Gamma-Ray Bursts and Fast Transients

Multi-wavelength Observations and Multi-messenger Signals

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Abstract The current status of observations and theoretical models of gamma-ray bursts and some other related transients, including ultra-long bursts and tidal disruption events, is reviewed. We consider the impact of multi-wavelength data on the formulation and development of theoretical models for the prompt and afterglow emission including the standard fireball model utilizing internal shocks and external shocks, photospheric emission, the role of the magnetic field and hadronic processes. In addition, we discuss some of the prospects for non-photonic multi-messenger detection and for future instrumentation, and comment on some of the outstanding issues in the field.

Keywords Gamma-rays · bursts · Black holes · Neutron stars · Shocks · Neutrinos · Gravitational waves

1 Introduction

Gamma-ray bursts (GRBs) and other one-shot, fast, high energy transients are likely to produce UHE Cosmic rays, VHE neutrinos and Gravitational waves in addition to radiation across the entire electromagnetic spectrum from radio through to VHE gamma-rays. Multi-wavelength observations have been and will, without doubt, continue to be crucial in the study of GRBs and the detection of multi-messenger signals, along side the high energy photon prompt emission, will broaden our understanding of the extreme physical conditions and processes which give rise to such high energy phenomena.

Many of the major breakthroughs and results in GRB studies to date have arisen from multi-wavelength observations. The realisation that all GRBs are extra galactic was initiated by the first X-ray afterglow detection made by the *BeppoSAX* soft X-ray narrow field

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instruments for the GRB 970228 (Costa et al. 1997). This provided a position with a 90% confidence error radius of 50 arc seconds which lead to the identification of the optical emission (Van Paradijs et al. 1997) and subsequent deep observations with the Keck telescopes gave a redshift of $z = 0.695$ (Bloom et al. 2001). The exceptionally bright GRB 030329 in 2003 was detected by all three instruments on the High Energy Transient Explorer satellite (HETE) across a wide photon energy range: *Fregate* 7–400 keV; the *WXM* 2–25 keV; *SXC* 2–10 keV. Rapid communication of the $2'$ error box 73 minutes after the burst allowed the detection of a counterpart in optical and radio emission (Vanderspek et al. 2004). This multi-wavelength coverage lead to the measurement of a redshift, $z = 0.1685$, the discovery of a supernova associated with the burst and established that long GRBs can be produced by the explosion of some extreme type Ic SNe.

The redshift distribution of GRBs is a moving target with new results being published all the time. A good up to date summary can be found at the web page maintained by Greiner.¹ The redshift measurements span the range 0.0085–9.4 with a mean of ~ 2.5 . This distribution is the product of intense multi-wavelength observation activity and is subject to many selection biases and constraints, e.g. Coward et al. (2013). HST imaging of the error boxes of long GRBs reveals that they occur predominantly in UV bright star forming regions of their host galaxies, e.g. Fruchter et al. (2006).

The detection and accurate positioning of GRBs combined with a rapid alert system and fast slewing response to initiate near immediate follow-up observations was pioneered by the *Swift* satellite (Gehrels et al. 2004). This has provided a wealth of new and intriguing results including the first accurate localizations and redshifts for short GRBs (Gehrels et al. 2005), the identification of the highest redshift GRBs (Cucchiara et al. 2011), a population of low luminosity GRBs often associated with supernovae (Stanek et al. 2003; Zhang et al. 2012), the detection of the brightest optical GRB, visible with the naked eye (Bloom et al. 2009) and detailed multi-wavelength light curves and spectra from the prompt through to the afterglow emission. With the rapid development of new facilities like *LIGO*, *Virgo*, *IceCube* etc. there is now the possibility of the simultaneous detection of multi-messenger signals, including gravitational wave and neutrinos, from GRBs. The likelihood of such detections is, of course, dependant on a multitude of factors such as the local rate of mergers of compact objects and the beaming angle of GRB jets but it is clear that a rapid response and rapid alert enabling multi-wavelength and multi-messenger observations from the prompt through to late afterglow will be mandatory if we hope to gain a detailed understanding of GRBs and other fast, high energy transients.

2 The Fireball Model Then and Now

The theoretical paradigm underpinning most investigations of GRBs is the standard fireball shock model (see Mészáros 2002, and references therein). At early times, and close to the central engine, internal shocks within the relativistically expanding fireball produce the highly variable prompt hard X-ray and Gamma-ray emission we see as the GRB (Rees and Mészáros 1994) and as the fireball is decelerated by interaction with the low-density circumburst medium an external shock forward shock develops to produce the longer lasting afterglow emission seen initially from the soft X-ray band through to the IR (Rees and Mészáros 1992). The predominant emission mechanism is expected to be synchrotron radiation from relativistic electrons accelerated in the shocks, both internal and external, gyrating in the magnetic field wound up by compression and turbulence in the same shocks. In

¹<http://www.mpe.mpg.de/~jcg/grbgen.html>.

Fig. 1 The Fermi GRM and LAT lightcurves for GRB 080916C (Abdo et al. 2009). The first pulse, 0.0–3.6 seconds is bright in the GBM but absent from the LAT

addition, inverse Compton up-scattering of low energy synchrotron photons by the relativistic electron population can produce a high energy component or tail to the expected synchrotron spectrum such that the broadband spectrum observed is described by a so-called Synchrotron-Self-Compton (SSC) model. When energy injection from the central engine ceases the forward shock emission enters a final power-law decay and produces a characteristic synchrotron radiation afterglow spectrum stretching from radio through to X-ray (Sari et al. 1998; Wijers and Galama 1999).

With the launch of *Fermi* late 2008, the detection of GRBs with both the Large Area Telescope (LAT, 20 MeV to > 300 GeV) and the Gamma-ray Burst Monitor (GBM, 8 keV to 40 MeV) has given us exceptional broadband spectra of the prompt emission over more than seven decades of energy. An interesting and unexpected finding is that for many GRBs the GeV emission starts with a noticeable delay after the MeV emission. For example, the first pulse of GRB 080916C is visible only in the MeV while the second pulse, that appears ~ 4 seconds later, is seen strongly in the GeV band by the LAT, Fig. 1 (Abdo et al. 2009). For GRB 080916C there is no evidence for a second spectral component; the spectrum is fitted by a single component that evolves from soft to hard and back to soft again. Furthermore,

Fig. 2 The Band function illustrated by spectrum of GRB 990123 with $E_{peak} = 720$ keV (Briggs et al. 1999)

for this and other LAT bursts the GeV emission persists into the afterglow phase >1000 s after the initial trigger. However, for some bursts, for example GRB 090902B (Abdo et al. 2009) and GRB 090926A (Ackermann et al. 2011), a distinct second hard spectral component is observed. Explaining the GeV–MeV time delays and the second distinct hard spectral component is difficult in the context of a one-zone (internal shocks) SSC mechanism (Ackermann and the Fermi collab. 2011). The initial GeV emission is obviously associated with the prompt pulse structure but the GeV emission extending into the afterglow, seen after the main prompt pulses, is unlikely to come from internal shocks and maybe SSC arising from the forward shock as the jet interacts with the surrounding circumburst medium.

Recent *Fermi* observations of the early prompt spectra of a few bursts have revealed a second mid-energy range spectral component in the emission again calling into question the validity of the one-zone internal shock/SSC radiation model for the prompt phase (Veres and Mészáros 2012). The new paradigm which may solve this problem evokes photospheric emission to explain at least part if not all of the prompt emission in the energy band 20 keV to 100 GeV.

3 The Prompt Emission

GRBs are primarily detected by virtue of the initial short burst of gamma-rays. A succession of instruments have provided GRB triggers, e.g. BATSE on *CGRO*, the Konus-Wind Experiment, FREGATE on *HETE-2*, IBIS on *INTEGRAL*, BAT on *Swift*, GRID on *AGILE* and the LAT and GRM on *Fermi*. The spectrum of the prompt emission is usually observed as a broken powerlaw characterised by the so-called Band function (Band et al. 1993), as shown in Fig. 2. The peak of the $E.F(E)$ spectrum, E_{peak} , represents the characteristic photon energy for the GRB. In order to get a reliable estimate of E_{peak} broad energy band coverage is required.

Fig. 3 The Amati Relation—a correlation between the characteristic photon peak energy, E_p , in the rest frame of the burst and the equivalent isotropic energy, E_{iso} . Long GRBs and X-ray Flashes lie in the correlation band which is ~ 1 dex wide in energy. All short GRBs are outliers and form a band of similar width but offset from the main correlation by ~ 2 dex in energy

There is a well known correlation, called the Amati Relation, between the E_{peak} energy expressed in the rest frame of the GRB and the isotropic energy, E_{iso} , estimated from the total fluence from the burst and the redshift (Amati et al. 2002; Amati 2006). This is illustrated in Fig. 3. The correlation is different for short ($T_{90} < 2$ seconds) and long ($T_{90} > 2$ seconds) with higher E_{peak} values for a given E_{iso} value for the short bursts. For both long and short bursts the correlation is not tight with a spread of $\sim$ factor 10. There has been much discussion as to whether the correlation is an intrinsic property of the GRB emission or an observational or selection artifact (Butler et al. 2007). It may be that the relation is a signature of something fundamental about the GRB emission but better broad energy band spectral observations are required, coupled with more accurate determination of other burst properties, to reveal the true nature of the relationship.

The prompt emission of a few bright GRBs observed by *Fermi* have hard X-ray and Gamma-ray spectra which, as expected, are dominated by a Band function, usually attributed to non-thermal emission from internal shocks, but also include a highly significant component fitted by a thermal spectrum, e.g. GRB 100724B (Guiriec et al. 2011). Simultaneous observation across a broad energy band 10–10⁷ keV is required to unambiguously confirm the presence of two components in the prompt spectra, see Fig. 4. Including the BB spectral component over the brightest part of the burst ($T_0 - 1.024$ s to $T_0 + 83.969$ seconds) shows a significant improvement in the fit compared to a Band function by itself however, the second component is weak compared to the dominant Band function and there is no guarantee that the additional component is thermal in origin and uniquely fitted by a Planck function. In GRB 100724B the two components seem to vary independently which favours the interpretation that the thermal component is of photospheric origin close to the central engine while the non-thermal component occurs at larger radii.

The challenge to any theoretical model is to produce a Band-function-like broadband spectrum for the prompt emission with a characteristic peak energy in the 0.2–1 MeV range (Gehrels et al. 2009), with spectral evolution soft-to-hard-to-soft or more simply hard-to-soft and to include a (delayed) GeV tail component and possibly a lower energy Planck-function-like second component. Within the SSC model the peak is produced by a combination of the underlying relativistic electron spectrum, synchrotron cooling, synchrotron self absorption and up-scattering of the synchrotron photons by inverse Compton from the relativistic electrons. The observed energy peak is dependent on the bulk Lorentz factor of the outflow. Whether it is possible to produce the range of observed Band function parameters by

Fig. 4 Time-integrated spectrum of GRB 100724B (Guiriec et al. 2011). *Top panels:* Band function plus Black Body. *Left panels:* count spectra. *Right panels:* deconvolved νF_ν spectra. The data points appear as colour crosses. *Dashed lines* indicate the individual spectral functions, and *solid lines* show the summed model fit

SSC has been questioned by many authors (e.g. Ghisellini et al. 2000; Preece et al. 2000) and the radiation efficiency of internal shocks is low, 5%–10%, unless the colliding shells have widely differing Lorentz factors (Beloborodov 2000). An alternative is to associate the energy peak to a blackbody at the comoving pair combination temperature in the fireball's photosphere (Eichler and Levinson 2000). The spectrum below the peak energy can then be attributed to the Rayleigh–Jeans part of the photospheric spectrum but the high energy power law tail and the GeV emission require an additional explanation (Meszaros and Rees 2000). If dissipation due to shocks or other processes occurs at or below the photosphere then a high efficiency is achievable and the thermal peak energies occur in the observed Band function range and Compton equilibrium of internal shock electrons or pairs with photospheric photons lead to spectra with a break at the right preferred energy and steep low energy slopes (Rees and Mészáros 2005; Pe'er et al. 2005, 2006). The photospheric model also provides a possible physical explanation for the Amati relation (or Ghirlanda relation, see below) (Thompson et al. 2007).

The magnetic field in the outflow plays a vital role. It is necessary for the production of synchrotron radiation and is certainly crucial in the acceleration of the relativistic charged particle distribution, by a Fermi mechanism, that ultimately produces the high energy tail of the spectrum via inverse Compton up-scattering. However, if the magnetic field is strong enough the magnetic stresses will be dominant and the whole dynamics of the jet will be driven by the magnetic field and must be modelled using magnetohydrodynamics (MHD). Magnetically dominated (or so-called Poynting dominated) GRB jets fall into two categories, baryon-free in which the baryons are absent or dynamically negligible (e.g. Drenkhahn 2002) and those with a non-negligible baryon load (e.g. Thompson 2006). In both cases the Alfvén (sound) speed in the ejecta is very high and therefore internal shocks maybe absent or weaker than in the standard hydrodynamics case. Similarly the reverse shock may be weaker although an external shock and associated forward blast wave will still be produced (Mészáros and Rees 1997). Any internal or reverse shocks that do form will have different radiation characteristics dependent on the magnetization parameter σ . Along side or in place of internal shocks “internal dissipation regions” formed by magnetic reconnection will lead to particle acceleration via electric fields produced by magnetic reconnection, rather than a Fermi mechanism, and a high radiative efficiency is likely. In order to get the isotropically equivalent luminosities of $L_\gamma \geq 10^{52} \text{ erg s}^{-1}$ seen in GRBs the magnetic fields at the base of the jet must be $B \sim 10^{15} \text{ G}$. The baryon-free Poynting jet models are like pulsar wind models. In a similar way to the purely hydro baryon-loaded models the initially high magnetic stresses, involving pairs and photons, lead to acceleration and growth of the Lorentz factor, $\Gamma \propto r$ up to a pair annihilation photosphere which provides the first prompt emission peaking in the hard X-ray to MeV with up-scattering adding a high energy power law tail. In the absence of internal shocks the external shock must provide photons in the GeV–TeV range via inverse Compton scattering. On the other hand, baryon-loaded magnetically dominated jets behave differently with acceleration leading to $\Gamma \propto r^{1/3}$ or similar intermediate power law dependencies (McKinney and Uzdensky 2012; Metzger et al. 2011). The spectral signatures expected from Poynting dominated jets have not been extensively studied. Calculations made using a one-zone steady state approximation for a simple magnetised outflow photosphere (Giannios and Spruit 2007) indicate that a Band-type spectrum can be produced. The time delays and spectral components of a simple baryon-loaded magnetic model have been calculated (Bošnjak and Kumar 2012) giving results in the range observed by *Fermi*.

In GRB jets with a significant baryonic content the charged baryons will be co-accelerated with the electrons in any shocks or magnetic reconnection zones, and hadronic

Fig. 5 The canonical GRB X-ray afterglow. The prompt emission typically ceases after ~ 100 seconds and ends in a rapid fall with temporal decay index > 2 . In the vast majority of bursts this rapid decay is halted by a late emission component which forms a plateau that decays slowly, temporal index ~ 0.5 . Finally, the plateau turns down to give a final afterglow decay with index ~ 1.5 . The duration and decay rate of each of the three phases vary considerably from burst to burst

processes may lead to secondary high energy photon emission and neutrinos. For example, the *Fermi* LAT observations of the short GRB 090510 were modelled by Asano et al. (2009) as electron synchrotron for the MeV component and photohadronic cascade radiation for the distinct GeV power law component. Furthermore, since the acceleration and cascade development take time, a one-zone model including hadronic effects might explain the GeV–MeV photon delays seen by *Fermi* (Razzaque 2010). The hadronic interactions might also modify the low energy branch of the Band spectrum resulting in a GRB optical flash (Asano et al. 2010). The spectral signatures and GeV–MeV time delay can be produced by combining a magnetically dominated, baryon loaded model with a hadronic component involving nuclear collisions as calculated by Mészáros and Rees (2011). Murase et al. (2012) attempt to self consistently produce the GeV radiation, the MeV Band component and the low energy optical power law using a hadronic model. Protons accelerated by shocks or magnetic reconnection regions give hadronic cascades which in produce both the GeV and optical power laws. Cooled electron secondaries are then re-accelerated via a Fermi second order mechanism in the turbulent MHD waves produced by the same shocks, or reconnection regions, to yield a MeV Band spectrum.

More simultaneous, early, broad energy band/multi-wavelength observations with high signal to noise are required to reveal the detailed temporal behaviour of the components contributing to the prompt phase and to discriminate between the many theoretical possibilities.

4 The Canonical GRB X-Ray Afterglow

Before the arrival of the first *Swift* *XRT* observations of the X-ray afterglow of GRBs, starting only ~ 100 seconds after the prompt trigger from the Burst Alert Telescope (BAT), it was expected that the X-ray (and optical) afterglows would fall as a single simple power law. On the contrary, the vast majority of X-ray afterglows have the canonical form shown in Fig. 5 (Nousek et al. 2006; Evans et al. 2007). The afterglow seems to arise from two components. The fading emission from the tails of the prompt GRB pulses seen as the initial rapid decay and the plateau which turns over into a final powerlaw decay, typically 10^4 – 10^5 seconds after the prompt emission has died, which most likely arises from the external shock formed

Fig. 6 Late X-ray flares not seen in the *Swift* BAT. The lightcurves are shown in two XRT bands 0.3–1.5 keV and 1.5–10 keV. The ratio of the fluxes in these bands gives us a measure of the soft X-ray spectra of the features seen. The afterglow component is indicated by the *dotted line*

as jetted material sweeps up the circumburst medium (O’Brien et al. 2006; Willingale et al. 2007).

The slow decay over the plateau phase was unexpected and is difficult to explain. It requires some form of energy injection, probably from the central engine, although the initial fast decay would suggest that the central engine has already switched off. In some cases the energy to sustain the plateau may come from the spin-down of a magnetar formed during the initial collapse (Zhang and Mészáros 2001; Rowlinson et al. 2010), but in most instances it is probably continued low level activity of the central engine. For a few GRBs the afterglow plateau persists for $>10^4$ seconds in which case the required total late energy injection would have to be large and comparable to the prompt energy. Another unexpected feature in the X-ray afterglows is the appearance of late flares, seen in the *Swift* XRT but not in the BAT (Chincarini et al. 2007), see Fig. 6. These flares are probably indicative that the central engine can and does remain active after the prompt Gamma-ray and hard X-ray emission has ceased. Figure 6 shows the afterglow decay in two XRT energy bands, 0.3–1.5 keV and 1.5–10 keV. In all bursts the ratio of the afterglow fluxes in these bands, over the plateau and in the final decay, remains constant indicating that there is no spectral evolution and that the temporal break from the end of the plateau into the final decay is achromatic.

If the relativistic outflow is collimated and slowing down, as the circumburst medium is swept up, we expect an achromatic break in the afterglow decay when the edge of the jet becomes visible as the relativistic beaming angle opens up. The standard formulation for so-called jet-breaks is given by Sari et al. (1999) and reference therein. Temporal breaks

Fig. 7 The optical/IR break seen in the afterglow of GRB 050904 (Tagliaferri et al. 2005). The profile of the break is the same in the z , J , H and K bands indicating that the break is achromatic. When combined with the redshift the break time can be used to estimate the collimation angle of the jet

Fig. 8 The Ghirlanda relation (Ghirlanda et al. 2004) between the photon energy E_{peak} and the collimated energy estimated from E_{iso} and the jet collimation angle (Campana et al. 2007; McBreen et al. 2010). The unlabelled black points are the original GRBs used by Ghirlanda. The other values are for *Swift* and *Fermi* bursts which don't all conform to the original tight correlation

identified as jet-breaks in the afterglow decay are often seen in the optical and IR, e.g. Tagliaferri et al. (2005), Fig. 7, and when combined with a redshift measurement and an estimate of the total equivalent isotropic energy released the break times can be used to estimate the collimation angle of the jet. However, although late breaks are sometimes seen in the X-ray afterglows they rarely coincide with a break at other wavelengths so the simple achromatic break scenario is probably complicated by other factors.

Using an estimate of the jet collimation angle, derived from the assumed jet-break time observed in the optical/IR, we can correct the isotropic energy E_{iso} to a true collimated energy value E_γ . An original analysis performed by Ghirlanda et al. (2004) using 18 bursts showed that the correlation of E_{peak} with E_γ (known as the Ghirlanda Relation) was significantly tighter than the Amati Relation for the same bursts. However, more recent analysis using *Swift* and *Fermi* bursts, illustrated in Fig. 8, are not so conclusive (Campana et al. 2007; McBreen et al. 2010). This again brings into question whether the optical late breaks are really jet-breaks and whether or not the E_γ estimates are valid. More high quality multi-

wavelength observations are required to tell us if the breaks are chromatic or achromatic to resolve this issue.

5 Prompt to Afterglow

The prompt Gamma-ray and hard X-ray emission from GRBs is very variable, both spectrally and temporally, but it can be characterised as a stochastic sequence of pulses each with a distinctive shape and spectral signature including a fast rise, slower decay and spectral softening. Several authors have attempted to model these pulses, e.g. Norris et al. (2005) using an empirical mathematical model and Willingale et al. (2010) using a physically motivated formulation. It is supposed that each pulse is associated with internal shocks within a thin ultra-relativistically expanding shell. The time profile we observe is produced by the relativistic aberrations and the Equal Arrival Time Surfaces (EATS) arising from the large Lorentz factor of the relativistic jet pointing towards us and the spherical geometry of the shell. Figure 9 shows the typical model pulse profile and an example of a GRB multi-energyband light curve fitted as a sequence of pulses and an afterglow component. The fitting is only possible because of the multi-energy band coverage and nearly continuous temporal coverage from the trigger to very late in the afterglow phase. When combined with a redshift the model provides rest frame timing and pulse/afterglow duration estimates and luminosity estimates for all the components.

On rare occasions the prompt emission is heralded by a precursor pulse which is bright enough to trigger the *Swift* BAT. In these cases the XRT and UVOT telescopes and alerted ground based instruments may be able to detect the latter stages of the prompt in which case we can get better multi-band coverage across the entire burst including the prompt phase as shown in Fig. 10. For GRB 080810 the burst also triggered the *Fermi* GBM so we also have simultaneous hard Gamma-ray coverage (Page et al. 2009) and for both GRB 061124 and GRB 080810 the afterglow flux was also detected in the radio as indicated on Fig. 10. Using data like these we can set up a temporally evolving Spectral Energy Distribution (SED) for both the prompt and afterglow emission. For GRB 061124 both the prompt and afterglow emission appear in the optical and the SED has a break between the optical and X-ray bands. The afterglow exhibits spectral evolution and decays too slowly compared with the standard synchrotron models. In addition there is evidence for a late break which might be a jet-break. For GRB 080810 the peak photon frequency in the SED, E_{peak} , evolves as a function of time and the afterglow optical-X-ray SED initially hardens but subsequently softens. The early rise and peak of the optical afterglow is also seen.

The rise and peak of the soft X-ray afterglow component is very rarely seen because it is hidden by the X-ray tail of the prompt hard X-ray and Gamma-ray emission. However, the early optical/IR afterglow peak can be observed (as in the case of GRB 080810 above). The optical emission most likely arises from the reverse shock which is expected to produce photons of lower energy than the forward shock which is responsible for the X-ray afterglow. The optical/IR afterglow peak can be assumed to correspond to the deceleration radius of the expanding fireball. The Lorentz factor of the outflow at the time of the peak, t_d , is half the initial value, Γ_0 (Sari and Piran 1999). From observations of t_d and using estimates of the isotropic energy released, E_{iso} , we can estimate the value of $\Gamma_0/2$. For both GRB 060418 and GRB 060607A the inferred deceleration radius is $R_{dec} \approx 10^{17}$ cm and $\Gamma_0 \sim 400$ giving us direct confirmation of the highly relativistic nature of the GRB fireballs (Molinari et al. 2007). Using values of the initial Lorentz factor derived in this way Liang et al. (2010) showed a correlation between Γ_0 and E_{iso} , Fig. 11. More recently the same authors published

Fig. 9 *Top left:* the model profile for prompt pulses. *Bottom left:* the combination of prompt pulses and an afterglow representing the entire light curve emission (in this case from GRB 060814). *Right:* the prompt and afterglow emission from GRB 061222A seen in a combination of the energy bands from the *Swift* BAT and XRT

Fig. 10 Multi-band observations of the prompt and afterglow for *left*: GRB 061124 (Page et al. 2007) and *right*: GRB 080810 (Page et al. 2009)

a 3-parameter correlation between the isotropic luminosity, L_{iso} , E_{peak} and Γ_0 (Liang et al. 2015). Clearly, multi-wavelength observations which cover the prompt emission and the early afterglow have a great potential to reveal the key parameters which are driving the burst fireball.

6 Ultra-long GRBs and Tidal Disruption Events

Recently it has been noted that a few GRBs have a prompt emission phase which lasts an extraordinarily long time, measured in kiloseconds (Levan et al. 2014). Figure 12 shows an example of such a burst monitored both by the *Swift* BAT and the *Konus-Wind* Experiment, GRB 130925A (Evans et al. 2014). There are currently just four bursts which have a prompt duration (T_{90}) that is an order of magnitude longer than the main population of long GRBs (GRB 101225A, GRB 111209A, GRB 121027A, GRB 130925A). It may be that the progenitor and emission mechanism that gives rise to such persistent bursts is distinct from the majority but at the moment we don't have a detailed explanation for these ultra-long bursts. In addition there are one or two events detected by *Swift* which have repeated outbursts over a period of many days. For example, GRB 110328A was originally designated as a GRB but produced several BAT triggers and it soon became clear that the light curve didn't look like a conventional GRB, showing repeated flaring that eventually lasted for greater than 5×10^6 seconds. It was established that it occurred in a host galaxy at a redshift of $z = 0.351$ and was most probably a Tidal Disruption Event (TDE) in which a star was ripped apart by tidal forces when it wandered too close to a massive galactic black hole (Cannizzo et al. 2011). This event was subsequently re-labelled as Sw 1644+57. We require continued operation of *Swift* and future satellites like *SVOM* (Cordier et al. 2015) coupled with extended multi-wavelength observations to find and characterise more of these oddball events which clearly don't match the paradigm of conventional GRBs.

7 Follow-up of Gravitational Wave and Neutrino Triggers

A flux of neutrinos is expected from gamma-ray bursts (Asano and Mészáros 2014), but so far searching retrospectively through neutrino data from *IceCube* (IceCube Collaboration 2012; Aartsen et al. 2015), and *ANTARES* (Adrián-Martínez et al. 2013), looking for matches corresponding to the time and location of GRB triggers has not yielded any positive results. Alternatively, we can choose to follow-up neutrino triggers with an instrument like the *Swift* XRT (Evans et al. 2015). The XRT field of view is 24 arc minutes in diameter and the error radius of *IceCube* triggers is typically 1 degree at 50% confidence so this can be covered by a tiling of 7 XRT pointings as shown in Fig. 13. Each pointing has an exposure of 1–2 ksec depending on the satellite orbit conditions at the time of the trigger. The delay from neutrino trigger to the tiling of X-ray observations is typically 1–3 hours. The *Swift* XRT has a sensitivity of 5×10^{-13} erg cm $^{-2}$ s $^{-1}$ in 1 ksec in the 0.3–10 keV band and can get source positions with a 90% confidence radius of 3.5 arcsec or better for brighter sources (Evans et al. 2009).

Gravitational waves are expected from a range of transients, in particular the merger of two neutron stars which is also expected to produce a short GRB. Targeted searches for gravitational waves from short GRBs have so far failed to produce detections (Abadie et al. 2010). Similarly, *Swift* XRT follow-up of gravitational wave triggers has so far also drawn a

Fig. 11 *Left:* the correlation between the initial Lorentz factor and the isotropic energy. *Right:* a 3-parameter correlation between the isotropic luminosity, E_{peak} and Γ_0

Fig. 12 The combined *Swift* BAT and *Konus-Wind* prompt light curve of GRB 130925A with a prompt duration of ~ 5000 seconds

Fig. 13 Exposure map of a 7-tile *Swift* XRT observation of an IceCube trigger. The blank lines and dots are bad columns and pixels on the CCD

blank (Evans et al. 2012), although this is to be expected because the error boxes associated with LIGO-Virgo triggers have to date been very large, many tens of square degrees.

The *Swift* XRT is probably the best instrument currently available for neutrino and gravitational wave follow-up, looking for the high energy transient counterparts, because of the reasonable sensitivity of the XRT in the 0.3–10 keV band and the rapid repointing response capability. However, it has a rather small field of view so tiling is required and the response time of a few hours means that any short transient may have faded significantly by the time

the observations begin. A high sensitivity soft X-ray transient monitor with a wide field of many square degrees is required to increase the probability of finding any fast transients associated with these triggers.

8 The Lobster Eye X-Ray Transient Monitor

The wide field detectors used to find and position GRBs and similar transients, listed in Sect. 3, all use collimation and/or coded shadow mask techniques to detect and estimate the position of hard X-ray/Gamma-ray transients. Such devices have the required large fields of view but the sensitivity is limited by the multiplex nature of the positioning capability. If the X-ray flux could be focused in some way, so that multiplexing of the detector imaging elements could be reduced or eliminated, the sensitivity would be greatly improved. The lobster eye X-ray focusing geometry originally described by Angel (1979) provides just that. In a lobster eye the image is produced by grazing incidence reflections off the inside walls of microscopic square pores which are arranged over a spherical surface all pointing towards a common centre of curvature. The image is formed on a spherical focal surface with half the radius of curvature of the square pore optic. Unlike a fly's eye optic, which uses an array of refracting lenses, the lobster eye produces a single continuous image of the sky. The field of view is limited only by the size of the optic and size of the detector and if an optic (and detector) could be constructed across a complete sphere the whole sky would be captured in a single continuous image.

The idea of using the lobster eye principle to produce a soft X-ray all-sky monitor was first proposed by Priedhorsky et al. (1996) and a method of manufacturing the square pore array has been described by several groups (Chapman et al. 1991; Wilkins et al. 1989; Fraser et al. 1993). Recent proposals for soft X-ray wide field transient monitors using lobster eye optics include *ISS Lobster* submitted to NASA December 2014 and the *Theseus* SXT submitted the ESA M4 call at about the same time. Figure 14 shows a schematic view of a typical module and the flux sensitivity it can achieve. Each module has a field of view of $\sim 1/6$ steradian so an array of 6 modules can view 1 steradian. An angular resolution of ~ 5 arc minutes is currently achievable using the available square pore micro-channel plate technology. The sensitivity is $\sim 2 \times 10^{-10}$ erg cm $^{-2}$ s $^{-1}$ in 100 sec in the 0.3–5 keV energy band. This is a factor of ~ 100 higher than the *Swift* XRT but the lobster eye transient monitor will see transients when they happen rather than 1–2 hours later, in response to a trigger. It is predicted that such a monitor would see greater than 90% of the GRBs seen by the *Swift* BAT and provide positions < 1 minute for all transients. A lobster eye X-ray transient monitor is the ideal instrument to hunt for and position fast soft X-ray transients or look for the X-ray counterparts to neutrino and gravitational wave triggers.

9 Discussion and Conclusion

The study of GRBs is entering an exciting new phase. After great advances obtained through multi-wavelength studies made possible by *CGRO*, *Beppo-SAX*, *HETE-2* and *Swift*, GRB studies have been extended well into the GeV range by the *Fermi* mission (Bissaldi et al. 2015a), and higher energies reaching the TeV range are being probed by the High Altitude Water Cherenkov Observatory (HAWC) (Lennarz et al. 2015) and the High Energy Stereoscopic System (HESS <https://www.mpi-hd.mpg.de/hfm/HESS/>). The next instruments after that are expected to be, at X-rays to MeV energies, the SVOM satellite (Cordier et al. 2015),

Fig. 14 *Top*: a typical lobster eye module with a focal length of 300 mm and total mass of ~ 20 kg. *Bottom*: the flux sensitivity of the module compared to typical flux ranges and timescales associated with types of transients. The *black dots* indicate the prompt flux from *Swift* GRBs detected by the BAT and the *green dots* are the afterglow flux levels seen in the afterglows by the XRT. The *black curve* is the module flux sensitivity in the energy band 0.15–5 keV as a function of integration time

and in the TeV to multi-TeV range the ground-based (air) Cherenkov Telescope Array (CTA) (Bissaldi et al. 2015b).

Non-photon messengers are also being probed, most notably high energy neutrinos, with *IceCube* setting strong constraints against classical (Swift-detected) GRBs providing

more than 1% of the observed neutrino background (Aartsen et al. 2015). One possibility is that the gamma-rays arise at lower radii, e.g. in the photosphere, while cosmic rays are only accelerated in shocks further out, where the efficiency for photo-hadronic interaction producing neutrinos is low (Asano and Mészáros 2016). For a discussion of the physics and gamma-ray emission from GRB photospheres, see Beloborodov and Mészáros, 2016, elsewhere in this volume.

Following the recent announcement of the first detection of gravitational waves from the merger of stellar mass binary black holes by LIGO (Abbott et al. 2016) results from non-photonic GW searches are now eagerly awaited. Neutron star or neutron star-black hole mergers are also expected to produce gravitational waves detectable by LIGO and VIRGO, and their detection in coincidence with a short GRB gamma-ray signal is the smoking gun signal being looked for in order to confirm the progenitor's identity.

Gamma-ray bursts continue to surprise us, and it is clear that the array of major new facilities that are being brought to bear on these sources will play a major role in solving some of the many questions that they pose.

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