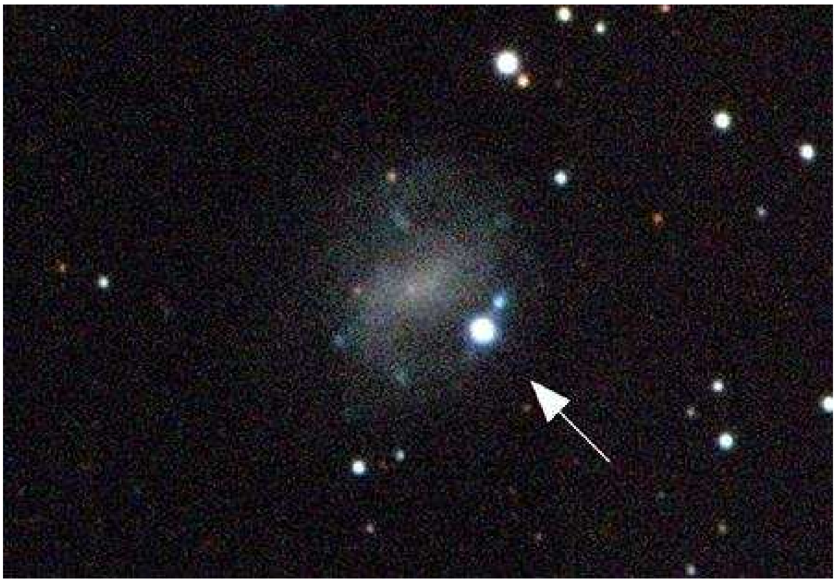
Gamma-ray burst host galaxies

HEAC course: Cosmology II/Galaxies



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Cover image: The spiral galaxy ESO 184-G82 was the host to both the supernova SN 1998bw and the gamma-ray burst GRB 980425 which were one and the same event [1].

1 Introduction

Gamma-ray bursts (GRB) are short-lived but intense bursts of gamma-ray radiation, lasting anywhere from milliseconds to a few minutes. They shine hundreds of times brighter than a typical supernova, making them briefly the brightest source of cosmic gamma-ray photons in the observable Universe. GRBs where first discovered serendipitously in 1967 by U.S. military satellites as a result of the Cold War. When the results were published in 1973, it immediately inspired a large number of more or less exotic theories for what causes them. GRBs were later found to have a highly isotropic distribution on the sky, indicating a cosmological origin. A bimodality in the duration distribution was also found, which roughly separated GRBs into two classes [2]: short events (<2 s) and longer ones (>2 s), although the distribution of these formed a continuum. The short account for ∼25% of the bursts, but there may be selection effects which may increase the true fraction. Both sets are distributed isotropically and inhomogeneously on the sky. The short-duration bursts range from a few milliseconds to 2 seconds, with an average duration time of about 0.3 seconds. The long-duration bursts last anywhere from 2 seconds to several minutes, with an average duration time of about 30 seconds. Their durations anticorrelate with their spectral hardness ratio: short GRBs are predominantly harder, and longer ones tend to be softer. This suggests that the two classes of bursts are created by fundamentally different physical mechanisms.

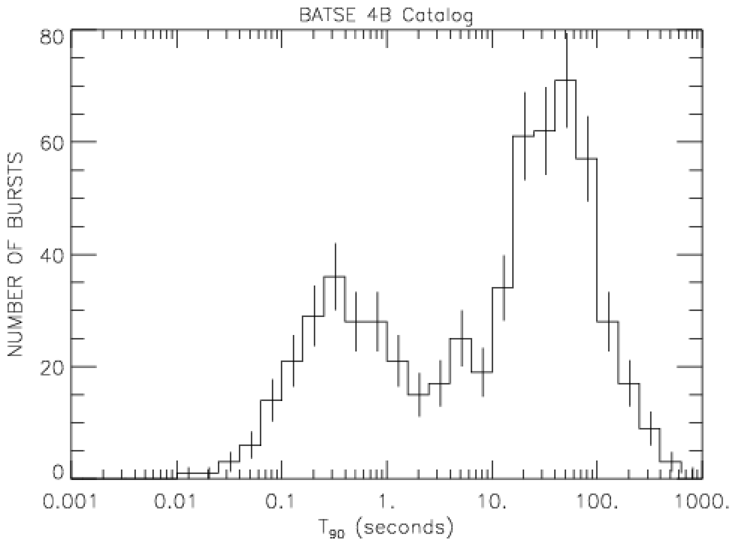

Figure 1: Distribution of durations of gamma-ray bursts detected by BATSE [3]. The duration is defined as the time, T90, between when 5% and 95% of the total number of counts are measured.

What the progenitors of GRBs are is not yet fully understood. With the help of special instruments aboard satellites, like NASA's Compton Gamma-Ray Observatory (CGRO) and the joint Italian-Dutch Beppo-SAX, some of the questions were answered, and with the recently launched NASA satellite Swift, scientists will get the ability to scrutinize GRBs like never before and hopefully solve the GRB mystery completely. Today roughly one GRB per day is detected. Identifying the host galaxy of the GRB, specifically in what type of galaxy and where in it the event takes place, is one of the key observations for understanding the progenitors.

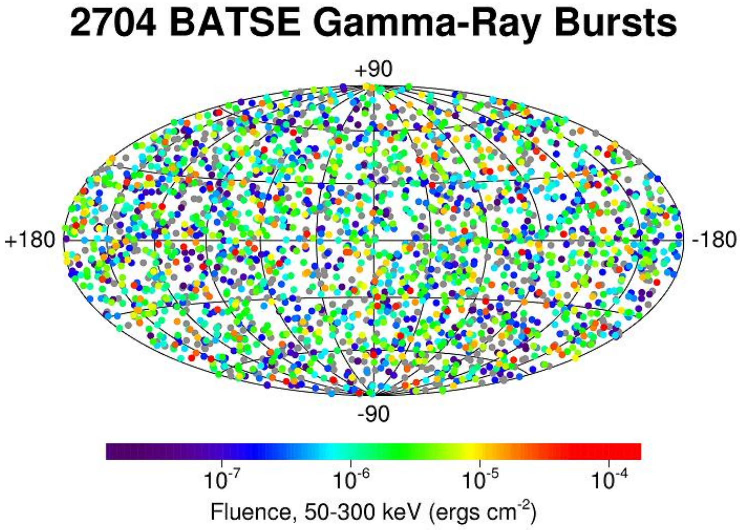

Figure 2: Gamma-ray burst distribution on the sky for bursts observed with the instrument BATSE on the CGRO [3]. Fluence means time integrated flux.

2 Long gamma-ray bursts

2.1 Progenitor

A connection between long gamma-ray bursts (LGRB) and supernovae (SN) has been firmly established, making SNe the prime candidates as the origin for LGRBs. Several LGRBs have been found to coincide with SNe. The remarkable thing is that all of the well-classified SNe associated with LGRBs are of type Ic, i.e. a core-collapse supernova which shows no hydrogen or helium lines in its spectrum. The first direct evidence for the connection came when the error box of GRB 980425 (a GRB is named after the date of its discovery) was found to coincide with the supernova SN 1998bw in the star-forming, barred spiral galaxy ESO 184-G82 at a redshift of only $z = 0.0085$ (see the front cover for an image of this). The most direct evidence for the SN/LGRB connection came from GRB 030329. This was by LGRB standards an extremely nearby LGRB with $z = 0.168$. When the LGRB power law spectrum seen during the first days was subtracted, it was found that the emission component coincided almost perfectly with that of SN 1998bw and the supernova consequently got the designation SN 2003dh.

Estimates of the rate of gamma-ray bursts give that it is several orders of magnitude lower than the rate of core-collapse supernovae [4]. This implies that special circumstances in the evolution leading to gamma-ray bursts are required. First of all, the connection to type Ic supernovae tells us that the progenitor of GRBs must be a very massive star that has lost most or all of its hydrogen and helium envelopes, either through a strong stellar wind or by mass transfer if the star fills its Roche lobe in a binary. In the standard GRB scenario (called the collapsar model) an additional requirement is a rapidly rotating stellar core, massive enough to form a black hole in the collapse [5]. The progenitor should thus be a so-called Wolf-Rayet star of mass $M \geq 30\ M_{\odot}$. All these requirements are needed to produce the relativistic jets and to get them out of the star. Given the large numbers of type Ic supernovae in comparison to the estimated numbers of LGRBs, it is likely that only a small fraction of type Ic supernovae produce LGRBs. A very massive star with a stripped envelope is probably alone not enough to produce a LGRB. The process of spin-up of the progenitor in a binary may decide which type Ic supernovae produce LGRBs.

2.2 Host galaxies

One would perhaps expect that the LGRBs and core-collapse supernovae should be found in quite similar galactic environments, since they are both related to the deaths of young, massive stars. It has been shown, however, that this expectation is wrong. A comparison [6] of the sizes, morphologies and brightnesses of the LGRB hosts with those of the supernovae revealed a surprising and substantial difference between the birthplace of these cosmic explosions. The LGRBs are found to be far more concentrated in the very brightest regions of their host galaxies than core-collapse supernovae. Furthermore, the host galaxies of the LGRBs are significantly fainter and more irregular than the hosts of the core-collapse supernovae, which by comparison are approximately equally divided between spiral and irregular galaxies. Together these results suggest that LGRBs are associated with the extremely massive stars and may be restricted to galaxies of limited chemical evolution, i.e. that the progenitors have a low metallicity.

LGRBs are generally found in extremely blue host galaxies [7] that exhibit strong emission lines, suggesting a significant abundance of young, very massive stars. The light from these stars is blue, so one could expect the LGRBs and the SNe to track this light (i.e. trace star formation), both in their distribution among galaxies and within their host galaxies themselves. Were the GRBs and SNe to track the light identically, their histograms would follow the diagonal line in Fig. 3. Whereas the SN positions do follow the light within the statistical error, the GRBs do not simply trace the blue light of the hosts; rather, they are far more concentrated on the blue light of their hosts than the light itself. A median projected angular (physical) offset of 20 LGRBs from their apparent host galaxy centers was found to be 0.17" (1.3 kpc) [8]. The median offset normalized by the individual host half-light radii was 0.98, suggesting a strong connection of LGRBs to star formation. The observed LGRB offsets were also compared to the expected offset distribution of delayed merging remnant progenitors (black hole-neutron star and neutron star-neutron star binaries). The results showed that delayed merging remnant progenitors, insofar as the predicted offset distributions from population synthesis studies are representative, can be ruled out at the 2×10^{-3} level. This is arguably the strongest observational constraint yet against delayed merging remnants as the progenitors of LGRBs.

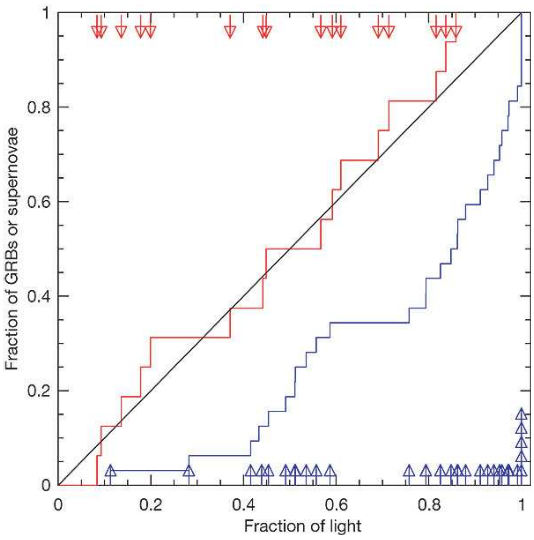

Figure 3: The locations of the explosions in comparison to the host light [6]. Blue arrows and histograms correspond to the LGRBs, and the red arrows and histograms correspond to the SNe.

Fig 4 shows a mosaic of 42 LGRB host galaxies, only one of which is a grand-design spiral, whereas almost half of the SN hosts in the comparison [6] are grand-design spirals. The situation remains essentially unchanged, even when the redshift distribution is taken into account. The host population differ strongly in ways other than morphology. Fig 5 shows a comparison of the absolute magnitude and the 80% light radius (r_{80}) of the LGRB (with $z < 1.2$) and supernova hosts. The two populations are found to differ substantially in their intrinsic magnitudes and size: the LGRB hosts are fainter and smaller than the SN hosts.

The LGRBs are associated with type Ic supernovae and must form from the most massive stars (O stars, or rather Wolf-Rayet stars). These are frequently found in large, extremely bright associations. However, O stars can be found in galaxies of all sizes. The fundamental difference between the LGRB and SN host populations is therefore not their size or luminosity, but rather their metallicity (or chemical evolution), which is found to be less than one-third solar in all the measured cases. The small size and low luminosity of the GRB hosts is then a result of the well-known correlation between galaxy mass and metallicity. Metal-rich, very massive stars have such large winds off their surfaces that

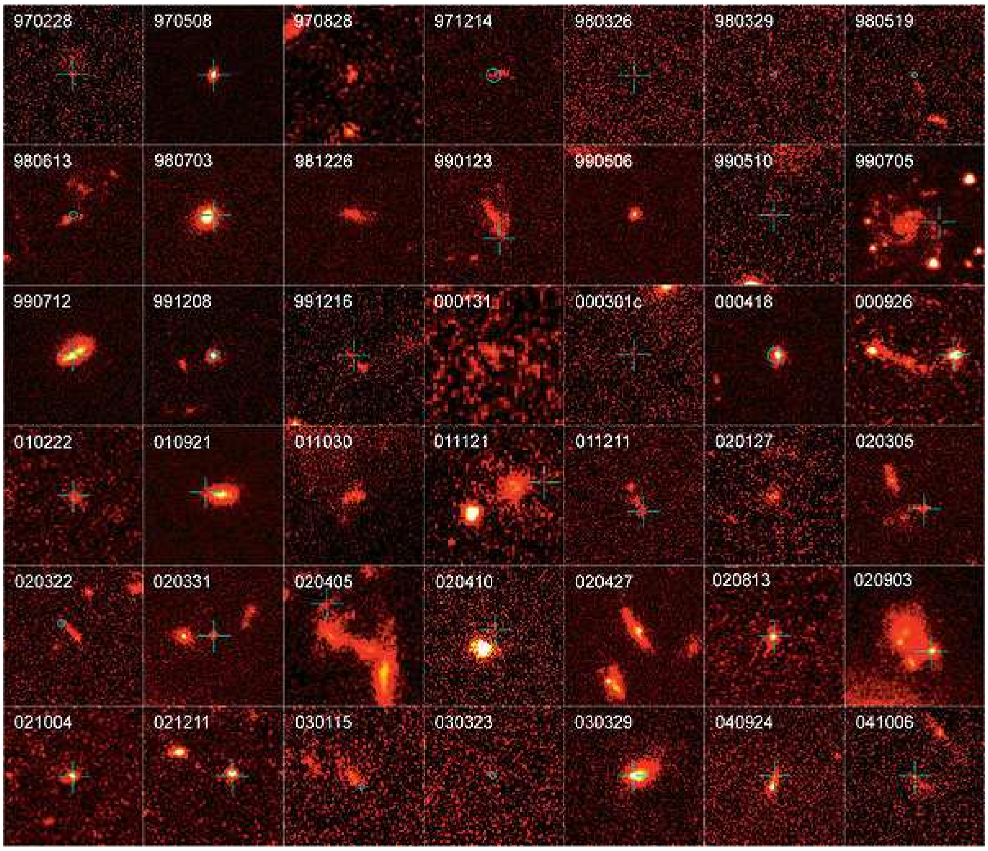

Figure 4: A mosaic of 42 long gamma-ray burst host galaxies imaged by HST [6]. In cases where the location of the GRB on the host is known to better than 0.15" the position of the GRB is shown by a green mark, either a cross-hair or a circle, depending on the positional error.

they lose most of their mass before they collapse, and therefore leave behind only neutron stars, rather than the LGRB-required black hole. A low metallicity in the stellar envelope thus reduces the mass loss and also inhibits the loss of angular momentum by the star. The low-metallicity preference of the LGRB hosts may also explain why none of them is a red, sub-millimeter bright galaxy and the fact that a substantial fraction of high-redshift LGRB hosts display strong Lyman-α emission.

The low-metallicity requirement should have further consequences. The local metallicity in spirals is known to be anti-correlated with distance from the centre of the galaxy. Thus one might expect LGRBs in spirals (though only a few such have been seen so far) to violate the trend for the LGRB population, and avoid the bright central regions of their hosts. Furthermore, when observing at higher redshift, where metallicities are lower than in most local galaxies, LGRBs should be more uniformly distributed among star-forming galaxies.

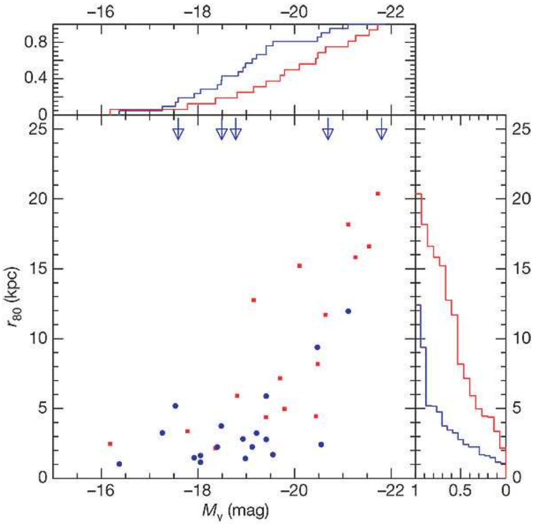

Figure 5: A comparison of the absolute magnitude and size distribution of the GRB (blue) and SN (red) hosts [6]. The plot is then projected onto the two side panels where a histogram is displayed for each host population in absolute magnitude and semi-major axis.

Using K-band observations of LGRB host galaxies in combination with other optical and near-infrared data from the literature, it has been concluded [7] that most of the LGRB hosts discovered so far belong to the population of faint and blue star-forming galaxies at high redshift (see Fig. 6). They have low masses, as suggested by their faint luminosity in the near-infrared, and are also sub-luminous sources at optical wavelengths compared to the general population of star-forming galaxies. Most of them are characterized by intrinsic R-K colours even bluer than those displayed by the starburst galaxies observed in the nearby Universe. A lack of LGRB detection toward luminous starbursts and/or reddened sources such as those observed in the infrared and submillimeter deep surveys seems to indicate a possible bias of the currently-known LGRB host sample against this type of object. This could be explained by the fact that the selection of LGRB host galaxies, so far, had to rely on the identification of optical LGRB afterglows likely probing unobscured star-forming galaxies.

The host galaxies of GRB 980425 and GRB 030329, together with the three other local LGRB hosts with associated supernovae, have been studied in terms of metallicity [9], which appears to be the critical physical parameter. It was found that they are all faint and metal-poor compared to the population of local star-forming galaxies. Fig. 7 shows the stiking result, that all of the local LGRB hosts lie at substantially lower metallicity than the vast majority of local galaxies in the Sloan Digital Sky Survey (SDSS) sample. Only a small fraction ($< 25\%$) of the current star formation occurs in galaxies with oxygen abundance 12+log(O/H) < 8.6, i.e. about half that of the Milky Way. However, all the five LGRB/SN hosts have oxygen abundance below this limit, which means that LGRBs

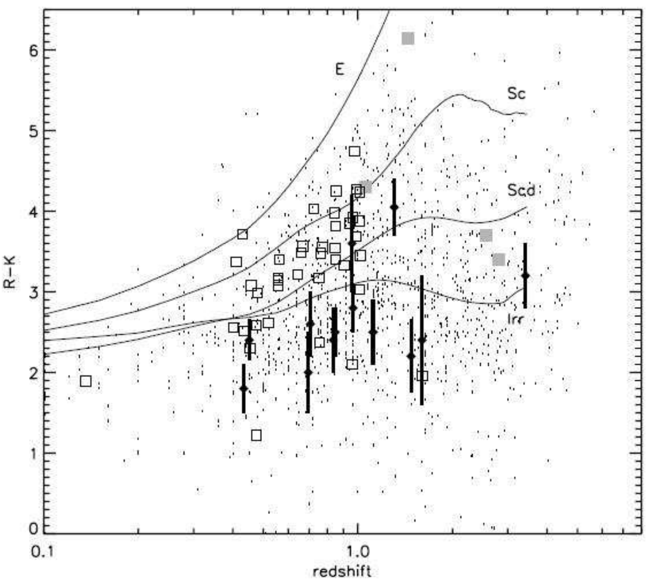

Figure 6: Observed R-K colours versus redshift for a sample of LGRB host galaxies (filled diamonds) [7] with optically-selected field sources (dots) and ISO (open squares) and SCUBA (filled squares) dusty starbursts. Solid curves indicate the observed colours of local E, Sc, Scd and Irr galaxies if they were moved back to increasing redshifts.

trace only low-metallicity star formation and that the Milky Way has been too metal rich to host LGRBs for at least the last several billion years. It was also found that the isotropic energy release, $E_{\rm iso}$ of these five LGRBs steeply decreases with increasing host oxygen abundance, meaning that the LGRBs in low-metallicity environments are more energetic (see Fig. 8). The results suggest an upper metallicity limit for "cosmological" LGRBs at ~ 0.15 $Z_\odot$.

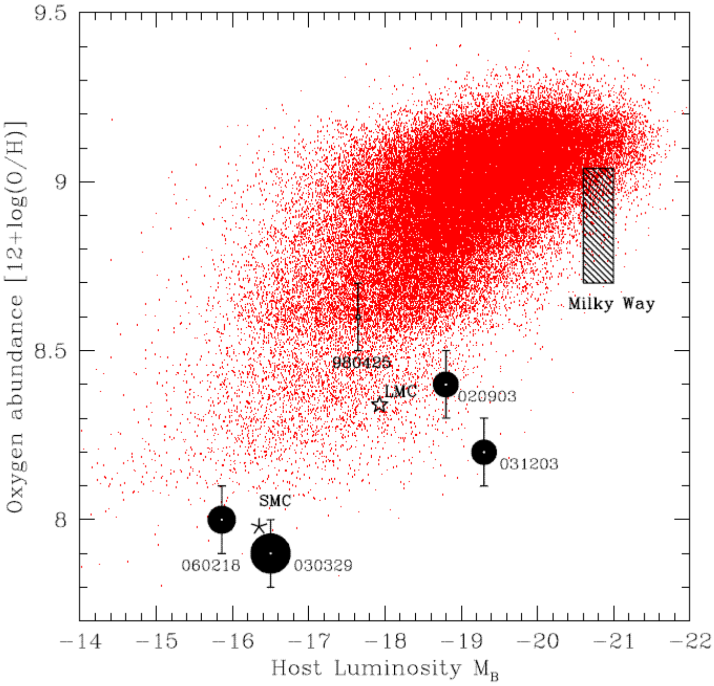

Figure 7: The five low-redshift LGRB/SN hosts (filled circles) [9] and 73 000 local star forming galaxies (SDSS sample) in the host luminosity-oxygen abundance diagram. The Milky Way, LMC and SMC are shown for comparison.

3 Short gamma-ray bursts

3.1 Progenitor

Short gamma-ray bursts (SGRB), while also extragalactic, appear to come from a lower-redshift population and are less luminous than LGRBs. They appear to be generally less beamed (or possibly not beamed at all in some cases) and intrinsically less energetic than their longer counterparts, typically by more than one order of magnitude, and are probably more frequent in the Universe despite being rarer observationally.

The progenitor of SGRBs has been proposed to be the merging of binary neutron stars (also a black hole-neutron star merger is a possibility). This type of binary system is known to exist. The neutron stars will spiral in and lose more and more of the orbital energy by gravitational radiation. The final merger will occur on a time scale of the order of milliseconds, in aggrement with the observed duration of SGRBs. Most of the mass will result in a black hole, but a substantial fraction will stay in the form of an extremely hot accretion disk, which then loses most of its internal energy as neutrinos.

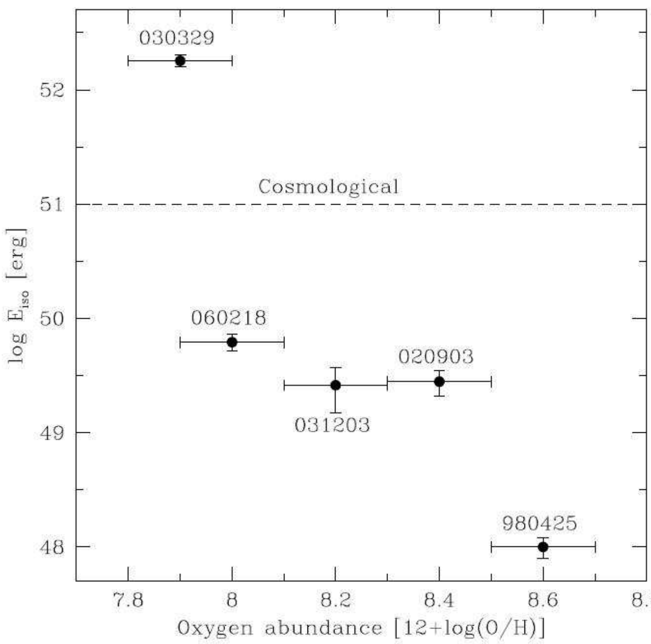

Figure 8: Isotropic energy release in gamma-rays, $E_{\rm iso}$ for the five local LGRB vs. the oxygen abundance of their hosts [9]. The dashed line at $E_{\rm iso} = 10^{51}$ erg indicates the approximate limit for the "cosmological" LGRBs.

3.2 Host galaxies

The nature of the SGRBs has remained a mystery, but this is due to change with the increasing number of observed SGRBs with the Swift satellite. By studying the environment in which the bursts occur, strong constraints can be put on the progenitors. Last year, the Swift satellite observed the first four SGRBs (GRB 050509b, GRB 050709, GRB 050724 and GRB 050813) to have X-ray afterglows and therefore could be precisely located [10]. In three of the four cases the SGRB has been plausibly associated with a galaxy to better than a 99% confidence level, all with comparatively low redshifts between 0.16 - 0.25. In the fourth case (GRB 050813) there are two galaxies located in the error circle with comparable magnitude and one may associate the event with either of these (z $\sim$ 0.72) In three of the cases the host galaxies were old and massive galaxies (ellipticals/early-type). The absence of observable Hα and [O II] emission constrains the unobscured star formation rates in these galaxies to $< 0.2 M_{\odot} yr^{-1}$, and the lack of Balmer absorption lines implies that the last significant star forming event occured $>$ 1 billion years ago. These are thus galaxies with essentially no current or recent star formation, and two of them have solar metallicities. The host galaxy of GRB 050709 was a late-type dwarf galaxy, which exhibits strong emission lines that indicate on-going star formation with a conservative lower limit of $> 0.3 M_{\odot} yr^{-1}$. These observations indicate that these SGRBs occured during the last ~ 7 billion years of the Universe ($z < 1$) in galaxies with diverse physical characteristics. SGRBs are thus found to originate in a variety of low-redshift environments that differ substantially from those of LGRBs , both on individual galaxy scales and on galaxy-cluster scales. Whereas SGRBs are associated to both star-forming galaxies and massive ellipticals dominated by old stellar populations, LGRB hosts are actively forming stars, have low metallicities and small stellar masses, and the LGRBs are significantly younger than the minimum ages derived for the early-type galaxies in the sample. Based on positions of the afterglows, two of four SGRBs (GRB 050509b and GRB 050913) are very likely associated with clusters of galaxies. This contrast strikingly with the observations that no well-localized LGRB has yet been associated with a cluster. One can thus conclude that the host galaxies of SGRBs, and by extension the progenitors, are not drawn from the same parent population of LGRBs.

No supernova signature was found in the two observed optical afterglows and the modeling of the spectrum and light curves of the afterglows indicate very low density environments. These results, along with the location in three of the cases in elliptical/early-type galaxies without current star formation, argues that the accepted progenitor model of LGRBs (the collapse of a massive star) is not tenable as a source for the SGRBs, but are instead consistent with what would be expected for a merger of two compact objects. The measured offsets of the SGRBs from their putative hosts are also compatible with the predicted site of merging compact remnant progenitors.

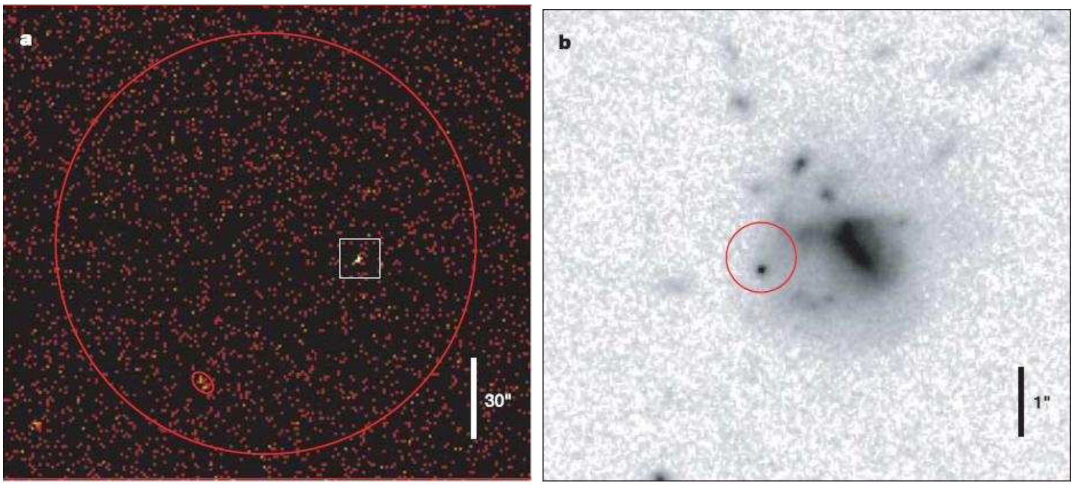

Figure 9: GRB 050709 was a short gamma-ray burst in a late-type dwarf galaxy detected by Swift [11].

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