New Frontiers in Black Hole Astrophysics
Proceedings IAU Symposium No. 324, 2016
A.C. Editor, B.D. Editor & C.E. Editor, eds.

DOI: 00.0000/X000000000000000X

Gamma-ray Bursts
Progress and Problems

N. R. Tanvir[1]

[1]University of Leicester, Department of Physics and Astronomy,
University Road, Leicester, LE1 7RH, United Kingdom
email: nrt3@le.ac.uk

Abstract. Our understanding of gamma-ray bursts (GRBs) has come a long way in the past fifty years since their first detection. We now know that GRBs arise in distant galaxies and that there are at least two distinct sub-classes, the long-duration class being produced by some rare massive star core collapse and the short-duration class likely by compact binary mergers involved neutron stars. In both cases, the final remnant will be a stellar-mass black-hole or a massive neutron star. The bursts themselves are associated with ultra-relativistic jetted outflows created by these events, and their afterglows by the impact of these outflows on the surrounding circumburst material. Increasingly GRBs are also being used as probes of the universe, both for understanding galaxy evolution back to the era of reionization, and for the physics of gravitational wave sources. However, many aspects of GRBs remain poorly understood, some pointers to which are given here.

Keywords. gamma rays: bursts, galaxies: high-redshift, galaxies: ISM

1. Introduction

Gamma-ray bursts have provided an enduring source of intrigue and mystery since their discovery in the late 1960s (Klebesadel et al. 1973). Their rapid time variability suggested an origin in a small (less than $\sim 10^3$ km) emitting region, but otherwise the lack of a distance scale led to a wide range of plausible progenitors being considered (Nemiroff 1994).

Whilst the possibility of a cosmological origin for GRBs was discussed early (Paczynski 1986), it did not become widely favoured until their isotropic distribution on the sky was convincingly demonstrated by the *CGRO*/BATSE experiment (Meegan et al. 1992). Subsequently, the first X-ray afterglow detections by the BeppoSAX satellite (Costa et al. 1997) enabled optical afterglow location (van Paradijs et al. 1997), and ultimately direct redshift measurements (Metzger et al. 1997). Thus GRBs were shown to be extremely powerful events in distant galaxies.

The necessary $\sim 10^{52}$ erg energy requirement can in principle be met from the potential energy reservoir associated with a massive star or compact binary (involving neutron stars or a neutron star and black-hole), providing there is sufficiently high efficiency in converting this energy to radiation. From the inferred compactness of the source, to allow emission of gamma-rays without attenuation from photon-photon pair production and consequent high opacity, it is required that the radiation be produced by an ultrarelativistic outflow: in the standard picture this is a jet with bulk Lorentz factor ~ 300. For an extensive recent review of the physics of GRB jets, see Kumar & Zhang (2015).

It was realised early-on that the observed GRB population splits into two sub-classes, the short-duration harder-spectrum class and the long-duration softer-spectrum class, with a dividing line at roughly 2 s (Mazets et al. 1981, Kouveliotou et al. 1993). In fact, arguments have been made for further possible sub-classes, including intermediate duration (e.g. de Ugarte Postigo et al. 2011), and most recently ultra-long duration (e.g. Levan et al. 2014). Both of these rarer proposed sub-classes are more controversial, although the latter has received much attention.

In this short review I will summarise some recent important developments in the field, focussing particularly on observational breakthroughs, many of which have been relied on the large samples of GRBs localised by the *Swift* satellite, and highlight a selection of outstanding problems going forward.

2. Long-duration bursts

2.1. *The progenitor*

From the first few long-GRB host galaxies identified, it was clear that they were all actively star forming, thus suggesting an association with massive star core-collapse. This received remarkable support with the observation that GRB 980425 was accompanied by a bright, broad-lined supernova, SN1998bw (Galama et al. 1998).

However, GRB 980425 was an unusually faint GRB and occurred in a galaxy at a redshift of only $z \approx 0.008$. At more typical redshifts, it is unfeasible to search for the much fainter supernova light, and the question remained whether high-luminosity long-GRBs were also accompanied by such SNe. This was settled in the affirmative by the spectroscopic confirmation of similar broad-lined supernovae accompanying first GRB 030329 (e.g. Hjorth et al. 2003), and most recently by the very bright GRB 130427A (Xu et al. 2013, Levan et al. 2014b). Although reassuring as this is, in supporting the standard collapsar picture of long-GRB production, it does remain puzzling that the observed supernova events associated with GRBs seem generally quite similar to each other (e.g. Cano 2016), even for extremely different GRBs (e.g. Tanvir et al. 2010).

2.2. *Probes of galactic and chemical evolution*

Long-duration gamma-ray bursts provide an important means of selecting star-forming galaxies over a large range of redshifts. The benefits of LGRB selection is that it does not depend on the luminosity of the host in any waveband, thus sampling the whole luminosity function. This benefit is partially lost in many GRB redshift samples, since they themselves are biased against dusty sight lines where the afterglow proves too faint for spectroscopic follow-up. However, in recent years, various campaigns have attempted to overcome this problem by selecting samples based only on their high energy properties, and attempting to complete the redshift determinations through identification and spectroscopy of the host galaxies.This has only been possible in the *Swift* era, since it relies on the few arcsec X-ray positions it provides to allow deep host searches. Even then, there is potentially some ambiguity about the faintest hosts.

Samples remain modest in size: the TOUGH sample of 69 galaxies (Hjorth et al. 2012), BAT6 sample (Salvaterra et al. 2012) and most recently the SHOALS sample (Perley et al. 2016). In many cases spectroscopy of the GRB afterglow provides not just a redshift, but also information about gas phase abundances, dust and molecular content, even of galaxies too faint to be otherwise detected. Fig. 1 shows a summary of the metallicity measurements made for LGRB hosts based on both absorption line analysis where the afterglow was observed (e.g. Thöne et al. 2013). This is challenging below $z \sim 2$ as Ly-α moves out of the optical band. However, in many cases these hosts are bright enough for emission line diagnostics of metallicity, and these are also shown on the same figure (Kruehler et al. 2015).

3. Short-duration bursts

3.1. *The progenitor*

Short-duration bursts are not only rarer, comprising only $\sim 10\%$ of detected *Swift* GRBs for example, but also have on average much fainter afterglows. When the first were localised, it became clear that they were associated with a much wider range of stellar populations, including some with only ancient stars (Gehrels et al. 2005). Furthermore, in some cases, the burst appeared at a large offset of 10s of kpc from their hosts (e.g. Fong et al. 2013), and lacked associated supernova counteparts (e.g. Hjorth et al. 2005). These properties are consistent with the bursts being produced during the mergers of compact objects, specifically binaries consisting of either two neutron stars or a neutron star and a black hole. Although these compact objects are formed during core-collapse events, the in-spiral times for such binaries can be very long (some systems would not merge in the lifetime of the universe), leading to mergers occurring long after a star formation episode.

A potential breakthrough in confirming this picture came about with the discovery of an apparent excess near-infrared flux in the days following short-GRB 130603B at $z = 0.36$ (Tanvir et al. 2013, Berger et al. 2013). This enhancement over the signal expected from the steeply declining afterglow is consistent with predictions of a so-called "kilonova" (or "macronova"), which is expected to follow a binary merger in which a small proportion of the neutron star material has been ejected. Heavy line blanketing should largely attenuate the optical flux.

Low redshift bursts for which such kilonova searches can be conducted are rare, and it remains of key importance to study further examples and explore their range of behaviour. A recent example of the difficulties faced is illustrated in Figure 2, which was a short-GRB originally associated with a $z = 0.3$ host galaxy, but for which deep *HST* imaging revealed an underlying, and likely more distant galaxy, which is more likely the real host.

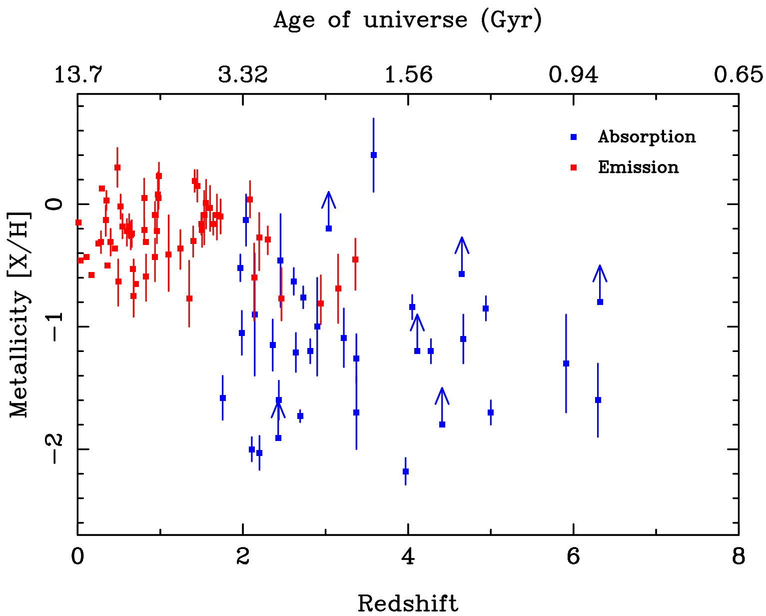

Figure 1. Measurements of metallicity via both galaxy emission lines and afterglow absorption lines for a sample of GRB hosts.

3.2. *Gravitational wave counterparts*

The first, epoch making detections of gravitational waves were made by the Advanced-LIGO detectors in September 2015. This source, and the other early detections and possible detections, were found to be consistent with binary black-hole mergers (Abbott et al. 2016a), and thus unlikely to produce significant electromagnetic emission. Nonetheless, a world-wide campaign of follow-up observations (Abbott et al. 2016b) demonstrated the capabilities that are now ready to search for the first unambiguous electromagnetic counterpart to a gravitational wave detection, presumed to be cases where at least one component of the binary is a neutron star.

4. Other populations

4.1. *Low luminosity GRBs*

The first GRB-related supernova, GRB 980425/SN1998bw, gave strong support to massive star progenitor models, but also high-lighted the huge range of intrinsic luminosities of long-GRBs, of $\sim 10^6$. Furthermore it has been suggested that the low-luminosity events form a separate population with much higher space density (Liang et al. 2007, Chapman et al. 2007), despite the rareness in current samples due to the limited range at which they can be detected. Furthermore, it has been suggested they are produced by shock-breakout rather than directly from the relativistic jets (Bromberg et al. (2011)). Clarification of the relationship between the low and high luminosity populations of long-GRBs is a high priority.

4.2. *Ultra-long GRBs*

The longest duration prompt emission seen by *CGRO*/BATSE was less than ~ 1500 s (e.g. Tikhomirova & Stern 2005), although longer events would have been hard to detect due to Earth occultation.

The prototype of a new class of what has come to be known as ultra-long duration was GRB 101225A. The event triggered *Swift* as an "image trigger", which provides sensitivity to transients that are spread out in time such the peak flux does not necessarily reach the threshold for triggering a "rate trigger", but for which reconstruction of the sky image over a timescale of ~minutes shows the presence of a new source. In this case, the event

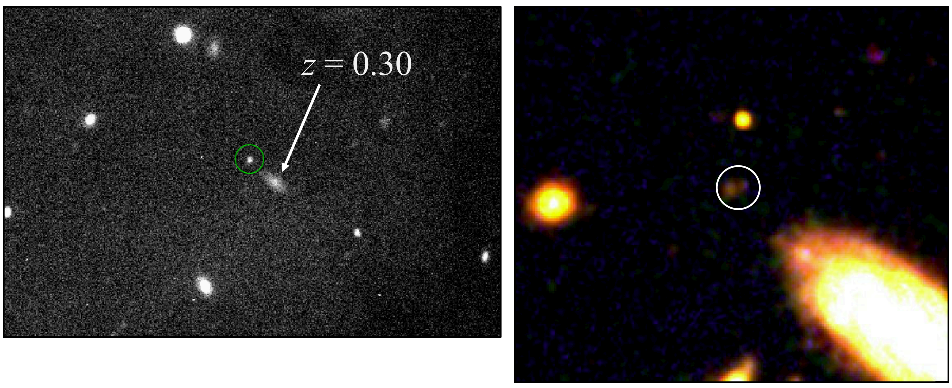

Figure 2. The field of short-GRB 150424A. The leftt panel ground-based image shows the afterglow (circled) close by a redshift $z = 0.30$ spiral galaxy that was initially presumed to be the host. However, deep *HST* imaging, shown in right panel, revealed an underlying, and likely more distant, faint galaxy (circled) for which a redshift is not currently available.

was detectable by *Swift*/BAT for at least ∼7000 s, and exhibited a strongly variable X-ray light-curve for ∼ 10 hr before fading rapidly. The burst was ultimately shown to be associated with a $z = 0.85$ star-forming host galaxy, which was faint and compact even by the standards of typical long-GRB hosts (e.g. Levan et al. 2014).

Several further examples (and candidates) of ultra-long GRBs have subsequently been identified, although the sample remains small and the ∼ 90 min low-Earth orbit of *Swift* is not ideal for finding such long-lived events. In all cases to-date where a host galaxy has been detected it is actively star forming, suggesting again a massive star progenitor, and a possible accompanying superluminous supernova signature has been seen in one case, namely GRB 111209 (Greiner et al. 2015). The relationship of these events to the bulk of long-duration bursts, and hence how their progenitors are distinguished, is a fascinating open question.

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