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Review

Galaxies as seen through the most energetic explosions in the universe

Sandra Savaglio[a,b,*]

[a] Physics Department, University of Calabria, I-87036 Arcavacata di Rende, Italy
[b] European Southern Observatory, D-85748 Garching bei München, Germany

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ABSTRACT

A gamma-ray burst (GRB) is a strong and fast gamma-ray emission from the explosion of stellar systems (massive stars or coalescing binary compact stellar remnants), happening at any possible redshift, and detected by space missions. Although GRBs are the most energetic events after the Big Bang, systematic search (started after the first localization in 1997) led to only 374 spectroscopic redshift measurements. For less than half, the host galaxy is detected and studied in some detail. Despite the small number of known hosts, their impact on our understanding of galaxy formation and evolution is immense. These galaxies offer the opportunity to explore regions which are observationally hostile, due to the presence of gas and dust, or the large distances reached. The typical long-duration GRB host galaxy at low redshift is small, star-forming and metal poor, whereas, at intermediate redshift, many hosts are massive, dusty and chemically evolved. Going even farther in the past of the universe, $z > 5$, long-GRB hosts have never been identified, even with the deepest NIR space observations, meaning that these galaxies are very small (stellar mass $< 10^7$ $M_\odot$). We considered the possibility that some high-z GRBs occurred in primordial globular clusters, systems that evolved drastically since the beginning, but would have back then the characteristics necessary to host a GRB. At that time, the fraction of stellar mass contained in proto globular clusters might have been orders of magnitude higher than today. Plus, these objects contained in the past many massive fast rotating binary systems, which are also regarded as a favorable situation for GRBs. The common factor for all long GRBs at any redshift is the stellar progenitor: it is a very massive rare/short-lived star, present in young regions whose redshift evolution is closely related to the star-formation history of the universe. Therefore, it is possible that GRB hosts, from the early Universe until today, do not belong to only one galaxy population.

1. Introduction

The discovery of a galaxy hosting a gamma-ray burst (GRB) was achieved for the first time in February 1997, with the identification of an afterglow, the event GRB 970228 (Costa et al., 1997). However, its redshift, $z = 0.695$, was measured later from the detection of emission lines in the host through Keck spectroscopy (Djorgovski et al., 1999). The very first gamma-ray burst redshift was measured in May 1997, for GRB 970508. The absorption lines seen in the Keck spectrum of the optical afterglow gave $z = 0.835$ (Metzger et al., 1997). Today, precise localization of afterglows (2 arcsecs or better) is routinely performed, at the level of several events per week, mainly thanks to the data collected with the most successful dedicated space mission, the NASA satellite *Swift*, launched at the end of 2004 (Gehrels et al., 2004). Since 1997, and as of the first half of 2015, gamma-ray instruments identified a total of more than 1400 GRBs. Although $\sim 90\%$ of *Swift* GRBs are localized, thanks to the X-ray instrument XRT, the afterglow localization for the whole population since 1997 was possible for only about half of them. These are mainly long GRBs (more than 90%), those for which the gamma-ray emission is longer than a couple of seconds, and associated with the death of a massive star (mass of the progenitor $M > 30$ $M_\odot$). The hosts are detected mainly for the long GRBs.

Fruchter et al. (2006) investigated the location where the GRB takes place and found that those at $z < 1.2$ prefer the most active regions in the galaxy, more than what done by core-collapse supernovae (CC-SNe). Following this early result, Kelly et al. (2008) found that GRB environments are more similar to those of SN type Ic rather than SN type II. This is consistent with the fact that spectroscopically confirmed SNe found a couple of weeks after the GRB are type Ic (see Hjorth and Bloom, 2012; for a review)). SN Ic's tend to be more luminous than the typical CC-SNe. Studies of the SN-GRB connection is limited basically to $z < 1$, where SN can spectroscopically be identified.

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[*] Correspondence to: Physics Department, University of Calabria, I-87036 Arcavacata di Rende, Italy.
E-mail address: sandra.savaglio@googlemail.com.

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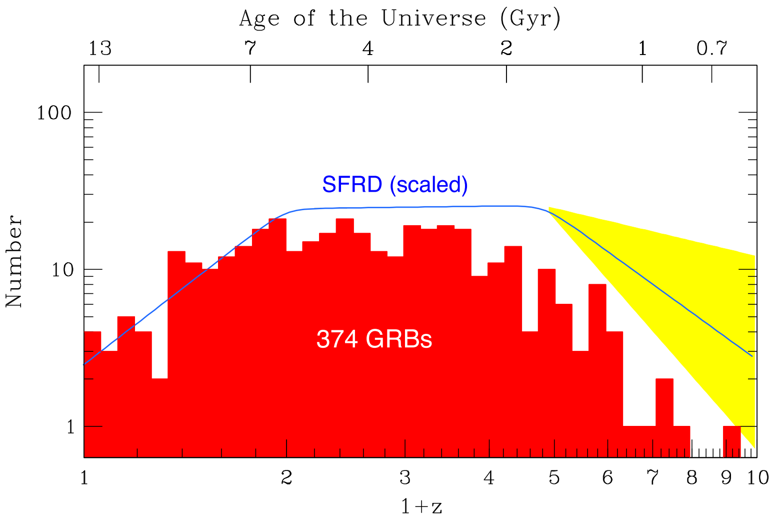

Fig. 1. Number of GRBs per redshift bin (as of May 2015). All 374 redshifts are spectroscopically determined, either from the afterglow or from the host galaxy. The blue curve and yellow shaded area represent the star-formation rate density (SFRD) of the Universe (from Wei et al., 2014), scaled to the GRB histogram for $1+z \leq 2$. The SFRD below $1+z \sim 5$ is the one determined by Hopkins and Beacom (2006) and Li (2008) from an observational compilation of UV galaxies. The $1+z > 5$ SFRD (yellow shaded area) is vaguely constrained by the GRB detection rate (Chary et al., 2007; Yüksel et al., 2008; Wang and Dai, 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

At higher redshift, it has been finally found that the role of dust is important. The TOUGH sample includes a complete investigation of 69 GRB hosts (median redshift $z = 2.14 \pm 0.18$). Hjorth et al. (2012) indicate that optically dark GRBs tend to occur in more massive and redder galaxies with respect to optically detected GRBs. The presence of large dust content was found in dark GRBs though radio and deep observations. The large sample SHOALS studied by Perley et al. (submitted for publication-a, submitted for publication-b) with multi-band optical-IR observations of 119 hosts revealed a relatively large fraction (20%) of dust obscured galaxies, which are also massive systems. Radio observations (Michałowski et al., 2012; Perley and Perley, 2013) have revealed that some have properties similar to sub-millimeter galaxies, but the majority does not have hidden high dust obscured star-formation rate (SFR).

Despite the numerous surveys which used with different means and selection criteria, we are still not sure how well GRB hosts represent the whole galaxy population. For instance, contradictory results are found on the galaxy luminosity function. Using the THOUGH sample, Schulze et al. (submitted for publication) compared the GRB-host luminosity function to the one of Lyman break galaxies (LBGs) and concluded that GRBs select metal poor galaxies. This was not confirmed by the high-redshift $3 < z < 5$ sample studied by Greiner et al. (accepted for publication).

Since the beginning, it was pursued the idea that GRBs prefer low-metallicity environments (e.g., Graham and Fruchter, 2013; Vergani et al., 2014; and references therein). From the theoretical and modelling point of view, this conclusion was reached at low (Niino et al., 2011; Boissier et al., 2013; Vergani et al., 2014) and high redshift (Chisari et al., 2010; Trenti et al., 2015). However, see the work by Campisi et al. (2011) and Elliott et al. (2012) for a different conclusion.

This shows that we are still far from a full comprehension and interpretation of the galaxy population hosting GRBs. Contrary to what is commonly believed, our main limitation is not the observational bias, but the small number statistics. Since the first afterglow in 1997, the number of detected hosts with spectroscopic redshift is only 1/4 (374) of the total number of identified afterglows.[1] The majority are long GRBs (351), 23 are short.[2] Eighteen years after the first afterglow localization, we are still dealing with a small number statistics. Nevertheless, the fact that GRBs are distributed over the entire redshift interval ever explored in the history of human kind (Fig. 1), from $z = 0.0085$ (GRB 980425 at 37 Mpc from the Milky Way; Galama et al., 1998) to $z = 8.23$ (GRB 090423; Salvaterra et al., 2009; Tanvir et al., 2009a), makes them the most valuable resources of exploration of the dawn of the universe.

2. The typical GRB host galaxy

The definition of the population of galaxies hosting GRBs is not precisely defined. When an optical afterglow is detected and a spectrum is obtained, it is often possible to measure the redshift from the identification of absorption lines, for instance the strong MgII$\lambda\lambda$2796, 2803 doublet (in the optical for the wide redshift interval $0.35 < z < 2.5$). We automatically assume that these absorption features are associated with the interstellar medium (ISM) of the host galaxy, thus implicitly conclude that the host is identified. However, when we talk about the properties of the host galaxy population as a whole, we generally refer to the detected stellar and gas emission of the galaxy which lies closest to the afterglow. By doing this, we not always give the proper emphasis to the results obtained from absorption line studies, because the direct identification of the galaxy is not always possible. Our view becomes more incomplete at $z > 1.5$, where galaxies become increasingly fainter. As a consequence, the 'GRB host population' we generally discuss includes basically galaxies detected in emission, photometrically and spectroscopically, mainly at $z < 1.5$, spanning about 2/3 of the entire history of the universe. What about the GRB hosts during the first 4.3 Gyr of life?

For only less than half of all GRBs with measured redshift (160) imaging has shown the presence of a galaxy. Multi-band photometry from optical to the near infrared (NIR) at low redshift is sufficient to derive with good accuracy the stellar mass of the galaxy. Of this population, another half or so are those with one (or more) emission lines detected, typically the strong [OII]λ3727 feature,

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[1] However, we notice that the fraction of detected hosts is much higher and at least 80% for well defined complete samples (e.g., TOUGH, or SHOALS surveys).

[2] This large long-to-short number ratio is partly and likely due to the rarity of short events, but mainly determined by the faintness of their X-ray/optical afterglow, which, together with the short duration, makes a precise localization and identification more difficult.