The Swift satellite lives up to its name, revealing cosmic explosions as they happen

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Gamma-ray bursts are the most powerful objects in the Universe. Discovered in the 1960s as brief flashes of gamma radiation, we now know that they emit across the entire electromagnetic spectrum, are located in distant galaxies and comprise two distinct populations, one of which may originate in the deaths of massive stars. The launch of the Swift satellite in 2004 brought a flurry of new discoveries, advancing our understanding of these sources and the galaxies that host them. I highlight a number of important results from the Swift era thus far.

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1. Introduction

(a) What are gamma-ray bursts?

The old saying ‘the early bird catches the worm’ is never truer than when studying the most powerful explosions in the Universe—gamma-ray bursts (GRBs). These monster events—second only to the Big Bang in energy release—are occurring every day all across the Universe, and were discovered accidentally during the ‘Cold War’ by spy satellites looking for the tell-tale signs of nuclear weapons testing (Klebesadel et al. 1973). The bursts of gamma rays they detected seemed to be coming not from the Earth but from space and galaxies beyond our own (later confirmed: Paczyński 1995; Metzger et al. 1997).

Decades on, astronomers have identified the origins of perhaps three-quarters of the GRB population: the so-called long GRBs with gamma-ray durations of more than a couple of seconds. They emerge from the deaths of very massive stars, where a black hole and a supernova are formed (see §4), together with two highly relativistic jets, one of which points directly at us. GRBs are the ultimate probes of extreme physical processes that cannot be simulated in any laboratory on Earth. We observed the radiation created by shocks in the jet at gamma- and X-ray wavelengths, lasting a few to a few hundred seconds and termed the prompt emission. The innermost region where the powerful jets are launched is known as the central engine (see §2). The prompt emission is followed by the so-called afterglow emission after the jet breaks out of the star and emits at

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longer wavelengths down through the optical and radio bands. It is this afterglow, fading to nothing on time scales of days to months, that has been the main catalyst for our understanding of GRBs.

But the hunt for GRB origins is not over. About a quarter of all detected GRBs exist only for a fraction of a second, seen as a single short spike against the gamma-ray background. Blink, and you have missed it! These sources, known as short GRBs, are also preferentially seen in the higher energy bands, making them spectrally harder than the long bursts (figure 1; e.g. Kouveliotou et al. 1993). The afterglows of this class of GRBs remained elusive for decades; their eventual discovery is described in §3.

GRBs are bright and hence can be seen out to great distances. They allow us to probe the furthest reaches of the Universe with look-back times currently stretching to 13 Gyr (e.g. Kawai et al. 2006). Section 5 explains their potential as very powerful tools to study the very first stars, how galaxies were assembled and how they have evolved to the present day.

(b) Introducing the Swift satellite

The Swift satellite (Gehrels et al. 2004), launched into low-Earth orbit in November 2004, detects GRBs at a rate of ca 100 per year. It carries three instruments: a wide-field gamma-ray telescope named Burst Alert Telescope (BAT), an X-ray telescope named XRT, and an optical and ultraviolet telescope named UVOT. When a flash of gamma rays is detected with the BAT, the spacecraft then quickly turns itself (slews) towards the GRB to begin on-board X-ray and optical/ultraviolet (UV) observations typically 70–100 s later. The GRB location on the sky is sent out automatically and can be picked up by ground-based observers. The first data are also relayed to the Earth in near real time and a number of important characteristics of the object can be measured, allowing informed decisions to be made on how to proceed with follow-up

Figure 1. Hardness-duration diagram for Swift bursts up to 2006 (data points with error bars) overlaid on the sample from Swift’s predecessor, the Burst And Transient Source Experiment. A bimodality can be seen in the GRB population. Adapted from Sakamoto et al. (2006). Dots, BATSE 4B; circles, Swift/BAT.
observations. In this game, the ability to turn the spacecraft around incredibly quickly (within minutes) is key to detecting the rapidly fading afterglows and therefore locating the GRB to high precision.

Swift’s unique fast-slew capability, unprecedented sensitivity and large field of view for GRB detection together with simultaneous coverage of several crucial wavelength regimes and the dedicated fast data-downlink system provide a wealth of details on how these sources behave with time (through light curves) and with wavelength (through spectra).

2. Probing extreme physical processes

The intrinsic luminosities of GRBs are immense, producing as much energy in tens of seconds as the Sun will emit in its entire lifetime. If this energy is emitted in all directions plausible, progenitor models are stretched to the limit (in some cases energies are in excess of $10^{53}$ erg) and so the radiation must be confined to a cone or jet. While the progenitors of short- and long-duration bursts are clearly different, the mechanisms producing the GRB and subsequent afterglow are similar. In both cases, we witness a blast wave propagating out from a central object, in which shocks create both the initial gamma-ray emission and the broad-band afterglow emission. The overall behaviour of the blast wave can be represented by a set of power laws characteristic of synchrotron emission generated by the acceleration of fast-moving particles in magnetic fields in the shock front (for a review, see e.g. Zhang & Mészáros 2004). The physical parameters can therefore be probed by observations with good temporal and spectral coverage—requiring a dedicated space mission.

No two GRBs look the same, but there are features common to many of the X-ray afterglows (figure 2; Nousek et al. 2006; O’Brien et al. 2006). After the initial prompt phase, the canonical afterglow decays very steeply before flattening out to what is known as a plateau phase. The light curve then breaks to the steeper decay rate known from pre-Swift data and may steepen again at a day or so after the GRB began, indicating the sideways spreading of the jet as the

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blast wave decelerates (Rhoads 1997). Swift has really uncovered the time zone in which the observed emission transitions from prompt GRB dominated to afterglow dominated.

Striking features—sharp peaks superposed on the steadily fading light—can be seen in around half of all Swift GRB X-ray light curves, and are called X-ray flares (e.g. Burrows et al. 2005). X-ray flares can be very intense—in one case a giant flare was observed that contained almost as much energy as the GRB itself (GRB 050502B, Falcone et al. 2006). This requires that, through some process, additional energy is injected into the blast wave. Further indications of the continuation of the central engine arise in particularly long-lasting GRB prompt emission continuing for hundreds of seconds (e.g. GRB 070616, Starling et al. 2008) and in lengthy afterglows, such as GRB 060729, which was observable in the X-rays for 125 days, far longer than any other GRB afterglow (Grupe et al. 2007). Energy is thought to have been re-injected into the moving blast wave or shock front in order for the afterglow to be bright for such a long time. Emission from jets is seen in various forms from many types of objects all across the Universe, from active galaxies to X-ray binaries to young stellar objects, where the GRB jets clearly have the fastest motion, approaching the speed of light. These new revelations in GRB science are bringing us closer to the central engine, allowing studies of fundamental processes such as acceleration mechanisms in shocks, jet collimation and magnetic field generation in shock fronts.

In a few particularly bright individual cases, the jet structure and physics of the internal engine have been revealed as never before. GRB 080319B was the second of the four GRBs to go off on 19 March 2008. This was truly the monster of all bursts: the brightest from optical to X-rays yet seen. The source briefly reached a visual magnitude of 5.3, meaning that if you happened to be looking up at the right time and place, you would have seen it with the naked eye! The light would be coming to you from redshift 1, equivalent to ca 7.5 gigayears ago, demonstrating the sheer power in these events. The dataset collected for this GRB is arguably the most complete to date, and efforts are now under way to understand the workings of the central engine (e.g. Racusin et al. in press).

3. The discovery of short burst afterglows

Progress in understanding the shortest duration GRBs, lasting less than 2 s in the high-energy gamma rays, has lagged far behind long burst studies. This was almost entirely due to the lack of significant detections of these sources using X-ray and optical telescopes. The most ground-breaking discovery made with the Swift satellite to date is undoubtedly the first detection of afterglow emission from any short burst. The location of the faint (just 11 source photons) X-ray afterglow of GRB 050509B (Gehrels et al. 2005) was accurate to within 4 arcseconds (error circle radius), and while no optical counterpart was identified, the local neighbourhood of the burst provided some clues as to the GRB progenitor. Within the Swift X-ray position error circle, a nearby (redshift \( z = 0.225 \)) galaxy cluster comprising a large elliptical and several smaller galaxies was seen through essential follow-up by ground-based telescopes including the Very
Large Telescope in Chile and Keck in Hawaii (figure 3; e.g. Hjorth et al. 2005a). The chance coincidence of a GRB with the large elliptical galaxy is very low, suggesting that this old red galaxy, no longer forming stars, may have hosted the GRB. Searches for the rise of an accompanying supernova component (expected for nearby long GRBs) found nothing to stringent limits, and, together with the elliptical host galaxy, this provided evidence in support of an origin for short bursts that is completely different from the massive star origins of their long-duration cousins: the compact binary merger scenario. This scenario was proposed for the origin of short-duration GRBs many years ago and works by allowing the orbits of the two stars to decay through gravitational inspiral, bringing them gradually closer together with time eventually to merge (see e.g. Nakar (2007) for a review). Given that a large fraction of stars in our Universe are thought to exist in pairs, orbiting each other in a binary system, a double-star merger seems to be a disaster waiting to happen in every corner of the Universe. However, for a powerful GRB to be produced, these stars must be extremely small and dense, and these systems are probably rare. Following the successful detection of an X-ray afterglow from the short GRB 050509B came the detection of an optical afterglow for the short GRB 050709 (Fox et al. 2005; Hjorth et al. 2005b). The subarcsecond position of the optical afterglow led to successful identification of the host galaxy, lying at a distance $z=0.16$. Thereafter several more afterglow detections were made at both X-ray and optical wavelengths. The sample shows that, while short GRB afterglows are generally less distant, their afterglows are intrinsically fainter than the long GRBs but follow the same decays and spectral shapes caused by synchrotron emission in a decelerating blast wave. There appears to be a tendency towards associations with late-type (elliptical) galaxies at $z<1$ with very little or
no current star formation. If these bursts originate in a binary merger (the currently favoured model), we might expect to see them more frequently in low-density environments, kicked out of the denser regions in which they were born during the earlier supernova phase. This is clearly in contrast to the highly star-forming regions in which we expect the long bursts to occur. There are notable exceptions to this rule however, and, while the sample size is still small, a complete picture is difficult to form.

Astronomers could recall a small number of similar short-duration bursts of gamma rays first seen back in 1979, which caused quite a stir. These gamma-ray flashes come from our own Galaxy and are not GRBs as we know today, but are in fact flares from so-called soft gamma repeaters (SGRs). Few such objects are known, and they are thought to be neutron stars with incredibly strong magnetic fields, also known as magnetars, on which a ‘star-quake’ may trigger intense flaring activity. In 2004 a giant flare erupted from known Galactic magnetar SGR 1806-20 (Palmer et al. 2005), prompting the following question: If such a flare were to go off in another galaxy, would we see it? The answer is yes. It could have been seen out to tens of megaparsecs in nearby galaxies, and would then be difficult to distinguish from a short GRB. Comparison of the locations of short GRBs and local galaxies led to a positive correlation for 10–25 per cent of the sample, suggesting that this fraction of apparent short-duration GRBs may in fact come from SGR flares in nearby galaxies (Tanvir et al. 2005).

While hard proof of the origins of short GRBs still lies at arm’s reach, we now know that there is more than a single progenitor for these brief high-energy flashes, and current and future technology affords more opportunities to go after their faint afterglows.

4. The GRB–supernova connection

A connection between long-duration GRBs and supernovae has long been established (MacFadyen & Woosley 1999). The association was made observationally when, within the error circle of GRB 980425, a bright and energetic supernova was found (SN1998bw, Galama et al. 1998). Initially, this was considered by some a chance coincidence, but in the spectra of subsequent long GRBs, further supernova signatures were apparent, most famously in GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003). This provided proof of the origin of at least some long GRBs in the core collapse of very massive stars that have lost their outer hydrogen layers, allowing the GRB to escape without being smothered by an extended stellar envelope. While all long GRBs could be accompanied by a supernova, the reverse is not true. It is estimated that core collapse supernovae are 1000–10 000 times more frequent than GRBs. GRB-related supernovae have been studied in small samples and are found to be brighter than ordinary supernovae of the same type when scaled to a common distance. The supernova ejecta radiates through radioactive decay, which can rise above the optical afterglow light from the GRB several days after the GRB has occurred but is frequently outshone by the afterglow.

A missing piece in this puzzle has been recovered by Swift observations of nearby GRB 060218 and SN2006aj. This source had a particularly weak afterglow, allowing a clear view of the supernova signatures. Not only was the
radioactive non-thermal emission bump seen in the optical, but a thermal emission bump was also apparent, moving from X-ray energies to the lower-energy UV band with time. This striking result is interpreted as shock breakout as the supernova emerges from the star (figure 4; Campana et al. 2006; Mazzali et al. 2006; Pian et al. 2006). This was the first observation of the onset of a GRB–supernova. In 2008 Swift serendipitously caught an ordinary (non-GRB) supernova in the act of exploding while observing an earlier supernova in the same galaxy. Supernovae are usually discovered by the rise in their optical emission from the radioactive-decay-driven ejecta. This spectacular observation showed an initial spike of X-ray emission right at the onset of the event, again most likely from shock breakout (Soderberg et al. 2008).

While the first signs of core collapse are being discovered, there remain two well-studied long GRBs for which no accompanying supernova could be found to very constraining limits (GRBs 060505 and 060614, e.g. Fynbo et al. 2006). Supernovae with no optical signatures were predicted long before the launch of the Swift satellite, and can now be tested with the high-quality data available. These two cases perhaps highlight our ignorance of the supernova mechanism, of what type of stars can produce GRBs, or reveal a link from long GRBs to the supernova-less short GRB population.

Figure 4. (a) Swift X-ray (XRT, 0.3–10 keV) and (b) optical/UV light curves. The bump seen first in X-rays and then in UV is interpreted as early emission from a supernova shock breakout. The later optical bump arises from the radioactive-decay-driven ejecta. Adapted from Campana et al. (2006, including colour version of this figure).
5. A glimpse into the very distant Universe

Swift’s first year of operation really did usher GRB science into a new era of discovery. The discovery of the most distant GRB to date, which exploded 13 Gyr ago, was made in September 2005. For some time, astronomers have been hopeful that GRBs would point us to the very first stars and to conditions in the early Universe at a time when most galaxies had not yet had time to form. As the most luminous objects in the Universe, long GRBs have enormous potential as probes of the early Universe. The bright afterglows act as a backlight illuminating all material between us and the burst. Gas and dust in the host galaxy that lies along the line of sight to the GRB absorbs the GRB emission and is imprinted on the afterglow spectrum. This reveals the chemical makeup of the host, and has led to an understanding of host galaxies made possible by target-of-opportunity programmes using ground-based telescopes through which GRBs can be observed very shortly after they have gone off. Robotic telescopes can automatically respond to GRB alerts directly from the satellite, and now the same is true of some of the larger world-class telescopes in what is termed Rapid Response Mode. In this mode, for example, the 8.2 m Very Large Telescope in Chile can repoint and make observations in just 8 min!

Long GRBs tend to lie in small, faint, blue galaxies. The average of the GRB redshift distribution falls at $z = 2.3$ (figure 5; Jakobsson et al. 2006). Hubble Space Telescope images of a large number of these hosts showed that the GRB commonly lies in the brightest region of the galaxy where star formation is most vigorous (Fruchter et al. 2006). Conditions in the host galaxies are used to feed back into models for long GRB progenitors. For example, afterglow spectroscopy has shown that these galaxies have a lower ratio of metals to hydrogen than does our local neighbourhood in the Milky Way, possibly reaching as metal-poor as 1/100th the metallicity of the Sun (e.g. Starling et al. 2005). The metal content of
a star moderates the outflow of material in its wind, and in turn the properties of the stellar wind are crucial in determining the nature of the star’s final demise (Yoon & Langer 2005; Woosley & Heger 2006).

One of the great successes from ground-based telescopes in the fast-response era came when astronomers witnessed the dramatic effects that a GRB can have on its environment. GRB 060418 was spectroscopically observed at the Very Large Telescope just 11 min after the GRB began. Gas in the host galaxy can be excited by the blast of high-energy radiation from the GRB, pushing electrons into higher states in their atoms. The gas then de-excites back to normal levels on a time scale of minutes to hours, and these variations have been measured in optical spectral lines (Vreeswijk et al. 2007). The variability as a function of time gives us a measure of the density, temperature and chemical composition of the faint and distant galaxies that host GRBs. We now know that we can locate these galaxies at just 700 Myr after the Big Bang (Kawai et al. 2006). Even at these imponderable look-back times, the bright afterglow, its light shifted to the near-infrared observing bands as it crossed a large expanse of the Universe, revealed a host galaxy. Gamma rays are not easily absorbed, unlike lower-energy radiation, and travel across the Universe from GRBs, pinpointing the locations of star-forming galaxies in all directions. This is a unique method of selecting galaxy samples that is complementary to the more established deep surveys of specific regions of sky.

6. What next?

The future for GRB science looks bright. The dedicated efforts of the Swift satellite—the fastest satellite in orbit—are bearing fruit. The large number of GRBs being detected and followed up are generating meaningful statistical samples to work with. A large number of key individual sources with excellent datasets continue both to answer existing questions and to raise new ones. The next generation of space- and ground-based telescopes promise to push even deeper into the darkness, to improve the clarity with which we see the Universe around us, to observe in new windows (very low-frequency radio waves, very high-energy gamma rays, neutrino and gravitational wave detection) and to provide ever faster responses to GRB triggers.

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References


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