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 10.4 m GTC. The GRBs have been organised into ultralong, long, intermediate and short events.

<table>
<thead>
<tr>
<th>GRB / SN</th>
<th>Redshift</th>
<th>T(_{90})</th>
<th>Observations</th>
<th>References</th>
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<tbody>
<tr>
<td>101225A</td>
<td>0.847</td>
<td>&gt; 1000</td>
<td>Photometry</td>
<td>Thöne et al. 2011</td>
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<td>111211A</td>
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<td>15</td>
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<td>de Ugarte Postigo et al. 2012</td>
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<td>71.5</td>
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<tr>
<td>130215A / SN 2013ez</td>
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<td>65.7</td>
<td>Spectroscopy</td>
<td>Cano et al. 2014</td>
</tr>
<tr>
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<td>163</td>
<td>Spectroscopy</td>
<td>Xu et al. 2013</td>
</tr>
<tr>
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<td>Cano et al. 2015</td>
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<td></td>
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<tr>
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<td>de Ugarte Postigo et al. 2015</td>
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<td>de Ugarte Postigo et al. 2011</td>
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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. GRB100418A

GRB100418A 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. GRB130215A / SN2013ez

GRB130215A 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
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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 $\sim 5000$ 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
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.
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2.7. **GRB 130603B**

GRB 130603B was the first short GRB for which a usable 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 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
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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