Supernova 1987A:30 years later - Cosmic Rays and Nuclei from Supernovae and their aftermaths
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The diversity of GRBs and their SNe: Observations from the 10.4m GTC

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Abstract. Observing the supernovae (SNe) associated to the different types of gamma-ray bursts (GRBs) is one of the few means to study their progenitors. In the past years, it has become clear that GRB-like events are more heterogeneous than previously thought. There is a marked difference between long GRBs, which are produced by the collapse of very massive stars and are normally associated with broad-lined type Ic SNe, and short bursts, which occur when two compact objects merge and that, at least in some cases, can produce an associated kilonova. Moreover, the SNe associated with different sub-types of long GRBs are also seen to differ, especially those associated with ultra-long duration GRBs. To address this issue in a systematic way we started an observing programme in 2010 at the 10.4m GTC telescope. Here we present some results of our programme, including the detection of 12 new GRB-SNe. Highlights of our sample are the discovery of the first spectroscopic SN associated with a highly energetic ($E_{\gamma,iso} \sim 10^{54}$ erg) "cosmological" burst (GRB 130427A), the study of the SN associated with a shock-breakout GRB (GRB 140606B) and the SN associated with the peculiar ultra-long GRB 101225A at $z = 0.85$. The sample includes also the follow-up of several short GRBs in search for kilonovae emission (GRB 130603B and GRB 160821B are important examples). Amongst our latest results we present the photometric and spectroscopic observations of the SNe associated with GRB 150818A and GRB 161219B.

Keywords. gamma rays: bursts, supernovae: general

1. Introduction

GRBs are the most luminous explosions that we can witness in the Universe. They are produced during a cataclysmic stellar collapse, in which a black hole is formed and ultrarelativistic jets are released. Thanks to their extreme luminosity, they can be observed from the local Universe (the closest one recorded was localised at a redshift of 0.0085, Galama *et al.* 1998) to deep into the reionisation era, when the first stars had been just recently formed (the current record holder with a spectroscopic redshift happened at $z = 8.2$, Tanvir *et al.* 2009; Salvaterra *et al.* 2009, although there is a photometric redshift at $z = 9.4$, Cucchiara *et al.* 2011). They are typically classified into short-hard and long-soft GRBs (Kouveliotou *et al.* 1993) although other classes could also be there, pointing to different types of progenitor or environmental conditions (intermediate GRBs Horváth *et al.* 1998; ultra-long GRBs Levan *et al.* 2014). The progenitors have been proposed to be collapsing very massive stars (generally accepted for long GRBs) or the coalescence of two compact objects (model accepted for short GRBs). These different progenitors are

Table 1. Overview of the GRB-SN follow-up programme at the 10.4m GTC. The GRBs have been organised into ultralong, long, intermediate and short events.

GRB / SN	Redshift	T_{90}	Observations	References
101225A	0.847	> 1000	Photometry	Thöne *et al.* 2011
111211A	0.478	15	Spectroscopy	de Ugarte Postigo *et al.* 2012
111228A	0.716	101.2	Photometry	—
120729A	0.80	71.5	Photometry	Cano *et al.* 2014
130215A / SN 2013ez	0.597	65.7	Spectroscopy	Cano *et al.* 2014
130427A / SN 2013cq	0.34	163	Spectroscopy	Xu. *et al.* 2013
140606B	0.384	23.6	Spectroscopy	Cano *et al.* 2015
141225A	0.915	40.24	Photometry	—
150518A	0.256	165	Spectroscopy	—
150818A	0.282	123.3	Spectroscopy	de Ugarte Postigo *et al.* 2015
160131A	0.97	325	Photometry	—
100418A	0.6235	7	Photometry	de Ugarte Postigo *et al.* 2011
100816A	0.804	2.9	Photometry	—
120422A / SN 2012bz	0.283	5.35	Spectroscopy	Schulze *et al.* 2014
141004A	0.573	3.92	Photometry	—
161219B / SN 2016jca	0.1475	6.94	Spectroscopy	Cano *et al.* 2017
111117A	2.211	0.47	Photometry	Sakamoto *et al.* 2013; Selsing *et al.* 2017
130603B	0.356	0.18	Photometry	de Ugarte Postigo *et al.* 2014
160303A	—	5	Photometry	—
160821B	0.16	0.48	Photometry	—

expected to have either an associated supernova, in the case of the collapse of a massive star, or a kilonova, in the case of compact star mergers. To study these events and derive properties of their progenitors from a statistical approach, observations need to be performed in a systematic way. However, early studies were mainly focused on peculiar events, limiting the value of the GRB-SN samples.

2. The GTC GRB-SN programme

In 2010, shortly after the 10.4 m GTC began operations, we initiated our GRB-SN follow-up programme. Its aim is to systematically obtain photometric follow-up of all GRB-SNe at redshifts lower than 1.0 and spectroscopic follow-up of all GRBs at $z < 0.6$. If the GRB has $z < 0.3$ the follow-up consists of multiple spectroscopic observations. This follow-up is not restricted to long GRBs but we follow all classes of events. In the case of short GRBs we only expect to detect a kilonova component for the very nearby events ($z \sim< 0.15$).

During this time we have followed 10 long-soft GRBs, 4 short-hard, 5 intermediate and 1 ultra-long. The redshift range spans between $0.14 < z < 0.97$. We have obtained 7 spectroscopic detections. These observations are summarised in Table 1. In the following sections we give some examples of GRBs followed by our programme.

2.1. *GRB 100418A*

GRB 100418A was an intermediate-duration GRB at a redshift of $z = 0.6235$, with a luminous afterglow and a bright host galaxy (with a r'-band magnitude of 22.1), which complicated the study of its associated SN. Nevertheless, through the use of image-subtraction techniques, we detect SN emission peaking at $r' = 24.8$ mag, equivalent to an absolute magnitude of $M_{r'} \sim -17.0$ mag, 1.7 magnitudes fainter than the canonical SN1998bw.

2.2. *GRB 130215A / SN 2013ez*

GRB 130215A was detected at a redshift of $z = 0.597$, at the limit of the spectroscopic capabilities of our programme. A single spectrum was obtained using GTC during the

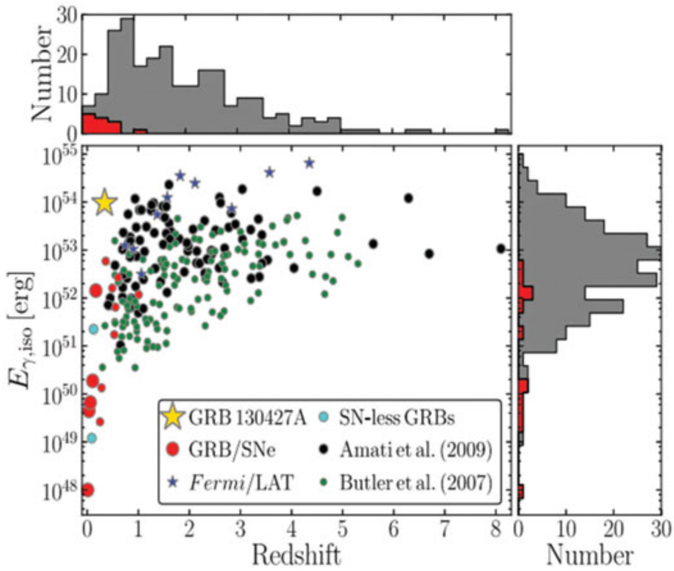

Figure 1. Comparison of isotropic equivalent energy release of different GRBs, showing that GRB 130427A was the first GRB-SN corresponding to the class of most energetic events, those with isotropic equivalent energy release in gamma rays of $E_{\gamma,iso} \sim 10^{54}$ erg. The histograms indicate the cumulative distributions of all GRBs (grey), and GRBs with identified supernova (red). The comparison also includes two GRBs that did not show a SN component in spite of deep searches (SN-less GRBs, Fynbo *et al.* 2006). From Xu *et al.* (2014).

maximum of the SN emission (de Ugarte Postigo *et al.* 2013a). This spectrum revealed broad absorption features typical of GRB-SNe. However, the ejecta was being expelled at a velocity of ~ 5000 km s^{-1}, significantly below the typical values for Ic-BL SNe at that time. This would mean that GRB 130215A / SN 2013ez would be the first non-broad-lined supernova associated with a GRB. The results of our study were published by Cano *et al.* 2014.

2.3. *GRB 130427A / SN 2013cq*

Most of the nearby GRB-SNe belong to a population of underluminous GRBs. This meant that our conclusions would be not representative of the overall population of GRBs, with a much larger range of gamma-ray energy releases. To overcome this, we studied several GRB-SNe that had intermediate luminosities in gamma-rays. However, it was not until GRB 130427A that we had the chance to observe the supernova associated with a highly energetic "cosmological" GRB, which is fully comparable to the bright GRBs usually only detected at $z > 1$. GRB 130427A had an isotropic equivalent gamma-ray energy release of $E_{\gamma,iso} = 9.6 \times 10^{53}$ erg, and was observed at a redshift of $z = 0.34$ (see Fig. 1). Its supernova was discovered by our team (de Ugarte Postigo *et al.* 2013b) as a typical broad-lined Ic, SN 2013cq, as was the case for all the other low- and intermediate-luminosity GRBs, implying that the properties of the supernovae associated with GRBs are independent of gamma-ray energetics. The data obtained by our programme were published by Xu *et al.* (2014).

2.4. *GRB 150818A*

GRB 150818A was detected at a redshift of $z = 0.282$. We performed a spectroscopic follow-up campaign covering the first month. 11 days after the GRB onset, we discovered the broad spectroscopic features characteristic of the Ic-BL SN. The discovery of the

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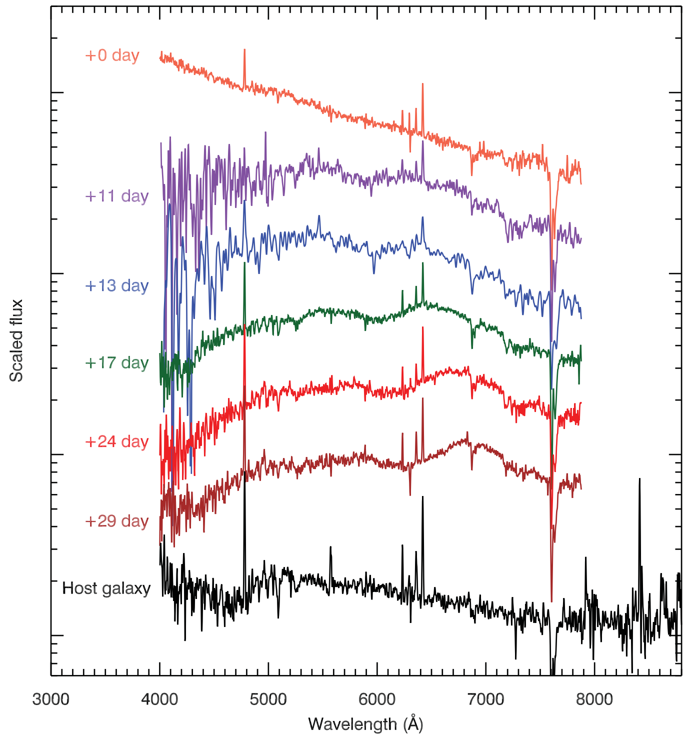

Figure 2. Spectroscopic follow-up of GRB 150818A, at a redshift of $z = 0.282$, ranging from the afterglow emission, shortly after the GRB, to 29 days later, showing the evolution of the supernova. At the bottom we show the host galaxy spectrum, obtained months later.

SN component associated with GRB 150818A was reported by de Ugarte Postigo *et al.* (2015). Figure 2 shows the spectral sequence obtained from GTC.

2.5. *GRB 161219B / SN 2016jca*

GRB 161219B is the latest GRB-SN studied by our programme at the time of this conference. At a redshift of $z = 0.1475$ it was amongst the closest GRB-SNe, and the nearest one since our programme began in 2010. The SN was spectroscopically discovered by our team (de Ugarte Postigo *et al.* 2016).We obtained multiple spectroscopic observations ranging over the first 3 months after the explosion. Our study has been presented by Cano *et al.* (2017), and it includes not only the study of the SN but also of its host galaxy, combining data from GTC and the Hubble Space Telescope.

2.6. *GRB 101225A*

GRB 101225A, also known as the *Christmas Burst*, was a very peculiar ultra-long GRB. It did not show a typical afterglow with a synchrotron emission, but instead, it presented what seemed to be a thermal emission, which evolved by cooling and expanding during the first days after the GRB. Starting 10 days after the event an additional component began to emerge, which we associate with a supernova that accompanied the burst. Although there was some confusion as to the origin of this event, which was reported as being of either Galactic (Campana *et al.* 2011) or extragalactic origin (Thöne *et al.* 2011), the later scenario was proved to be correct through host galaxy spectroscopy (Levan *et al.* 2013). At a redshift of $z = 0.847$ the supernova of GRB 101225A would be a luminous blue supernova, similar in brightness to SN 1998bw but with a bluer colour.

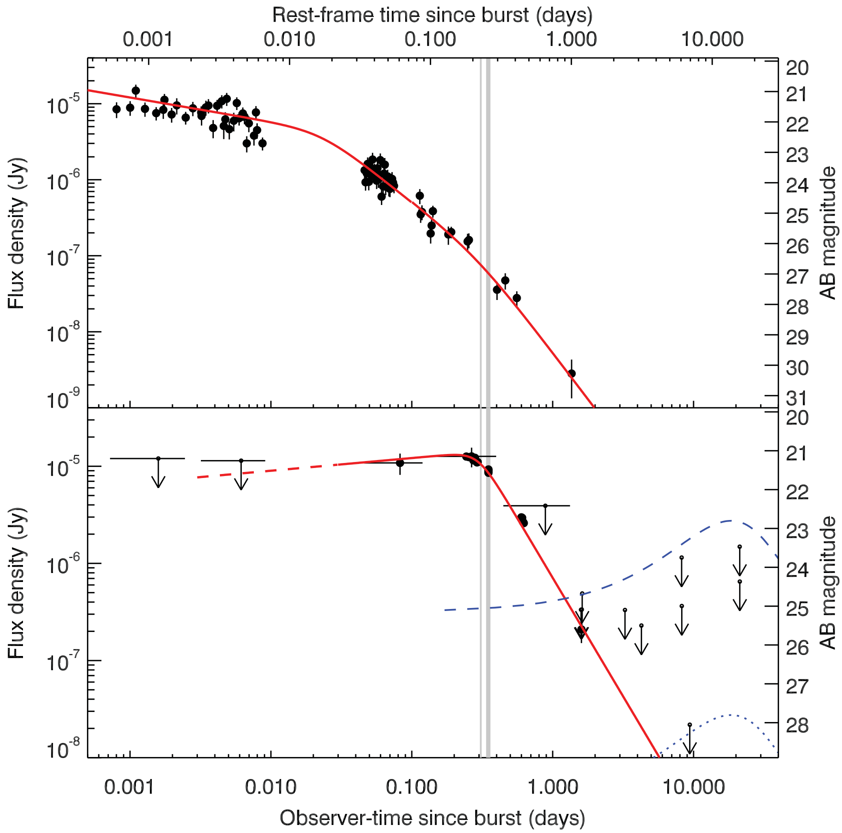

Figure 3. Light curve of the short GRB 130603B in X-rays (top) and optical (botom), showing the deep late limits compared to the prototypical GRB-SN, SN 1998bw marked by a dashed blue line. Our limits implied an emission dimmer than 100 times SN 1998bw (dotted blue line). From de Ugarte Postigo *et al.* (2014).

2.7. *GRB 130603B*

GRB 130603B was the first short GRB for which a useable afterglow spectrum was ever obtained (Thöne *et al.* 2013; de Ugarte Postigo *et al.* 2014). We measured for it a redshift of $z = 0.356$ and did a follow-up campaign to both study the afterglow emission and search for possible supernova or kilonova emission. Our deep observations set strong constraints to possible supernova emission (see Fig. 3), and constrained the afterglow evolution well enough to be able to later search for the kilonova with HST. Combining the GTC and the HST data it was, for the first time, possible to detect the emission of a kilonova emission associated with a short GRB (Tanvir *et al.* 2013). At present we are continuing to study in a similar way the emission of GRB 160821B at a possible redshift of $z = 0.16$.

3. Conclusions

During the early years of GRB-SN studies, the follow-up had been focused on peculiar events, which lead to biases in any possible statistical studies. To avoid this, in 2010 we began a systematic search for GRB-SNe at $z < 1.0$ using the 10.4m GTC telescope. Until now we have studied 20 objects (10 long, 5 intermediate, 1 ultra-long and 4 short). Amongst the accomplishments of our programme, we have the first SN detection for an

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ultra-long GRB, the first SN associated with a highly energetic “cosmological” event, the observation of an under-luminous SN associated with GRB 100418A as well as the measurement of a SN with slow ejecta, associated with GRB 130215A.

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