High-energy transients

Neil Gehrels\(^1\) and John K. Cannizzo\(^{1,2}\)

\(^1\)Astroparticle Physics Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
\(^2\)CRESST/Joint Center for Astrophysics, University of Maryland, Baltimore County, Baltimore, MD 21250, USA

We present an overview of high-energy transients in astrophysics, highlighting important advances over the past 50 years. We begin with early discoveries of \(\gamma\)-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.

1. Early discoveries in \(\gamma\)-ray astronomy: \(\gamma\)-ray bursts, solar flares and supernovae

Some of the early discoveries in \(\gamma\)-ray astronomy were unexpected for different reasons. Some unveiled entirely new phenomena, whereas others showed that \(\gamma\)-rays could accompany previously known phenomena that had not been suspected to have a high-energy component. The discovery of \(\gamma\)-ray bursts (GRBs) in the 1960s 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 \(\gamma\)-ray and X-ray detectors. On 2 July 1967, a flash of \(\gamma\)-radiation, unlike that expected from nuclear testing, was observed by a team led by Ray Klebesadel. Years later when the puzzling results were fully analysed and understood, they became the basis of the discovery paper for GRBs [1]. 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 3\(^\circ\)–20\(^\circ\) for individual bursts. Their isotropy over the sky hinted at a cosmological origin. In 1997, the first arcminute localizations (done by
The Giuseppe ‘Beppo’ Occhialini Satellite for X-ray Astronomy; BeppoSAX) led to the identifications of galaxies within which GRBs had occurred, and subsequent redshift determinations showed them to lie at cosmological distances [2,3].

The discovery of $\gamma$-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 $10^{-4} L_\odot$, releasing energy across the full electromagnetic spectrum from radio waves to high-energy $\gamma$-rays. The first detection of $\gamma$-radiation from a solar flare was 4 August 1972 by OSO-7 using a $3'' \times 3''$ (7.62 cm $\times$ 7.62 cm) NaI crystal detector [4].

The discovery of $\gamma$-rays in supernovae (SNe) was not unexpected, but the early arrival after the initial supernova (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 large magellanic cloud (LMC) on 24 February 1987 gave astronomers a ringside seat to the nearest SN in 400 years. The detection of a $\gamma$-ray signal in SN 1987A by the Solar Maximum Mission (SMM) [5] and the Gamma-Ray Imaging Spectrometer (GRIS) balloon flight from Alice Springs, Australia on 1 May 1988 [6] at a little over 1 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 indicated.1 The GRIS observations were made on day 433 after the SN, whereas a spherically symmetric shock breakout was not expected by theorists for several years. Teegarden et al. [6] observed line emission at 1.238 MeV with a full width at half maximum of 16.3 $\pm$ 6 keV (figure 1). The optical light curve of SN 1987A indicated a production of 0.075 M$_\odot$ of radioactive $^{56}$Ni in

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1The detection of a hard X-ray continuum in August 1987 [7,8] led to a revision in theoretical prediction for the time of appearance of the $\gamma$-ray signal [9].

Figure 1. GRIS spectra of 1987A in the 1238 keV region [6]. (a) The sum of all SN 1987A target segments, (b) the sum of all background segments and (c) the sum of all data from the second half of the GRIS flight (where the primary target was the galactic centre). The inset shows the instrumental line profile derived from the calibration line. Reprinted by permission from Macmillan Publishers Ltd: Nature [6], © 1989.
the initial explosion. Comparison of the radioactive output of the daughter product \(^{56}\text{Co}\) with
the measured GRIS 1.238 MeV line flux indicates only about 13 per cent of the 1.238 MeV \(\gamma\)-rays escaping—under the assumption of spherical symmetry.

2. The modern era

(a) Missions

Currently, operating satellites carrying \(\gamma\)-ray detectors benefit from decades of experience plus technological advances. Three of the mainstays in present day \(\gamma\)-ray astronomy are the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), Swift and Fermi.

INTEGRAL [10] was launched in 2002 into a 72 h orbit with a perigee of 10 000 km and an apogee of 153 000 km. It has four coaligned instruments. (i) The imager on-board the INTEGRAL satellite observes between 15 keV and 10 MeV, with an angular resolution of 12 arcmin. It consists of a \(95 \times 95\) mask of rectangular tungsten tiles 3.2 m above a detector consisting of \(128 \times 128\) CaTe tiles backed by \(64 \times 64\) CsI tiles. The detectors are surrounded by tungsten/lead shielding. (ii) The main spectrometer, the SPectrometer for INTEGRAL (SPI) is sensitive from about 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 approximately 2 keV at 1 MeV. (iii) The AntiCoincidence Shield (ACS) is composed of a mask shield of plastic scintillator behind a detector shield of tungsten tiles and bismuth germanate (BGO) scintillator tiles. The all-sky coverage of the ACS makes it a valuable GRB detector, and one of the components of the InterPlanetary Network (IPN) for localizing GRBs. (iv) There are dual Joint European X-ray Monitor units that observe from 3 to 35 keV using gas scintillation detectors in a microstrip layout.

Swift [11] was launched in 2004 into a standard low Earth orbit (600 km). It carries three science instruments. (i) The Burst Alert Telescope (BAT) 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 more than 1 sr fully coded (approx. 3 sr partially coded) and detects and localizes GRBs to less than about 14 arcmin within 15 s. Its energy range is 15–150 keV. (ii) The X-ray Telescope (XRT) uses a Wolter Type I X-ray telescope with 12 nested mirrors focused onto a single metal oxide semiconductor charge-coupled device. It has sensitivity in the range 0.2–10 keV. (iii) The Ultraviolet/Optical Telescope (UVOT) is the other NFI that is used to study GRB afterglow. It can obtain positions to less than 1 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 [12]) was launched in 2008 into a standard low Earth orbit (550 km). It has two instruments. (i) The Large Area Telescope (LAT), an imaging \(\gamma\)-ray detector has a field of view of 2.4 sr and sensitivity between 30 MeV and 300 GeV. It is a natural successor to the Energetic Gamma Ray Experiment Telescope instrument on the CGRO. (ii) The Gamma-ray Burst Monitor (GBM) can detect GRBs over the entire non-Earth occulted sky and has a 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.

(b) Science

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

Terrestrial \(\gamma\)-ray flashes (TGFs) were first seen by the Burst and Transient Source Experiment (BATSE) on the CGRO. 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 \(\gamma\)-rays via bremsstrahlung. A process known as runaway electron avalanche is
Figure 2. RHESSI position projected onto the Earth’s surface during each recorded TGF, plotted over (a) the expected distribution of observed TGFs if the population were evenly distributed over the globe and (b) the long-term lightning frequency data [15]. Reprinted with permission from AAAS. (Online version in colour.)

Table 1. High-energy transients. TGF, terrestrial γ-ray flash; GRB, γ-ray burst; SGR, soft γ repeater; TDE, tidal disruption event; SN, supernova; BH, black hole; NS, neutron star; AGN, active galactic material.

<table>
<thead>
<tr>
<th>source</th>
<th>typical duration</th>
<th>energy source</th>
<th>$E_{\text{\gamma-ray}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGF</td>
<td>milliseconds</td>
<td>$E$-field</td>
<td>$10^{10}$ erg</td>
</tr>
<tr>
<td>GRB</td>
<td>milliseconds–minutes</td>
<td>gravity</td>
<td>$10^{51}$ erg</td>
</tr>
<tr>
<td>SGR</td>
<td>milliseconds–seconds</td>
<td>$B$-field</td>
<td>$10^{44}$ erg</td>
</tr>
<tr>
<td>TDE</td>
<td>days–years</td>
<td>gravity</td>
<td>$10^{52}$ erg</td>
</tr>
<tr>
<td>solar flare</td>
<td>minutes</td>
<td>$B$-field</td>
<td>$10^{62}$ erg</td>
</tr>
<tr>
<td>SN/nova</td>
<td>minutes–years</td>
<td>nuclear</td>
<td>$10^{49}$ erg</td>
</tr>
<tr>
<td>accreting BH/NS</td>
<td>seconds–days (variable)</td>
<td>gravity</td>
<td>$10^{36}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>AGN</td>
<td>hours–days (variable)</td>
<td>gravity</td>
<td>$10^{45}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>

thought to be relevant, but the details are uncertain [13,14]. Subsequent observations by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) have revealed TGFs with much higher energies and show that about 500 TGFs occur per day (figure 2, from [15]), which is a small fraction of the total number of daily lightning strikes on Earth (approx. $3–4 \times 10^6$). 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 100 per year; some are even detected by Fermi/LAT during special Earth-pointed observations. This high rate has held since 2009 when the BGOs were included in the triggering algorithm. Perhaps the most spectacular discovery has been that of 511 keV emission from $e^-/e^+$ annihilation in TGFs [16]. It is unsettling to consider the fact that terrestrial processes are capable of producing antimatter in significant quantities.

GRBs are intense flashes of radiation produced at cosmological distances $z \approx 2$. GRBs come in two primary flavours, long and short, with the dividing point being roughly 2 s [17]. 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 $10^{49}$–$10^{50}$ erg for SGRBs and $10^{50}$–$10^{51}$ erg for LGRBs. These ranges are based on observed isotropic-equivalent energies of about $10^{51}$ erg for SGRBs and about $10^{53}$ erg for LGRBs, and estimates for jet beaming for each class, $\eta_0 \sim 5^\circ$ for LGRBs and $\eta_0 \sim 5^\circ$–$15^\circ$ for SGRBs [18–20]. Beaming angles for SGRBs are still highly uncertain. The $L_X/E_{\gamma,iso}$ values at 11 h post-GRB are similar between LGRBs and SGRBs [21]. The SGRBs have weaker X-ray afterglows, a mean value of $7 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ versus $3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ for LGRBs. Although many of the details are uncertain, the two mechanisms are thought to be collapsars for LGRBs and merging neutron stars for SGRBs [22]. LGRBs are intrinsically very bright, the brightest explosions in the Universe. The highest redshift LGRBs were far above detector threshold. SGRBs, by contrast, constitute a flux-limited sample, and are seen primarily nearby, $z \lesssim 1$.

Soft $\gamma$ repeaters (SGRs) emit bursts of $\gamma$-rays and X-rays that are thought to be due to the rearrangement of powerful magnetic fields in magnetars – pulsars with magnetic fields of $10^{15}$ 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 [23]. 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 $5 \times 10^{44}$ erg, compared with $10^{41}$ erg for a typical SGR burst. An 8 s periodicity thought to be the neutron star (NS) spin period is plainly evident in the data. Thompson & Duncan [24] 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 5 March 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 favour 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 $10^{4}$ year age of N49, (ii) a very strong $B$-field suppresses the $e^-$-scattering cross section below the standard Thomson value by the ratio $(B/B_{\text{QED}})^{-2}$, where $B_{\text{QED}} = m_e^2c^2/(\varepsilon h) = 4.4 \times 10^{13}$ G (the point at which the non-relativistic Landau energy $\hbar eB/(m_ec)$ equals the electron rest energy $m_ec^2$), 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 $\simeq 7 \times 10^{35}$ erg s$^{-1}$ [25, 26] 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 5th event [23, 27] with the internal Alfvén crossing time leads to $B \simeq 7 \times 10^{14}$ G.

On 27 August 1998, a second giant flare from an SGR was seen. SGR 1900+14 became the brightest extra-solar system $\gamma$-ray source ever. The 5.16 s spin period of the pulsar could be easily seen directly in the light curve [28], and produced ionization changes in the upper atmosphere of the Earth. Thompson & Duncan [29] 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 December 2004, a giant $\gamma$-ray flare was seen from SGR 1806-20 (figure 3, from [30]) with a peak flux of about 5 erg cm$^{-2}$ 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 an NS ($L \sim 10^2$–$10^3 L_{\text{Edd}}$ versus $L \sim L_{\text{Edd}}$), and they also have harder spectra than ordinary X-ray bursts.
Tidal disruption events (TDEs) are caused by the tidal disruption of stars that venture too close to the massive black holes (MBHs) at the centres of galaxies [31,32]. Prior to March 2011, nearly all our observational information was based on optical/UV studies [33,34] or long-term X-ray data with poor time sampling [35]. This changed with the discovery by Swift of GRB 110328A/Swift J1644 (= Sw1644), a TDE viewed down the jet axis of an MBH in the nucleus of a galaxy at redshift $z = 0.35$ [36–38]. Continued observations for over 1 year 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 disc [39]. 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 ‘disc accretion’ ($L \propto t^{-4/3}$) [32,40] 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. $\gamma$-ray bursts in the Swift era

Swift has brought about a revolution in GRB research. Redshifts from GRBs discovered prior to Swift amount to 41 in total. (At the time of Swift’s launch, this number was roughly 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 the frequency histogram distribution for redshifts, excluding uncertain values and photometric redshifts. As a first approximation, the GRB rate history traces the volume of the Universe. The deviations between the observed distributions and the purely volumetric curves are consistent with empirical models for the star formation rate [41]. Of the 243 total redshifts, we have now, 187 are from GRBs discovered by Swift. There are 18 from High-energy Transient Explorer, 15 from BeppoSax, 10 from IPN, six from Fermi and four from INTEGRAL.

4. Oddball events seen by Swift

*Short ‘GRB’ 050925.* This unusual burst triggered the BAT with a single peaked outburst of duration $T_{90} = 70$ ms [42,43]. It occurred near the galactic plane, and nothing was seen in the
UVOT. However, the V-band extinction towards the source was $A_V = 7.05$ mag. The XRT spectra and light curve show no significant X-ray emission in the field, suggesting that any X-ray counterpart to this burst was faint. Markwardt et al. [43] were able to fit a power-law spectrum to the BAT data, with a photon index $1.74 \pm 0.17$; 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.

**GRBs 060505 and 060614.** GRB 060505 and GRB 060614 were nearby GRBs ($z = 0.089$ and 0.125, respectively) with no coincident SN, to deep limits [44]. GRB 060614 was bright ($15–150$ keV, fluence of $2.2 \times 10^{-5}$ erg cm$^{-2}$), and, with a $T_{90}$ of 102 s, seemed to be a secure long GRB. Host galaxies were found [44–46], and deep searches were made for coincident SNe. All other well-observed nearby GRBs have had SNe, but GRB 060614 did not to limits greater than 100 times fainter than previous detections [44–46]. GRB 060614 shares some characteristics with SGRBs [47]. The BAT light curve shows an initial short hard flare lasting about 5 s, followed by an extended softer episode, lasting 100 s. The light curve is similar to some Swift SGRBs and a subclass of BATSE SGRBs [48]. GRB 060614 also falls in the same region of the lag–luminosity diagram as SGRBs (figure 5). Thus, GRB 060614 is problematic to classify. It is an 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.

**Hostless GRB 070125.** There was not an obvious host galaxy for the long-duration ($\gtrsim 200$ s) GRB 070125 localized by IPN-BAT [49]. Deep ground-based imaging reveals no host to $R < 25.4$ mag. Cenko et al. [50] present an analysis of spectroscopic data that 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 of about $10^4$ km s$^{-1}$ over the roughly 20 Myr lifetime of the massive progenitor. The only known way of achieving this would have been a prior close interaction with an MBH. However, this interpretation was muddied by Chandra et al. [51], 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, with 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/Wide-band All-sky Monitor [52].
Figure 6. Optical high time resolution light curve of Sw1955+26 for \( t - T_0 < 4 \text{ d} \), where \( T_0 \) is the time of GRB 070610. Reprinted by permission from Macmillan Publishers Ltd: Nature [63], © 2008.

Galactic ‘GRB’ 070610/Sw1955+26. 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 novae containing a BH. It had a duration of about 5 s and also shows large variability. Kasliwal et al. [53] discuss several possibilities for this source and propose an analogy with V4641 Sgr, an unusual BH binary that had a major outburst in 1999 [54]. V4641 Sgr is a binary with a B9 III star orbiting a BH [55] and also exhibited strong and fast X-rays and optical variability. The analogue 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 behaviour in the accretion disc and/or jet rather than the mass donor star. A 5 s burst is certainly distinct from the month long fast-rise exponential decay seen in systems like A0620-00 in 1975 [56,57] which are thought to be due to large-scale storage and dumping of material in an accretion disc [58,59], and may be more in line with either a disc–corona [60] or disc–jet instability [61]. Rea et al. [62] 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.

Stefanescu et al. [63] present observations of extremely bright and rapid optical flaring behaviour in Sw1955+26 (figure 6) reminiscent of the high-energy light curves of soft $\gamma$-ray repeaters and anomalous X-ray pulsars. They show that the flares have peak extinction-corrected I-band isotropic luminosities of $1-2 \times 10^{35}$ erg s$^{-1}$ for $d = 5$ kpc, and concomitant total energies $3-5 \times 10^{36}$ erg. A blackbody temperature of $10^7$ K would be required to account for this radiation, but it is more likely that a non-thermal source such as synchrotron emission is responsible. Stefanescu et al. [63] present strong arguments in favour of a magnetar interpretation. They criticize the analogy with V4641 Sgr advocated by Kasliwal et al. [53], noting that the optical properties they observe in Sw1955+26 are quite different from those of V4641 Sgr: the optical variability of V4641 Sgr is much less extreme, both in terms of amplitude and time scale.

Pulsing GRB 090709. Analysis of the Swift/BAT data revealed a quasi-periodic signal at 8.06 s, with a Q-factor of about 11. Markwardt et al. [64] discuss a magnetar scenario, with 8 s representing the pulsar spin. Götz et al. [65] 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 [66]. De Luca et al. [67] reanalysed the Swift and INTEGRAL data, and excluded any significant modulation at 8.1 s. Their fitting of Swift/XRT
and X-ray Multi-Mirror Mission-Newton/European Photon Imaging Camera 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 spikes 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. [66] 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. [64] and Götz et al. [65] at only 2σ significance. Perley et al. [68] 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.

**XRO 080109–SN 2008D.** On 9 January 2008, Swift/XRT serendipitously discovered an extremely bright X-ray transient [69] 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 $\gamma$-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 $6 \times 10^{43}$ erg$^{-1}$ is much greater than the Eddington luminosity for a 1 M$_\odot$ 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 h showed a brightening, Gemini North 8 m telescope observations beginning at 1.7 day revealed a spectrum suggestive of a young SN [69]. 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.

Soderberg et al. [69] argue that the X-ray flash (figure 7) indicates a trans-relativistic shock breakout from an 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. [69] estimate a circumstellar density, which yields an inferred pre-SN mass loss rate of about $10^{-5}$ M$_\odot$ year$^{-1}$, reinforcing the notion of a Wolf–Rayet progenitor. The similarity between the shock-breakout 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. [69] of SN 2008D are the earliest ever obtained for a normal-type Ibc SN. At $t < 10$ day, the X-ray and peak radio luminosities

**Figure 7.** X-ray light curve of XRO 080109/SN 2008D. Reprinted by permission from Macmillan Publishers Ltd: Nature [69], (C) 2008. (Online version in colour.)
Figure 8. Light curves of GRB 101225 in five energy bands: X-rays at 1 keV (curve with highest flux at early time), UV at 2634 Å (second highest flux) and 2030 Å (third highest flux), and optical at 6400 Å (R band, fourth highest flux) and 7700 Å (I band, lowest flux) [80]. The inset (with $t$ in seconds) shows the Swift/XRT light curve. Shaded regions highlight the periastron passages calculated using a tidal disruption model [80]. Reprinted by permission from Macmillan Publishers Ltd: Nature [80], © 2011. (Online version in colour.)

are orders of magnitude less than those of GRB afterglows [70,71], but comparable to those of normal-type Ibc SN [72,73].

**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 with the overall energy distribution for long GRBs. The spectral peak in prompt emission at roughly 5 keV places GRB 060218 in the X-ray flash category of GRBs [74], the first such association for a GRB–SN event. Combined BAT–XRT–UVOT observations provided the first direct observation of shock breakout in an SN [74]. 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 of two than the previous SNe associated with GRBs, but still approximately two to three times brighter than normal SN Ic not associated with GRBs [75,76]. 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 5–10 times more common in the Universe than normal GRBs [77]. It is worth noting that an alternative to the shock-breakout interpretation of the early optical/X-ray emission was provided by Ghisellini et al. [78] who point out that if the emission is thermal, the data imply very large luminosities. They propose that the early emission arises from synchrotron emission accompanying the dissipation of the fireball bulk kinetic energy.

**GRB 101225 ‘Christmas burst’.** GRB 101225 was quite unusual: it had $T_{90} > 1700$ 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 colour change from blue to red was seen; Hubble Space Telescope (HST) observations at 20 days found a very red object with no apparent host. Observations from the Spanish Gran...
Telescopio Canarias at 180 days detected GRB 101225 at $g_{\text{AB}} = 27.21 \pm 0.27$ mag and $r_{\text{AB}} = 26.90 \pm 0.14$ [79]. Considered together, these characteristics are unique to this burst (figure 8), and led Campana et al. [80] to propose that it was caused by a minor body like an asteroid or comet becoming disrupted and accreted by an NS. Depending on its composition, the tidal disruption radius would be $10^5$–$10^6$ km. Campana et al. find an adequate fit to the light curve by positing a $5 \times 10^{20}$ g asteroid with a periastron radius 9000 km. If half the asteroid mass is accreted, they derive a total fluence $4 \times 10^{-5}$ erg cm$^{-2}$ and a distance of 3 kpc.

Thöne et al. [79] offer a different explanation for GRB 101225—the merger of an He star and an 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 days as being an 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.

**EV Lacertae (Lac) superflare.** On 25 April 2008, a hard X-ray superflare from the dMe star EV Lac triggered the BAT (figure 9, from [81]). Flaring activity in this system had been seen previously spanning radio to X-ray wavelengths using the Very Large Array, HST and Chandra [82]. The April 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 $5.3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ was 7000 times the star’s quiescent coronal flux [82,83]. The soft X-ray spectrum of the flare shows evidence for Fe K$\alpha$ emission at 6.4 keV. Osten et al. [81] model the K$\alpha$ emission as fluorescence from the source of the flare irradiating photospheric Fe, and derive loop heights $h/R_\ast \approx 0.1$. However, a strong caveat to this result comes from Pagani et al. [84], who considered degradation in the XRT due to radiation damage since launch. Using a revised gain file, they repeat the analysis by Osten et al. [81] for EV Lac, and show that, although the main Fe line at 6.7 keV persists and is in fact better defined than in the original analysis, the fluorescence line at 6.4 keV disappears. Thus, this result from Osten et al. [81] appears to have been spurious. 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

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**Figure 9.** Light curves during the flare from EV Lac [81]. Reproduced by permission of the AAS. (Online version in colour.)
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.

RS Ophiuchi (Oph) 2006. Classical and recurrent novae can occur in interacting binaries containing a white dwarf (WD) accretor and are due to the thermonuclear detonation of accreted material on the surface of a WD [85]. 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 novae studies. To date, Swift has observed 28 galactic novae. A similar number of novae has been studied in M31. An overview of the Swift sample of novae (52 galactic plus magellanic cloud) is given by Schwarz et al. [86]. Swift has detected keV emission from shocked ejecta and supersoft (SS) emission from the WD surface. Extensive observations (approx. 400 ks) of the 2006 nova outburst from RS Oph found an unexpected SS state and 35 s quasi-periodic oscillations [87]. Detailed analysis of Swift observations revealed a mass ejection of $3 \times 10^{-5} M_{\odot}$ at 4000 km s$^{-1}$ into the wind of the mass losing red giant companion in the system.

5. Summary

The last 50 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 GRBs on the most distant scales, to TGFs right here on the 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.

References


79. Thöne CC et al. 2011 The unusual γ-ray burst GRB 101225A from a helium star/neutron star merger at redshift 0.33. Nature 480, 72–74. (doi:10.1038/nature10611)


