10^{50} - 10^{51}$ erg for lGRBs. These ranges are based on observed isotropic-equivalent energies of $\sim 10^{51}$ erg for sGRBs and $\sim 10^{53}$ erg for lGRBs, and estimates for jet beaming for each class, $\theta_j \sim 5^\circ$ for lGRBs and $\theta_j \sim 5 - 15^\circ$ for sGRBs (Burrows et al. 2006, Grupe et al. 2006, Fong et al. 2012). Beaming angles for sGRBs are still highly uncertain. The corresponding beaming

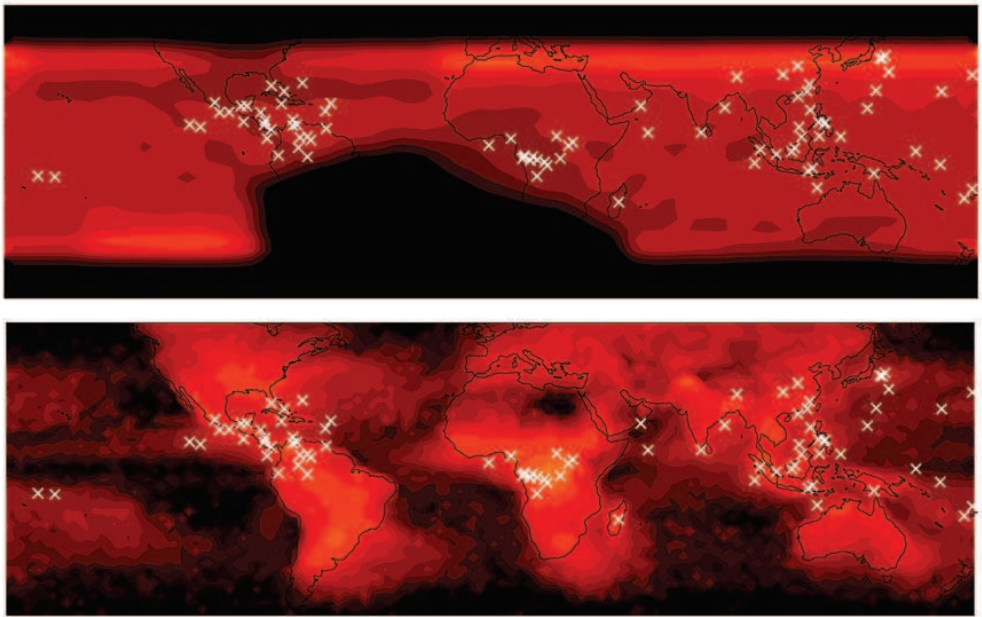


Figure 2. *RHESSI* position projected onto the Earth's surface during each recorded TGF, plotted over (i) the expected distribution of observed TGFs if the population were evenly distributed over the globe, and (ii) the long-term lightning frequency data (Smith et al. 2005).

factors $f_b = 1 - \cos \theta_j \simeq \theta_j^2/2$ are roughly 1/300 for lGRBs and 1/30 for sGRBs. The $L_X/E_{\gamma-\text{iso}}$ values at 11 hr post-GRB are similar between lGRBs and sGRBs (Gehrels et al. 2008). The sGRBs have weaker X-ray afterglows, a mean value of $\sim 7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ versus $\sim 3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ for lGRBs. Although many of the details are uncertain, the two mechanisms are thought to be collapsars for long GRBs (lGRBs) and merging neutron stars for short GRBs (sGRBs) (Gehrels, Ramirez-Ruiz, & Fox 2009). LGRBs are intrinsically very bright, the brightest explosions in the Universe. The highest redshift lGRBs were far above detector threshold. SGRBs are intrinsically less luminous by a factor $\sim 10^3$, and are seen primarily nearby, $z \lesssim 1$.

Soft gamma repeaters (SGRs) emit bursts and γ -rays and X-rays which are thought to be due to the rearrangement of powerful magnetic fields in magnetars – pulsars with magnetic fields of $\sim 10^{15}$ G. The first one seen was the “March 5th Event” from 1979 which was observed by two Soviet interplanetary spacecraft *Venera 11* and *Venera 12* (Mazets et al. 1979). This event, SGR 0526-66, was localized to the SN remnant N49 in the LMC. Given a distance of ~ 50 kpc, the isotropic equivalent energy emitted was $\sim 5 \times 10^{44}$ erg, compared to $\sim 10^{41}$ erg for a typical SGR burst. A ~ 8 s periodicity thought to be the NS spin period is plainly evident in the data. Thompson & Duncan (1995) present an extensive model of the March 5th event and other SGRs as magnetars, i.e., $|B| \simeq 10^{15}$ G. They argue that the March 5 burst was due to a large-scale readjustment of the stellar magnetic field, while the more standard SGR bursts are caused by the release of magnetic stresses within a more localized patch of the crust. Thompson & Duncan put forth a variety of independent arguments in favor of the magnetar scenario, including (i) the necessity of a very high B -field to spin down the pulsar to ~ 8 s within the inferred $\sim 10^4$ yr age of N49, (ii) a very strong B -field suppresses the e^- -scattering cross section below the standard Thomson value by the ratio $\sim (B/B_{\text{QED}})^{-2}$, where $B_{\text{QED}} = m_e^2 c^2 / (e\hbar) = 4.4 \times 10^{13}$ G (the point at which the nonrelativistic Landau energy $\hbar eB/(m_e c)$ equals the electron rest energy $m_e c^2$), therefore enabling $L \simeq 10^4 L_{\text{Edd}}$ for surface fields $\gtrsim 10^{14.5}$ G, (iii) persistent X-ray emission from SGR 0526-66 at $\simeq 7 \times 10^{35} \text{ erg s}^{-1}$ (Rothschild et al. 1993, 1994) implies $B_{\text{crust}} \gtrsim 10^{15}$ G, and (iv) an identification of the ~ 0.15 s duration of the hard spike of the March 5 event (Mazets et al. 1979, Cline et al. 1980) with the internal Alfvén crossing time leads to $B \simeq 7 \times 10^{14}$ G.

On Aug 27, 1998 a second giant flare from an SGR was seen. SGR 1900+14 became the brightest extra-solar system γ -ray source ever. The 5.16 s spin period of the pulsar could be easily seen directly in the light curve (Kouveliotou et al. 1999), and produced ionization changes in the upper atmosphere of the Earth. Thompson & Duncan (2001) argue that the extremely high luminosity $L \gtrsim 10^6 L_{\text{Edd}}$ during the initial ~ 0.5 s spike in SGR 1900+14 demands $B \gtrsim 10^{15}$ G. Shortly after the launch of *Swift*, on 27 Dec 2004, a giant γ -ray flare was seen from SGR 1806-20 (Figure 3, from Palmer et al. 2005) with a peak flux of $\sim 5 \text{ erg cm}^{-2} \text{ s}^{-1}$. SGR bursts are much brighter than ordinary X-ray bursts, which are due to thermonuclear flashes of accumulated hydrogen on the surface of a NS ($L \sim 10^3 - 10^4 L_{\text{Edd}}$ vs. $L \sim L_{\text{Edd}}$) and have harder spectra.

Tidal disruption events (TDEs) are caused by the tidal disruption of stars that venture too close to the massive black holes (MBHs) at the centers of galaxies (Rees 1988, Phinney 1989). Prior to March 2011, nearly all our observational

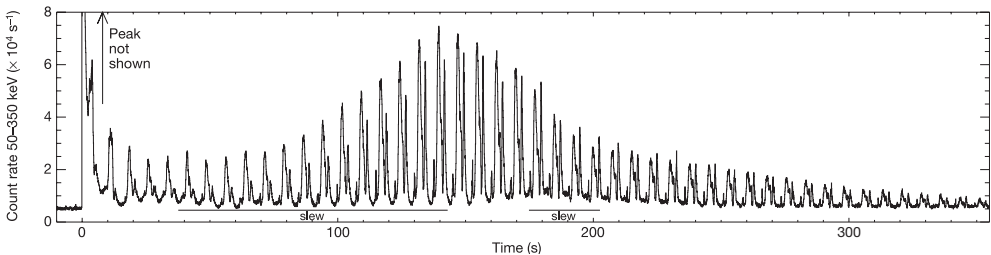


Figure 3. The spike and tail light curve for SGR 1806-20 from *Swift*/BAT (Palmer et al. 2005).

information was based on optical/UV studies (Gezari et al. 2006, 2008) or long-term X-ray data with poor time sampling (Komossa et al. 2004). This changed with the discovery by *Swift* of GRB 110328A/*Swift* J1644, a TDE viewed down the jet axis of a MBH in the nucleus of a galaxy at redshift $z = 0.35$ (Bloom et al. 2011, Burrows et al. 2011, Levan et al. 2011). Continued observations for over 1 yr with the *Swift*/XRT has shown an apparent long term decay law $L_x \propto t^{-\alpha}$ with $\alpha \simeq -1.3$, which may be consistent with the decay of a freely expanding, advectively dominated slim disk (Cannizzo, Troja, & Lodato 2011). The this decay law appears to hold as early as $t \simeq 10$ d, indicating that the conventional dividing point between “stellar fallback” ($L \propto t^{-5/3}$) and “disk accretion” ($L \propto t^{-4/3}$) (Phinney 1989, Cannizzo, Lee, & Goodman 1990) may have been at $\lesssim 10$ d, indicative of a deeply plunging disruption. This is in contrast to the more probable event where a disruption occurs close to the classical tidal disruption radius, in which case the dividing point would lie at years to decades. If Sw1644 was deeply plunging, that may also be part of the reason it was a powerful, jetted TDE.

3. GRBs in the *Swift* Era

Swift Has brought brought about a revolution in GRB research. Redshifts from GRBs discovered prior to *Swift* amount to 41 total. (At the time of *Swift*’s launch this number was ~ 25 , but continued observation of identified host galaxies with time has increased the pre-*Swift* total.) Now there are over 200 redshifts. The total number of *Swift* GRBs is approaching 700. Figure 4 shows a plot of frequency histogram distribution for redshifts, excluding uncertain values and photometric

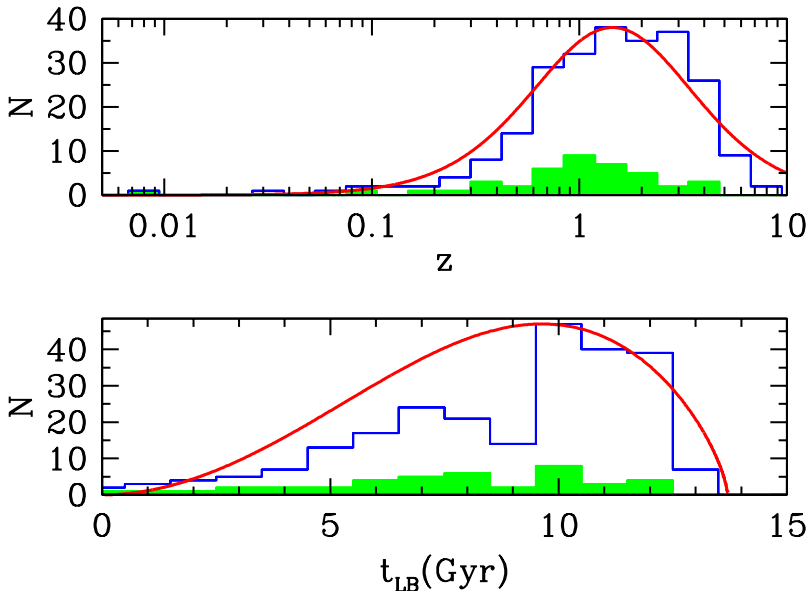


Figure 4. The frequency histogram distribution for all spectroscopic GRB redshifts determined to date (243 - shown in blue) as well as the pre-*Swift* era distribution (41 - shown in green). The top panel shows the distribution in z , and the bottom panel in look-back time. The red curves indicate the evolution of a slice of comoving volume $(dV/dz)(1+z)^{-1}$, where the factor $(1+z)^{-1}$ corrects for cosmological time dilation, given that the GRB rate has effective units of volume $^{-1}$ time $^{-1}$.

redshifts. As a first approximation, the GRB rate history traces a the volume of the universe. Of the 243 total redshifts we have now, 187 are from GRBs discovered by *Swift*. There are 18 from *HETE*, 15 from *BeppoSax*, 10 from *IPN*, 6 from *Fermi*, and 4 from *INTEGRAL*.

4. Oddball Events

Short “GRB” 050925: This unusual burst triggered the BAT with a single peaked outburst of duration $T_{90} = 70$ ms (Holland et al. 2005, Markwardt et al. 2005). It occurred near the galactic plane, and nothing was seen in the UVOT. However, the V -band extinction toward the source was $A_V = 7.05$ mag. The XRT spectra and lightcurve show no significant X-ray emission in the field, suggesting that any X-ray counterpart to this burst was faint. Markwardt et al. (2005) were able to fit a power law spectrum to the BAT data, with a photon index 1.74 ± 0.17 ; they found a better fit could be obtained with a blackbody spectrum $kT = 15.4 \pm 1.5$ keV, a value consistent with small-flare events from SGRs. The low galactic latitude and soft spectrum indicate a possible galactic source or SGR.

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 was longer (35 min) and softer than any previous burst, and was associated with SN 2006aj at only $z = 0.033$. SN

2006aj was a (core-collapse) SN Ib/c with an isotropic energy equivalent of a few 10^{49} erg, thus underluminous compared to the overall energy distribution for long GRBs. The spectral peak in prompt emission at ~ 5 keV places GRB 060218 in the X-ray flash category of GRBs (Campana et al. 2006), 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 (Campana et al. 2006). 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 SN, 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 (Pian et al 2006, Mazzali et al 2006). GRB 060218 was an underluminous burst, as were two of the other three previous cases. Because of the low luminosity, these events are only detected when nearby and are therefore rare. However, they are actually $\sim 5 - 10$ times more common in the universe than normal GRBs (Soderberg et al. 2006).

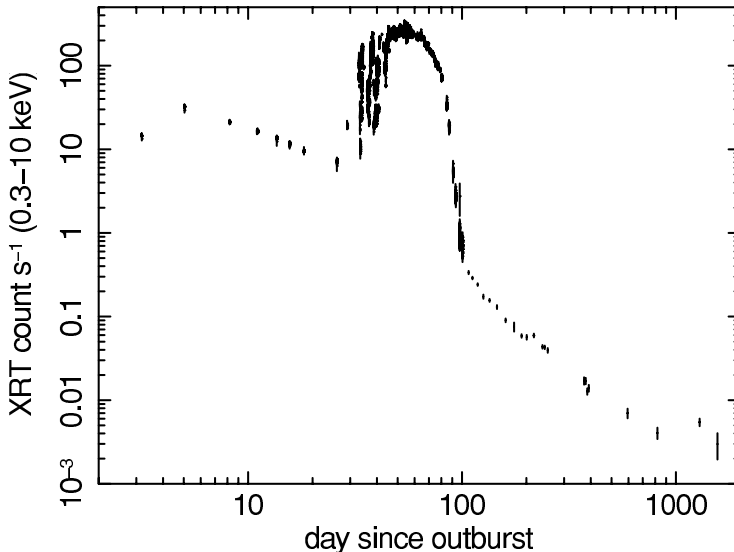


Figure 5. The 2006 nova outburst from RS Oph (Osborne et al. 2011).

RS Oph 2006: Novae can occur in interacting binaries containing a WD accretor and are due to the thermonuclear detonation of accreted material on the surface of a WD (Gallagher & Starrfield 1978). This can occur if the temperature and pressure at the base of the accumulated layer of accreted matter are in the appropriate regime. *Swift* has opened a new window on nova studies. To date *Swift* has observed 28 novae. It has detected keV emission from shocked ejecta and supersoft (SS) emission from the WD surface. Extensive observations (~ 400 ks) of the 2006 nova outburst from RS Oph (Figure 5) found an unexpected SS state, and 35 s QPO (Osborne et al. 2011). Detailed analysis of *Swift* observations revealed a mass ejection of $\sim 3 \times 10^{-5} M_{\odot}$ at ~ 4000 km s $^{-1}$ into the wind of the mass losing red giant companion in the system.

GRBs 060505 & 060614: GRB 060505 and GRB 060614 were nearby GRBs ($z = 0.089$ and 0.125 , resp.) with no coincident SN, to deep limits (Fynbo et al. 2006). GRB 060614 was bright ($15 - 150$ keV fluence of 2.2×10^{-5} erg cm^{-2}), and, with a T_{90} of 102s, seemed to be a secure long GRB. Host galaxies were found (Gal-Yam et al. 2006, Fynbo et al. 2006, della Valle et al. 2006) and deep searches were made for coincident SNe. All other well-observed nearby GRBs have had SNe, but GRB 060614 did not to limits > 100 times fainter than previous detections (Gal-Yam et al. 2006, Fynbo et al. 2006, della Valle et al. 2006). GRB 060614 shares some characteristics with sGRBs (Gehrels et al. 2006). The BAT light curve shows an initial short hard flare lasting ~ 5 s, followed by an extended softer episode, ~ 100 s. The light curve is similar to some *Swift* sGRBs and a subclass of BATSE sGRBs (Norris & Bonnell 2006). GRB 060614 also falls in the same region of the lag-luminosity diagram as sGRBs (Figure 6). Thus GRB 060614 is problematic to classify. It is a lGRB by the traditional definition, but lacks an associated SN. It shares some similarities with sGRBs, but the soft episode is brighter, which would be difficult to account for in the NS-NS merger scenario.

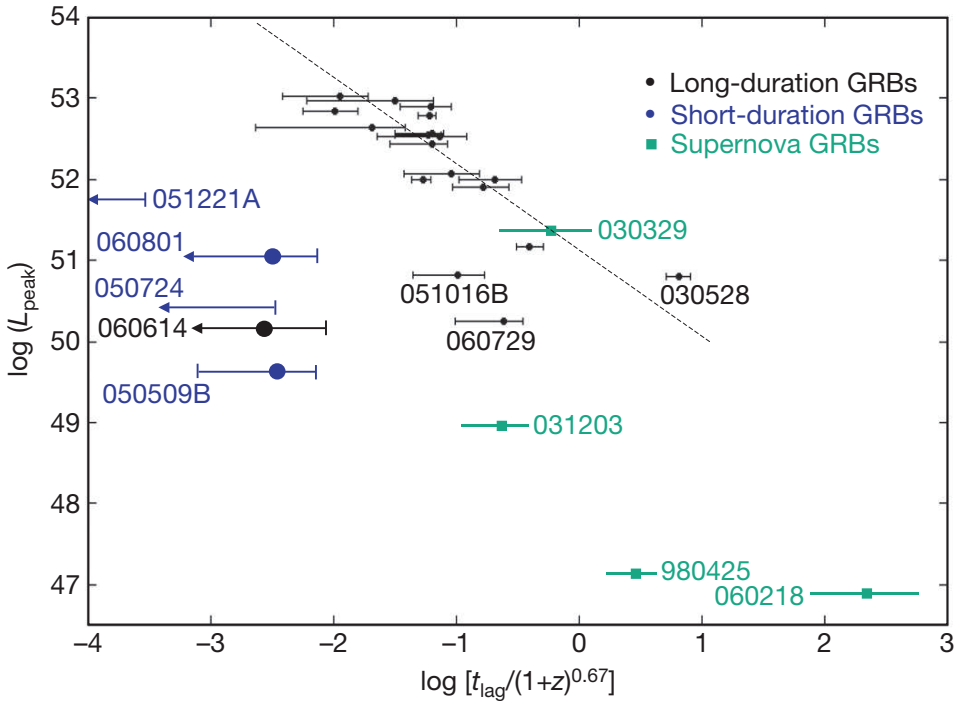


Figure 6. Spectral lag as a function of peak luminosity showing GRB 060614 in the region of short-duration GRBs (Gehrels et al. 2006).

Hostless GRB 070125: There was not an obvious host galaxy for GRB 070125. Deep ground-based imaging reveals no host to $R > 25.4$ mag. Cenko et al. (2008) present an analysis of spectroscopic data which reveals weak Mg II

lines indicative of halo gas. In the field are two blue galaxies offset by $\gtrsim 27$ kpc at $z = 1.55$. If there is an association with one of them, it would imply a velocity $\sim 10^4$ km s $^{-1}$ over a ~ 20 Myr lifetime of the massive progenitor. The only known way of achieving this would have been a prior close interaction with a massive BH. However, this interpretation was muddled by Chandra et al. (2008), who inferred a dense environment, based on bright, self-absorbed radio afterglow. They proposed a scenario in which the high density material lies close to the explosion site, and the lower density material further away. They note GRB 070125 was one of the brightest GRBs ever detected, with an isotropic release of 10^{54} erg (by comparison, $M_{\odot}c^2 \simeq 2 \times 10^{54}$ erg). The prompt emission from GRB 070125 was also seen by *Suzaku*/WAM (Onda et al. 2010).

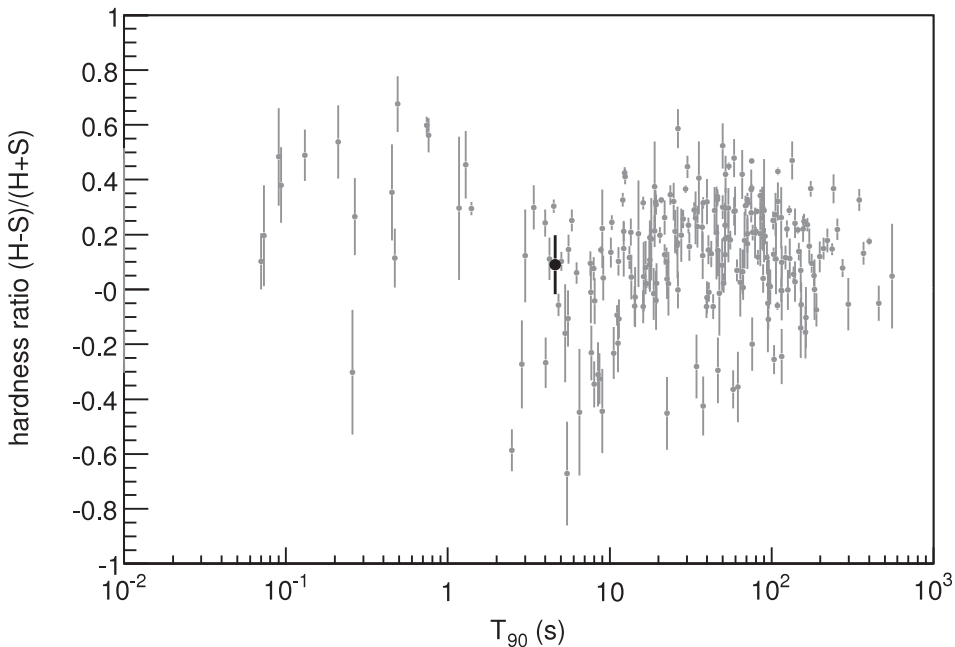


Figure 7. Duration (T_{90}) and hardness ratio (HR) of 226 Swift bursts from GRB 041217 to GRB 070616, where $HR \equiv (H - S)/(H + S)$, and S and H are energy fluences in the 15 – 50 and 50 – 150 keV bands, respectively (Kasliwal et al. 2008). The values of T_{90} and HR GRB 070610 (large filled black circle) are 4.6 ± 0.4 s and 0.09 ± 0.11 , respectively.

Galactic “GRB” 070610: Discovered initially as GRB 070610, this object, now dubbed Swift J195509.6+261406 (Sw1955+26), is thought to represent a member of a relatively new class of fast X-ray nova containing a BH. It had a duration of ~ 5 s, and also shows large variability. Kasliwal et al. (2008) discuss several possibilities for this source (Figure 7), and propose an analogy with V4641 Sgr, an unusual BH binary which had a major outburst in 1999 (in’t Zand et al.

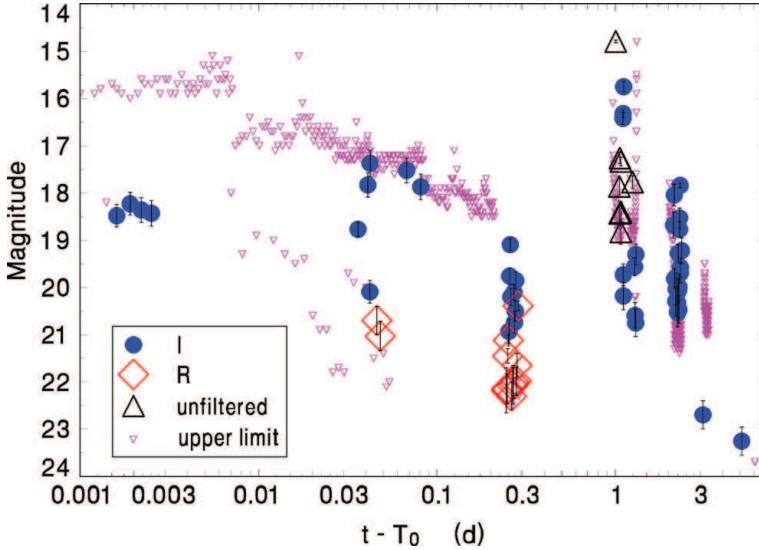


Figure 8. The light curve of SWIFT J1955+2614 in several photometric bands for $t - T_0 < 7$ d, where T_0 is the time of GRB 070610 (Šimon et al. 2012).

2000). V4641 Sgr is a binary with a B9 III star orbiting a $\sim 9M_{\odot}$ BH (Orosz et al. 2001) and also exhibited strong and fast X-ray and optical variability. The analog is imperfect in that the normal star in Sw1955+26 is a cool dwarf rather than a B9 giant, suggesting a physical origin for the bursting behavior in the accretion disk and/or jet rather than the mass donor star. A ~ 5 s burst is certainly distinct from the $\sim$ month long fast-rise exponential decay seen in systems like A0620-00 in 1975 (Tanaka & Shibazaki 1996, Remillard & McClintock 2006) which are thought to be due to a large scale storage and dumping of material in an accretion disk (Cannizzo et al. 1995, Cannizzo 1998, 2000), and may be more in line with either a disk-corona (Nayakshin et al. 2000) or disk-jet instability (McKinney & Blandford 2009). Rea et al. (2011) derive stringent upper limits on the quiescent X-ray emission from Sw1955+26 using a ~ 63 ks *Chandra* observation, and use this to argue against a magnetar interpretation. Šimon et al. (2012) present an analysis of optical emission during the 2007 outburst and find the optical emission manifests as spikes which decrease in duration as the burst progresses. They show that the emission can be explained by pure synchrotron emission. The main part of the optical outburst following the *Swift*/BAT trigger lasted ~ 0.3 d, with subsequent “echo outbursts” between 1 and 3 d, as in X-ray novae (Figure 8, from Šimon et al. 2012). The main part of the outburst has an exponential decay reminiscent of the 1975 outburst in A0620-00, but with a much shorter duration. If the global accretion disk limit cycle (Cannizzo et al. 1995, Dubus et al. 2001) is the mechanism for this outburst, it suggests a much shorter orbital period than the 7.75 hr for A0620-00 (McClintock & Remillard 1986).

XRO 080109 - SN 2008D: On 2008 January 9 *Swift*/XRT serendipitously discovered an extremely bright X-ray transient (Soderberg et al. 2008) while undertaking a preplanned observation of the galaxy NGC 2770 ($d = 27$ Mpc). Two days earlier *Swift*/XRT had observed the same location and did not see a source. X-ray outburst (XRO) 080109 lasted about 400 s and occurred in one of the galaxy’s spiral arms. XRO 080109 was not a GRB (no γ -rays were detected), and the total X-ray energy $E_X \simeq 2 \times 10^{46}$ erg was orders of magnitude lower than a GRB. The peak luminosity $\sim 6 \times 10^{43}$ erg s $^{-1}$ is much greater than the Eddington luminosity for a $\sim 1M_\odot$ object, and also from type I X-ray bursts. Therefore the standard accretion and thermonuclear flash scenarios are excluded.

Simultaneous *Swift*/UVOT observations did not reveal a counterpart, but UVOT observations at 1.4 hr showed a brightening. Gemini North 8-m telescope observations beginning at 1.7 d revealed a spectrum suggestive of a young SN (Soderberg et al. 2008). Later observations confirmed the spectral features. The transient was classified as a type Ibc SN based on the lack of H, and weak Si features.

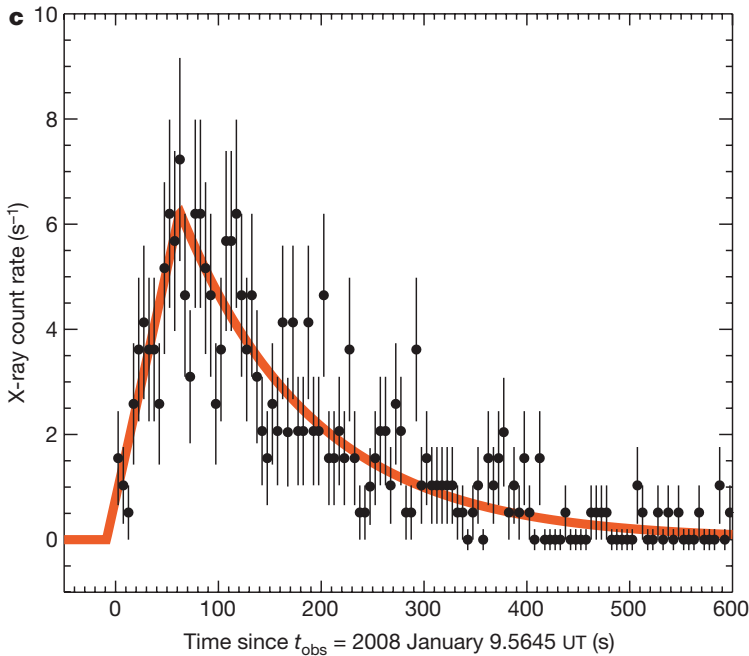


Figure 9. X-ray light curve of XRO 080109/ SN 2008D (Soderberg et al. 2008).

Soderberg et al. (2008) argue that the X-ray flash (Figure 9) indicates a trans-relativistic shock breakout from a SN, where the radius at breakout is $\gtrsim 7 \times 10^{11}$ cm, and the shock velocity at breakout is $\gamma\beta \lesssim 1.1$. Soderberg et al. (2008) estimate a circumstellar density which yields an inferred pre-SN mass loss rate $\sim 10^{-5}M_\odot$ yr $^{-1}$, reinforcing the notion of a Wolf-Rayet progenitor. The similarity between the shock break-out properties of the He-rich SN 2008D and the He-poor

GRB-associated SN 2006aj are consistent with a dense stellar wind around a compact Wolf-Rayet progenitor.

X-ray and radio observations presented by Soderberg et al. (2008) of SN 2008D are the earliest ever obtained for a normal type Ibc SN. At $t < 10$ d, the X-ray and peak radio luminosities are orders of magnitude less than those of GRB afterglows (Berger et al. 2003a, Frail et al. 2003), but comparable to those of normal type Ibc SN (Berger et al. 2003b, Kouveliotou et al. 2004).

EV Lac superflare: On 25 Apr 2008 a hard X-ray superflare from the dMe star EV Lac triggered the BAT (Figure 10, from Osten et al. 2010). Flaring activity in this system had been seen previously spanning radio to X-ray wavelengths using the VLA, *HST*, and *Chandra* (Osten et al. 2005). The Apr 2008 event was the first large stellar flare from a dMe flare star to cause a *Swift*/BAT trigger based on its hard X-ray intensity. Its peak 0.3 – 100 keV flux of 5.3×10^{-8} erg cm $^{-2}$ s $^{-1}$ was ~ 7000 times the star’s quiescent coronal flux (Osten et al. 2005, 2006). The soft X-ray spectrum of the flare shows evidence for Fe K α emission at 6.4 keV. Osten et al. (2010) model the K α emission as fluorescence from the source of the flare irradiating photospheric Fe, and derive loop heights $h/R_* \simeq 0.1$. It is interesting that with the sensitivity of BAT, one finds a small population of very energetic flares producing hard X-ray flux at levels commensurate with those seen from GRBs. The frequency of flares this large in M stars is unknown; a better understanding of the rate would be an important factor in determining the habitability of planets around M stars, given the disastrous consequences of such a large energy release on the atmosphere of a nearby planet.

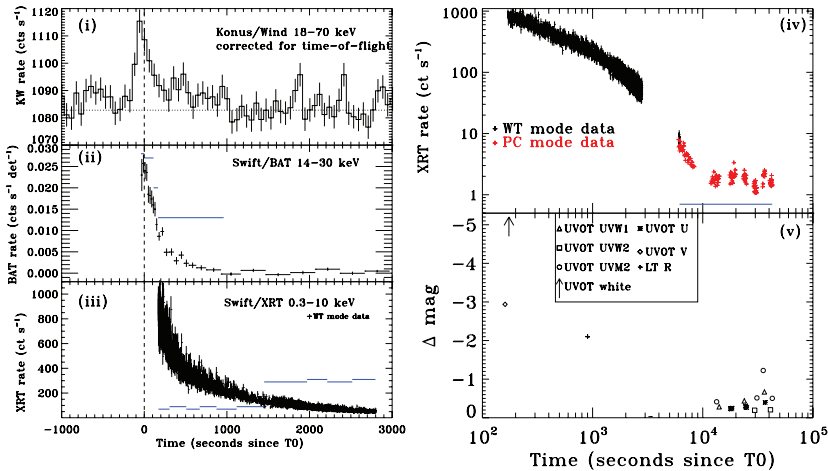


Figure 10. Light curves during the flare from EV Lac (Osten et al. 2010).

Pulsing GRB 090709: Analysis of the *Swift*/BAT data revealed a quasiperiodic signal at 8.06 s, with a Q -factor of ~ 11 (Markwardt et al. 2009). Markwardt et al. discuss a magnetar scenario, with 8 s representing the pulsar spin. Götz et al. (2009) confirmed the periodicity with a finding of a 8.11 s signal in *INTEGRAL*/SPI-ACS data. However, detailed follow-up work suggests a more pedestrian scenario – a standard long GRB (Figure 11, from de Luca et al. 2010; Cenko et al. 2010). De Luca et al. (2010) reanalyzed the *Swift* and *INTEGRAL* data and excluded any significant modulation at 8.1 s. Their fitting of *Swift*/XRT and *XMM-Newton*/EPIC X-ray spectra imply a redshift $z \sim 4 - 5$, too far to be a magnetar. They also note the lack of short ($\lesssim 0.5$ s) and hard very bright initial spike that are seen in SGR giant flares, and the lack of an obvious nearby galaxy progenitor. The huge energy requirement implied by the apparent cosmological distance works against the SGR giant flare hypothesis. Cenko et al. (2010) present broadband observations of GRB 090709 and also conclude it was probably a standard long GRB at cosmological distances. They detect the periodic signal reported by Markwardt et al. (2009) and Götz et al. (2009) at only $\sim 2\sigma$ significance. Perley et al. (2010) discovered a faint galaxy at the afterglow location ($K' = 22.0 \pm 0.2$ mag), confirming the extragalactic, cosmological nature of the burst. To date, a firm spectroscopic redshift has not been obtained.

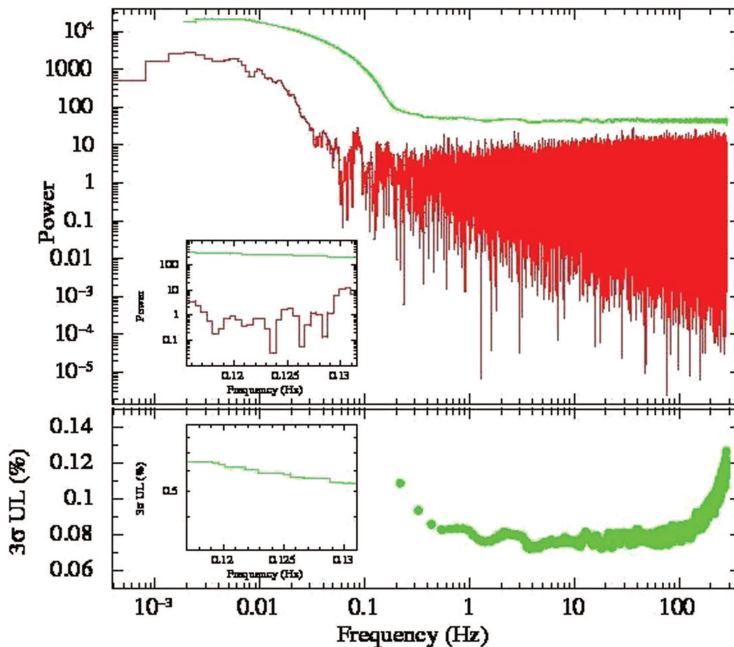


Figure 11. The upper panel indicates the power spectrum for the *Swift*/XRT light curve of GRB 090709 between $T_0 + 77$ and $T_0 + 539$ s, along with the threshold for the detection of sinusoidal signals at the 3σ confidence level. The lower panel shows the upper limits on the pulsed fraction. The XRT data are in WT mode (from De Luca et al. 2010).

GRB 101225 “Christmas burst”: GRB 101225 was quite unusual: it had a $T_{90} > 1700$ s and exhibited a curving decay when plotted in the traditional $\log F -$

$\log t$ coordinates. The total BAT fluence was $\gtrsim 3 \times 10^{-6}$ erg cm $^{-2}$. The XRT and UVOT found a bright, long-lasting counterpart. Ground based telescopes followed the event, mainly in R and I , and failed to detect any spectral features. At later times a color change from blue to red was seen; *HST* observations at 20 d found a very red object with no apparent host. Observations from the Spanish Gran Telescopio Canarias at 180 d detected GRB 101225 at $g_{AB} = 27.21 \pm 0.27$ mag and $r_{AB} = 26.90 \pm 0.14$ (Thöne et al. 2011). Considered together, these characteristics are unique to this burst (Figure 12), and led Campana et al. (2011) to propose that it was caused by a minor body like an asteroid or comet becoming disrupted and accreted by a NS. Depending on its composition, the tidal disruption radius would be $\sim 10^5 - 10^6$ km. Campana et al. find an adequate fit to the light curve by positing a $\sim 5 \times 10^{20}$ g asteroid with a periastron radius ~ 9000 km. If half the asteroid mass is accreted they derive a total fluence 4×10^{-5} erg cm $^{-2}$ and distance ~ 3 kpc.

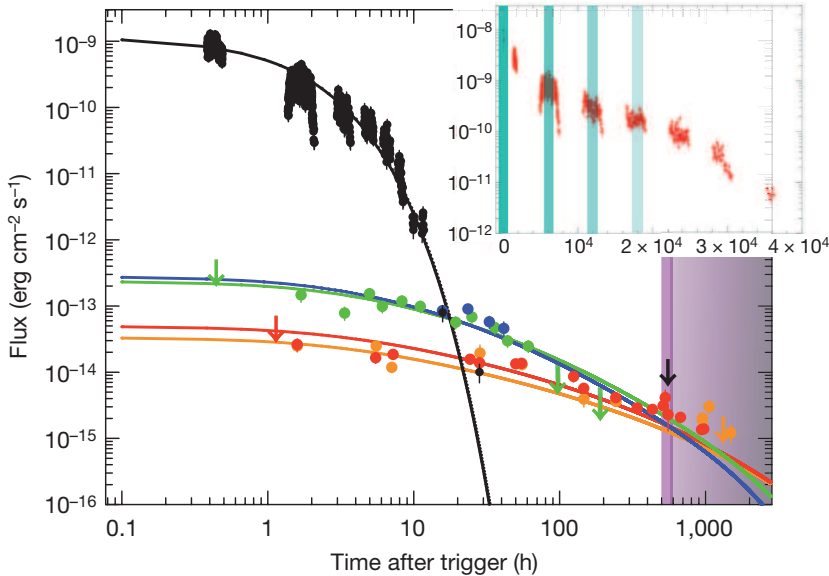


Figure 12. Light curves of GRB 101225 in five energy bands: X-rays at 1 keV (black), UV at 2030 Å (green) and 2634 Å (blue), and optical at 6400 Å (R band, red) and 7700 Å (I band, orange) (Campana et al. 2011). The inset (with t in seconds) shows the *Swift*/XRT light curve. Shaded regions highlight the periastron passages calculated using a tidal disruption model (Campana et al. 2011).

Thöne et al. (2011) offer a different explanation for GRB 101225 – the merger of a He star and a NS leading to a concomitant SN. They derive a pseudo-redshift $z = 0.33$ by fitting the spectral-energy distribution and light curve of the optical emission with a GRB- SN template. Thus in their interpretation the event was much more distant and energetic. They argue for the presence of a faint, unresolved galaxy in deep optical observations, and fit the long term light

curve with a template of the broad-line type Ic SN 1998bw associated with GRB 980425. If their distance is correct as well as their interpretation of a component emerging at 10 d as being a SN, then its absolute peak magnitude $M_{V, \text{abs}} = -16.7$ mag would make it the faintest SN associated with a long GRB. The isotropic-equivalent energy release at $z = 0.33$ would be $> 1.4 \times 10^{51}$ erg which is typical of other long GRBs but greater than most other low-redshift GRBs associated with SNe.

5. Summary

The last fifty years has been an exciting time of great discoveries in high energy astrophysics, enabled by innovative advances in detectors. The universe has been revealed to be a more wondrous and sometimes violent place than previously imagined, from γ -ray bursts on the most distant scales, to terrestrial γ -ray flashes right here on Earth. We have been surprised by the seemingly low energy phenomena that turned out to have high energy emission associated with them, as well as the discoveries of entirely new phenomena. Given our incomplete understanding of many of these phenomena, there is enormous opportunity for more detailed follow-up. The future is bright for time domain astrophysics.

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