

# Introduction: recent developments in the study of gamma-ray bursts

BY ALAN WELLS<sup>1,\*</sup>, RALPH A. M. J. WIJERS<sup>2</sup> AND MARTIN J. REES<sup>3</sup>

<sup>1</sup>*Space Research Centre, Department of Physics and Astronomy,  
University of Leicester, Leicester LE1 7RH, UK*

<sup>2</sup>*Astronomical Institute, ‘Anton Pannekoek’, University of Amsterdam,  
Kruislaan 403, 1098J Amsterdam, The Netherlands*

<sup>3</sup>*Institute of Astronomy, University of Cambridge, Madingley Road,  
Cambridge CB3 0HA, UK*

Gamma-ray bursts (GRBs) are immensely powerful explosions, originating at cosmological distances, whose outbursts persist for durations ranging from milliseconds to tens of seconds or more. In these brief moments, the explosions radiate more energy than the Sun will release in its entire 10 Gyr lifetime. Current theories attribute these phenomena to the final collapse of a massive star, or the coalescence of a binary system induced by gravity wave emission.

New results from Swift and related programmes offer fresh understanding of the physics of GRBs, and of the local environments and host galaxies of burst progenitors. Bursts found at very high red shifts are new tools for exploring the intergalactic medium, the first stars and the earliest stages of galaxy formation.

This Royal Society Discussion Meeting has brought together leading figures in the field, together with young researchers and students, to discuss and review the latest results from NASA’s Swift Gamma-ray Burst Observatory and elsewhere, and to examine their impact on current understanding of the observed phenomena.

**Keywords:** gamma-ray bursts; gamma-ray burst afterglows; cosmology; collapsar model; binary system mergers; Swift

## 1. Introduction

Gamma-ray bursts (GRBs) are immensely powerful explosions, originating at cosmological distances, whose outbursts persist for durations ranging from milliseconds to tens of seconds or more. In these brief moments, the explosions radiate more energy than the Sun will release in its entire 10 Gyr lifetime. Current theories attribute these phenomena to the final collapse of a massive star, or the coalescence of a binary system induced by gravity wave emission.

The Royal Society’s Discussion Meeting in September 2006 addressed *Recent developments in the study of gamma-ray bursts* and brought together leading figures, young researchers and students, from many countries, to discuss and

\* Author for correspondence (alan.wells@star.le.ac.uk).

One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.

review the latest observational results, particularly those from NASA's Swift Gamma-ray Burst Observatory, and to examine the impact of these results on current understanding of the underlying physics of the observed phenomena. Review talks by invited speakers were accompanied by shorter contributions and posters which provided opportunities for the presentation of key results emerging from new investigations.

This issue of *Phil. Trans. R. Soc. A* is a collection of refereed papers that have been developed from contributions presented at the meeting. The papers are organized around topics that deal with different aspects of current understanding of GRB phenomena, in particular, progenitors for short and long bursts, jet behaviour, afterglows, connections with supernova events, ultra-high energy and gravitational wave emissions from bursts and bursts as cosmological probes.

## 2. Background

GRBs were first discovered in the late 1960s (Klebesadel *et al.* 1973). They come in two classes: long (more than 2 s) soft spectrum bursts and short hard events (Kouveliotou *et al.* 1993). Results from the *Compton Gamma-ray Observatory* (CGRO) showed them to be distributed isotropically over the sky occurring at a rate of approximately 300 per year (Meegan *et al.* 1992). The BeppoSAX mission made the important discovery of X-ray afterglows associated with long bursts (Costa *et al.* 1997). Follow-up observations found afterglows at optical (van Paradijs *et al.* 1997) and radio (Frail *et al.* 1997) wavelengths and provided red shift (and hence distance) measurements to place upper bounds on the total energy (more than  $10^{51}$  ergs  $\text{s}^{-1}$ ) of the bursts. Identification of the hosts showed—at least for the BeppoSax sample—that long GRBs emanated from regions of high star formation rate in high-red-shift galaxies. The afterglow observations provided compelling evidence in support of the fireball model, which associates the burst and the subsequent afterglow with shocks generated within highly relativistic jets ejected from the progenitor (Mészáros & Rees 1997). BeppoSax and HETE-2 between them found a small sample of closer GRBs, most notably GRB 030329/SN 2003d, in association with Type 1c supernovae pointing to collapse of the central core of a massive early type star and formation of a black hole as the precursor to the GRB outburst (MacFadyen & Woosley 1999). However, prior to Swift, most afterglow data were collected hours after the burst, so little was known about the origins of the short bursts or about the early emission behaviour of the high-red-shift long bursts.

## 3. Observational contributions from Swift

The Swift satellite (Gehrels *et al.* 2004) was specifically designed to study early GRB emissions and to detect the afterglows by automatically slewing to a GRB as soon as it had been detected on-board. Swift carries a sensitive coded mask burst alert telescope (BAT) and finds new GRBs by detecting gamma-ray emission in the 15–150 keV range. When BAT detects a new burst, subject to certain visibility constraints, Swift autonomously re-points to bring the GRB within the field of view of the X-ray telescope (XRT) and the UV/optical telescope (UVOT). Observations with these instruments start very quickly

after the initial burst detection from which precision location of the bursts, to arc-second accuracy, is usually obtained. Accordingly, Swift routinely provides prompt detections of GRBs and their afterglows and automatically transmits their locations and other information obtained from the three instruments via the TDRSS satellites and the Gamma-ray Burst Coordinate Network to observers and robotic telescopes around the world.

Swift was launched on 20 November 2004 and has since been detecting GRBs at the predicted rate of approximately 100 per year. At the time of the Royal Society meeting, 168 GRBs had been detected and, for 90% of these, the spacecraft was able to slew to the source within 5 min of the initial detection, often much more quickly. X-ray afterglows were detected on-board in virtually all of these promptly observed bursts, whereas optical/UV afterglows were detected on-board in only 30% of the prompt detections, rising to 50% when ground-based detections are taken into account (see also the review by [Gehrels 2007](#)).

Swift is locating many more high-red-shift ( $z > 2$ ) bursts than the previous missions. Indeed, the majority of Swift GRB detections to date have been of the long-burst variety, and studies of the early afterglows, previously inaccessible, have added to evidence supporting the view that long-duration bursts are produced during the collapse of a massive star. Red shifts have now been measured for over 50 long bursts, including the first GRB at very high red shift ( $z > 6$ ; [Cusumano et al. 2006](#); [Haislip et al. 2006](#); [Kawai et al. 2006](#)). These bursts are providing new ways to probe the high-red-shift universe (as reviewed by [Ghirlanda 2007](#); [Lamb 2007](#)) and [Tanvir & Jakobsson \(2007\)](#) discuss conditions under which GRBs may be used as a tracer of the star formation rate in high-red-shift galaxies.

Swift's multi-wavelength measurements (gamma ray to optical/UV) of the exceptional nearby burst GRB 060218 ( $z = 0.033$ ) have provided a direct observation of the shock breakout in a supernova collapse ([Campana et al. 2006](#); [Blustin 2007](#); [Zhang et al. 2007](#)), this observation adding to the small sample of previously observed nearby long GRBs associated with supernova collapse. Conversely, Swift has found two bursts, GRB 060614 and GRB 060505, for which no supernova association has been found down to deep limits ([Watson et al. 2007](#); and references therein).

Swift also made the first X-ray afterglow localization of a short burst and has since found 13 more along with two additional detections with HETE-2 ([Gehrels 2007](#); and references therein). Most Swift short bursts have X-ray afterglow detections and about half have host identifications and red shifts. [Barthelmy \(2007\)](#) and [Gehrels \(2007\)](#) remark on the similarity of the emission of GRB 060614 with the peak luminosity and spectral lags seen in short bursts, while its afterglow emissions are more characteristic of a low-red-shift long burst despite the non-detection of a coincident supernova to deep limits.

Various new features of GRB phenomenology, such as the soft tail in the spectra of short hard bursts; X-ray flares in the early afterglow indicating extended activity of the central engine in GRBs; GRBs associated with supernovae; GRBs with no supernovae; energetic supernovae with no GRBs; are all discoveries from the Swift era. All offer new challenges to current theoretical understanding. Many have been addressed in the papers in this issue.

#### 4. Models, progenitors and jets

Woosley & Zhang (2007) remark on this diversity of burst phenomena and argue in favour of a single basic model for the central engine operating in a massive star but allowing for variable pre-supernova mass and different rotation and mass loss rates. Metallicity is a key factor affecting all the three of these properties. The central engine must generate both a narrowly collimated, highly relativistic jet to make the GRB, and a wide-angle, sub-relativistic outflow responsible for exploding the star and illuminating the supernova. As the two components may vary independently, it is possible to produce a variety of jet energies and supernova luminosities. They go on to explore the production of low-energy bursts and find a lower limit ( $10^{48} \text{ ergs s}^{-1}$ ) to the power that a jet requires in order to escape a massive star before that star either explodes or the core is accreted. Lower-energy bursts may be particularly prevalent when the metallicity is high, i.e. in the nearby Universe at low red shift. Conversely, Podsiadlowski (2007) discusses the potential of a variety of binary merger models to account for the diversity of long-duration GRBs.

Pe'er *et al.* (2007) suggest that thermal radiation may accompany the first stages of a GRB, to explain observed features in the prompt gamma emission that are inconsistent with the optically thin synchrotron emission more commonly associated with the fireball model. Lazzati *et al.* (2007) model hydrodynamic propagation of a relativistic jet through a massive star and find radiative phases in the jet propagation, which could contribute to the GRB light curves. The scenario of jet evolution described in this work may also provide an explanation for the long dead times between the precursor and the main GRB emission seen occasionally with BAT and previously with BATSE bursts from *CGRO*.

#### 5. Afterglows

Swift has filled the temporal gap between the prompt emission and the afterglow that earlier missions were generally unable to probe. O'Brien & Willingale (2007) have shown that light curves combined from BAT and XRT show an essentially smooth transition between the non-thermal prompt X-ray emission and the decaying X-ray afterglow. They and others (Burrows *et al.* 2007; Panaitescu 2007; Piran & Fan 2007 and references therein) agree on the generic nature of early GRB light curves as illustrated in figure 1 with the proviso that not all phases in the afterglow evolution shown in the figure are present in all bursts thus suggesting that several dissipation processes may be involved.

When present as the dominant feature, the initial steep decay is usually attributed to large-angle 'high-latitude' emission produced from internal shocks; when the slower unbroken power-law decay is dominant, this is attributed to forward shock emission from a narrow jet. Most bursts appear to exhibit a combination of both features. About half of the afterglows have X-ray flares superimposed on the broken power-law (Burrows *et al.* 2007) also indicative of continuing activity within the central engine for extended periods after the initial outburst. Panaitescu (2007), Piran & Fan (2007) and others have discussed the added complexity to afterglow models needed to fully understand these new features.

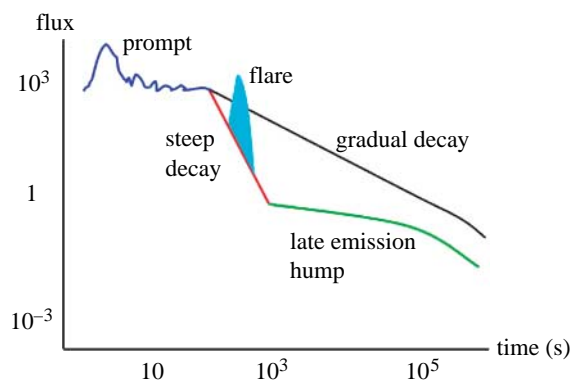


Figure 1. A schematic view of the early GRB X-ray light curve. Following the prompt emission, which typically lasts for a few tens of seconds, the decay tends to follow one of the two paths: (i) a steep decay, during which the flux can fall by several orders of magnitude, followed by a shallower, ‘late emission hump’ starting at approximately  $10^3$  s or (ii) a more gradual decay. Either decay path can end with a break at greater than  $10^4$  s to a steeper decay. X-ray flares can occur during either decay path, most prominently during the first hour (O’Brien & Willingale 2007).

Optical afterglows have been monitored on-board Swift with the UVOT (Mason *et al.* 2007) as well as with ground-based telescopes (e.g. Antonelli *et al.* 2007). Results indicate considerably more complexity in many bursts than would be expected from the standard fireball model and varying degrees of correspondence between the X-ray and the optical light curves. In this respect, GRB 050525A may be an exception as it exhibits an achromatic jet break at  $\sim 10^4$  s, although, even in this case, the decay indices are shallow compared with what might be expected from the standard model (Zhang *et al.* 2007; and references therein). Afterglow behaviour from other bursts is not so easily interpreted and the absence of jet breaks in the X-ray afterglow, when present in the optical, remains to be understood.

Radio monitoring of GRB afterglows enables the evolution of GRB explosions to be monitored long after the X-ray and optical afterglows have faded. GRB 030329 is still visible at radio wavelengths 1100 days after the burst trigger (van der Horst *et al.* 2007), and continuing monitoring is revealing structural evolution of the burst and indicating transition from a collimated relativistic outflow to spherical non-relativistic outflow over this period.

## 6. Short hard gamma-ray bursts

Swift’s discovery of the first afterglows from short hard GRBs is being followed by a systematic study of short bursts through X-ray, optical and radio afterglow measurements of multiple short bursts (Barthelmy 2007; Fox & Roming 2007; Levan 2007; Zane 2007; and references therein). Their distance scale ( $z > 0.1$ ) and energetics ( $E > 10^{48}$  erg) are now established, and they have been revealed definitively as a cosmological phenomenon. The short bursts have been found among old stellar populations—in elliptical galaxies, galaxy clusters and the outskirts of younger galaxies and the absence of associated supernovae appear to

Table 1. International Scientific Committee.

Martin Rees, Cambridge,	Keith Mason, PPARC
Len Culhane, MSSL	Peter Mészáros, Penn State University
Neil Gehrels, GSFC	Luigi Piro, IASFC, Rome
Don Lamb, Chicago	Nial Tanvir, University of Leicester
Chryssa Kouveliotou, MSFC	Ralph Wijers, Amsterdam
Shri Kulkarni, Caltech	Alan Wells, University of Leicester

rule out an origin in the deaths of massive stars. This is in contrast to the now accepted view of the origins of long-duration GRBs, whose host galaxies, red shifts and associated supernovae are all consistent with the collapsar–supernova model. The effect of these discoveries has been to strongly favour the compact object merger model for short bursts. The observed properties point to coalescence of a compact-object binary, either neutron star–neutron star or neutron star–black hole (King 2007) and enabling the prospects for gravitational wave detection to be reassessed, as discussed at this meeting by Hough (2007).

7. Facilities for future GRB studies

Prospects for GRB detections in other energy regimes were reviewed by Chadwick (2007) (very high energy gamma-ray detections), Hough (2007) (gravitational wave detections) and Waxman (2007) (neutrino detections). These contributions, together with the review by Piro (2007) of new ground- and space-based facilities (GLAST, AGILE, JWST, LOFAR, ALMA) that will become operational within the next few years, emphasize the prospect of detection of unambiguous and direct signatures of the formation of the central engine of GRBs and of the importance of multi-messenger astrophysics in achieving further advancement in the understanding of GRBs.

8. Summary

Over 200 people registered to attend this 3-day discussion meeting on gamma-ray bursts. The programme was developed by the International Scientific Committee comprising those outlined in table 1.

The framework of the meeting was established around a series of 17 invited review papers, all of which were of excellent quality and timeliness. A high degree of participation among the attendees was achieved through a competitive call for key result papers, with emphasis being placed on contributions from early career scientists. The response was almost overwhelming, with offers of 70 papers from which only 20 short presentations could be selected. The International Scientific Committee rose (wo)manfully to this challenge and their sage advice was invaluable in helping us to decide which contributions to accept as a talk or a poster, or which to reject. The poster session proved to be a considerable success due to two factors. Poster displays were attractively located and easily accessible during session breaks. Perhaps more significantly, through the generosity of the Particle Physics and Astronomy Research Council, prizes were on offer for the



three best posters, as judged by a panel chaired by Ralph Wijers. Short papers by the three winners (Speirits *et al.* 2007; Eldridge 2007; Medvedev 2007) are included in this issue.

The organizers are indebted to the Royal Society for hosting the meeting. We should particularly like to express our thanks to the local organizers, Chloe Sykes, Katherine Hardaker and Helen Ross (Publishing Editor, *Phil. Trans. R. Soc. A*) for their help and to Mike Shepherd for the efficient management of the audio visual technology. AW wishes to acknowledge his Leverhulme Emeritus Fellowship which has supported his contribution to this meeting, and RAMJW wishes to acknowledge NWO for support of this work through a VICI grant.

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