ARTICLES

Long γ-ray bursts and core-collapse supernovae have different environments

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When massive stars exhaust their fuel, they collapse and often produce the extraordinarily bright explosions known as core-collapse supernovae. On occasion, this stellar collapse also powers an even more brilliant relativistic explosion known as a long-duration γ-ray burst. One would then expect that these long γ-ray bursts and core-collapse supernovae should be found in similar galactic environments. Here we show that this expectation is wrong. We find that the γ-ray bursts are far more concentrated in the very brightest regions of their host galaxies than are the core-collapse supernovae. Furthermore, the host galaxies of the long γ-ray bursts are significantly fainter and more irregular than the hosts of the core-collapse supernovae. Together these results suggest that long-duration γ-ray bursts are associated with the most extremely massive stars and may be restricted to galaxies of limited chemical evolution. Our results directly imply that long γ-ray bursts are relatively rare in galaxies such as our own Milky Way.

It is an irony of astrophysics that stellar birth is most spectacularly marked by the deaths of massive stars. Massive stars burn brighter and hotter than smaller stars, and exhaust their fuel far more rapidly. Therefore a region of star formation filled with low mass stars still early in their lives, and in some cases still forming, may also host massive stars already collapsing and producing supernovae. Indeed, with the exception of the now famous type Ia supernovae, which have been so successfully used for cosmological studies[1,2] and which are thought to be formed by the uncontrolled nuclear burning of stellar remnants comparable in mass to the Sun[3], all supernovae are thought to be produced by the collapse of massive stars. The collapse of the most massive stars (tens of solar masses) is thought to leave behind either black holes or neutron stars, depending largely on the state of chemical evolution of the material that formed the star, whereas the demise of stars between approximately 8 and 20 solar masses produces only neutron stars[4].

Gamma-ray bursts (GRBs), like supernovae, are a heterogeneous population. GRBs can be divided into two classes: short, hard bursts, which last between milliseconds and about two seconds and have hard high-energy spectra, and long, soft bursts, which last between two and tens of seconds, and have softer high-energy spectra[5]. Only very recently have a few of the short bursts been well localized, and initial studies of their apparent hosts suggest that these bursts may be formed by the binary merger of stellar remnants[6,7]. In contrast, the afterglows of over 80 long GRBs (LGRBs) have been detected in the optical and/or radio parts of the spectrum. And as a result of these detections, it has become clear that LGRBs, like core-collapse supernovae, are related to the deaths of young, massive stars. It is these objects, born of the deaths of massive stars, that we study here.

LGRBs are generally found in extremely blue host galaxies[8–11] that exhibit strong emission lines[12,13], suggesting a significant abundance of young, very massive stars. Furthermore, whereas the light curves of the optical transients associated with LGRBs are often dominated by radiation from the relativistic outflow of the GRB, numerous LGRBs have shown late-time 'bumps' in their light curves consistent with the presence of an underlying supernova[14–16]. In several cases spectroscopic evidence has provided confirmation of the light of a supernova superposed on the optical transient[17–20]. Indeed, given the large variations in the brightnesses of optical transients and supernovae, and the limited observations on some GRBs, it seems plausible that all LGRBs have an underlying supernova[21]. And although the energy released in a LGRB often appears to the observer to be orders of magnitude larger than that of a supernova, there is now good evidence suggesting that most LGRBs are highly collimated and often illuminate only a few per cent of the sky[22,23]. When one takes this into account, the energy released in LGRBs more closely

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resembles that of energetic supernovae. However, not all core-collapse supernovae may be candidates for the production of GRBs. The supernovae with good spectroscopic identifications so far associated with GRBs have been type Ic—that is, core-collapse supernovae that show no evidence of hydrogen or helium in their spectra. (Type Ib supernovae, which are often studied together with type Ic, have spectra that are also largely devoid of hydrogen lines but show strong helium features.) A star may therefore need to lose its outer envelope if a GRB is to be able to burn its way through the stellar atmosphere[24]. Studies that have compared the locations of type Ib/c supernovae with the more numerous type II supernovae (core-collapse supernovae showing hydrogen lines) in local galaxies so far show no differences in either the type of host or the placement of the explosion on the host[25,26]. This result led the authors of ref. 25 to argue that core-collapse supernovae all come from the same mass range of progenitor stars, but that type Ib/c supernovae may have had their envelopes stripped by interaction with a binary stellar companion. Whether type Ic supernovae come from single stars, or binary stars, or both, it is very likely that only a small fraction of these supernovae produce GRBs[27].

Given the common massive stellar origins of core-collapse supernovae and LGRBs, one might expect that their hosts and local environments are quite similar. It has long been argued that core-collapse supernovae should track the blue light in the Universe (the light from massive stars is blue), both in their distribution among galaxies and within their host galaxies themselves. One would expect similar behaviour from LGRBs, and indeed rough evidence for such a correlation has been reported[28]. Here we use the high resolution available from Hubble Space Telescope (HST) images, and an analytical technique developed by us that is independent of galaxy morphology, to study the correlation between these objects and the light of their hosts. We also compare the sizes, morphologies and brightnesses of the LGRB hosts with those of the supernovae. Our results reveal surprising and substantial differences between the birthplaces of these cosmic explosions. We find that whereas core-collapse supernovae trace the blue light of their hosts, GRBs are far more concentrated on the brightest regions of their hosts. Furthermore, while the hosts of core-collapse supernovae are approximately equally divided between spiral and irregular galaxies, the overwhelming majority of GRBs are on irregulars, even when we

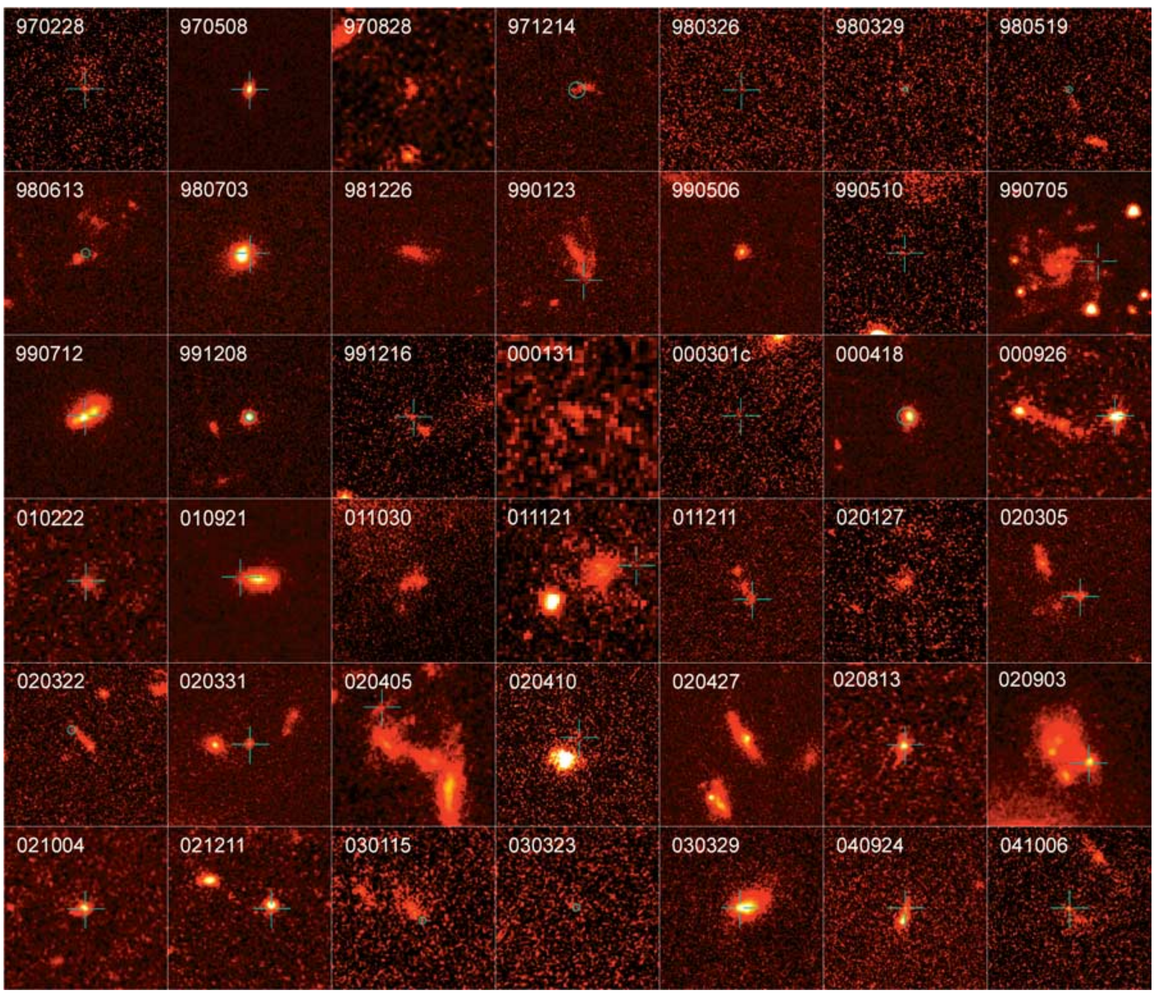

Figure 1 | A mosaic of GRB host galaxies imaged by HST. Each individual image corresponds to a square region on the sky 3.75″ on a side. These images were taken with the Space Telescope Imaging Spectrograph (STIS), the Wide-Field and Planetary Camera 2 (WFPC2) and the Advanced Camera for Surveys (ACS) on HST. 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. If the positional error is smaller than the point spread function of the image (0.07″ for STIS and ACS, 0.13″ for WFPC2) the position is marked by a cross-hair; otherwise the positional error is indicated by a circle. The STIS images were all taken in white light (no filter), and in most cases the WFPC2 and ACS images are in the F606W filter (though in a few cases where images in this filter were not available we have used images in F555W or F775W). The STIS and F606W images can be thought of as broad 'V' or visual images, and are, for galaxies exhibiting typical colours of GRB hosts, the single most sensitive settings for these cameras. F555W is close to the ground-based Johnson V band, and F775W corresponds to the ground-based Johnson I band. Owing to the redshifts of the hosts, these images generally correspond to blue or ultraviolet images of the hosts in their rest frame, and thus detect light largely produced by the massive stars in the hosts.

restrict the GRB sample to the same redshift range as the supernova sample. We argue that these results may be best understood if GRBs are formed from the collapse of extremely massive, low-metallicity stars.

The sample

Over 40 LGRBs have been observed with the HST at various times after outburst. The HST is unique in its capability easily to resolve the distant hosts of these objects. Shown in Fig. 1 is a mosaic of HST images of the hosts of 42 bursts. These are all LGRBs with public data that had an afterglow detected with better than 3σ significance and a position sufficiently well localized to determine a host galaxy. A list of all the GRBs used in this work can be found in Supplementary Tables 1–3.

The supernovae discussed here were all discovered as part of the Hubble Higher z Supernova Search[29,30], which was done in cooperation with the HST GOODS survey[31]. The GOODS survey observed two ~150 arcmin^2 patches of sky five times each, in epochs separated by 45 days. Supernovae were identified by image subtraction. Here we discuss only the core-collapse supernovae identified in this survey. A list of the supernovae used is presented in Supplementary Table 4, and images of the supernova hosts can be seen in Fig. 2.

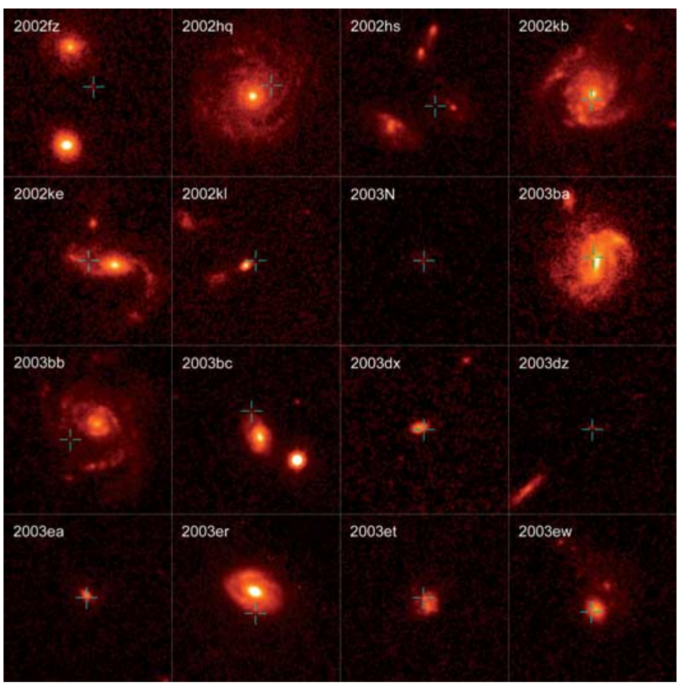

Figure 2 | A mosaic of core-collapse supernova host galaxies imaged with HST as part of the GOODS programme. Each image in the mosaic has a width of 7.5″ on the sky, and thus twice the field of view of each image in the GRB mosaic. The position of each supernova on its host galaxy is marked. In all cases, these positions are known to sub-pixel accuracy. Supernovae in the GOODS sample were identified by ref. 30 as either type Ia or core-collapse supernovae on the basis of their colours, luminosities and light curves, as data allowed (a supernova exploding near the beginning or end of one of the multi-epoch observing runs would have much less data, and sometimes poor colour information). Thus bright type Ib and Ic supernovae, which have colours and luminosities similar to type Ia supernovae, would probably have been classified as type Ia (unless a grism spectrum was taken—however, only a small fraction of objects were observed spectroscopically). On the other hand, fainter type Ib and Ic supernovae ($M_B \gtrsim -18$) could in principle be identified from photometric data; however, in practice the data were rarely sufficient for a clear separation from other core-collapse supernovae. On the basis of surveys of nearby galaxies, one might expect approximately 20% of the core-collapse supernovae to be type Ib or Ic[49,50].

Positions of GRBs and supernovae on their hosts

If LGRBs do in fact trace massive star formation, then in the absence of strong extinction we should find a close correlation between their position on their host galaxies and the blue light of those galaxies. However, many of the GRB hosts and quite a few of the supernova hosts are irregular galaxies made up of more than one bright component. As a result, the common astronomical procedure of identifying the centroid of the galaxy's light, and then determining the distance of the object in question from the centroid, is not particularly appropriate for these galaxies—the centroid of light may in fact lie on a rather faint region of the host (examine GRBs 000926 and 020903 in Fig. 1 for excellent illustrations of this effect). We have therefore developed a method that is independent of galaxy morphology. We sort all of the pixels of the host galaxy image from faintest to brightest, and ask what fraction of the total light of the host is contained in pixels fainter than or equal to the pixel containing the explosion. If the explosions track the distribution of light, then the fraction determined by this method should be uniformly distributed between zero and one. (A detailed exposition of this method can be found in Supplementary Information).

As can be seen in Fig. 3, the core-collapse supernovae do track the light of their hosts as well as could be expected given their small number statistics. A Kolmogornov–Smirnov (KS) test finds that the distribution of the supernovae is indistinguishable from the distribution of the underlying light. The situation is clearly different for LGRBs. As can be seen in Fig. 3, the GRBs do not simply trace the blue light of the hosts; rather, they are far more concentrated on the peaks of light in the hosts than the light itself. A KS test rejects the hypothesis that GRBs are distributed as the light of their hosts with a probability greater than 99.98%. Furthermore, this result is robust:

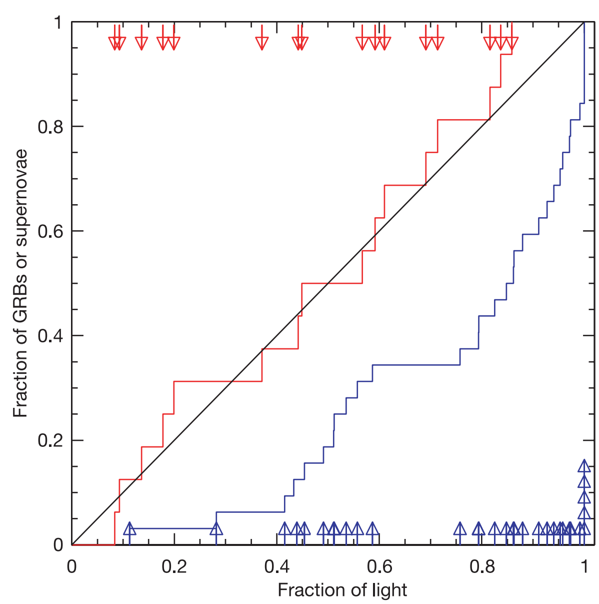

Figure 3 | The locations of the explosions in comparison to the host light. For each object, an arrow indicates the fraction of total host light in pixels fainter than or equal to the light in the pixel at the location of the transient. The cumulative fraction of GRBs or supernovae found at a given fraction of the total light is shown as a histogram. The blue arrows and histogram correspond to the GRBs, and the red arrows and histogram correspond to the supernovae. Were the GRBs and supernovae to track the light identically, their histograms would follow the diagonal line. Whereas the supernova positions do follow the light within the statistical error, the GRBs are far more concentrated on the brightest regions of their hosts. Thus although the probability of a supernova exploding in a particular pixel is roughly proportional to the surface brightness of the galaxy at that pixel, the probability of a GRB at a given location is effectively proportional to a higher power of the local surface brightness.

it shows no dependence on GRB host size or magnitude. And in spite of the relatively small number of supernova hosts for which a comparison can be made, the two populations are found by the KS test to be drawn from different distributions with ~99% certainty. In the next section, we show that the surprising differences in the locations of these objects on the underlying light of their hosts may be due not only to the nature of their progenitor stars but also that of their hosts.

A comparison of the host populations

An examination of the mosaics of the GRB and supernova hosts (Figs 1 and 2) immediately shows a remarkable contrast—only one GRB host in this set of 42 galaxies is a grand-design spiral, whereas nearly half of the supernova hosts are grand-design spirals. One might wonder if this effect is due to a difference in redshift distribution—the core-collapse supernovae discovered by the GOODS collaboration all lie at redshift $z < 1.2$, whereas LGRBs can be found at much larger redshifts where grand-design spirals are rare to non-existent. Yet if we restrict the GRB population to $z < 1.2$ (and thus produce a population with a nearly identical mean and standard deviation in redshift space compared to the GOODS core-collapse supernovae), the situation remains essentially unchanged: only one out of the eighteen GRB hosts is a grand-design spiral. (For a detailed comparison of GRB hosts to field galaxies, rather than the supernova selected galaxies shown here, see ref. 32.)

Were the difference in spiral fraction the only indication of a difference in the host populations, we could not rule out random chance—given the small number statistics, both populations are barely consistent with each other and a spiral fraction of ~25%. However, the host populations differ strongly in ways other than morphology.

In Fig. 4 we compare the 80% light radius (r_{80}) and absolute magnitude distributions of the GRB and supernova hosts. Included in the comparison are all LGRBs with known redshifts $z < 1.2$ at the time of submission and the 16 core-collapse supernovae of GOODS with spectroscopic or photometric redshifts (see the Supplementary Tables for a complete list of the GRBs, supernovae and associated parameters used in this study). The small minority of GRB hosts in this redshift range without HST imaging are compared only in absolute magnitude and not in size. The absolute magnitudes have been derived from the observed photometry using a cosmology of $\Omega_m = 0.27$, $\Lambda = 0.73$ and $H_0 = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and the magnitudes have been corrected for foreground Galactic extinction[33]. For a technical discussion of the determination of the magnitude and size of individual objects, see Supplementary Information.

As can be readily seen, the two host populations differ substantially both in their intrinsic magnitudes and sizes. The GRB hosts are fainter and smaller than the supernova hosts. Indeed, KS tests reject the hypothesis that these two populations are drawn from the same population with certainties greater than 98.6% and 99.7% for the magnitude and size distributions, respectively.

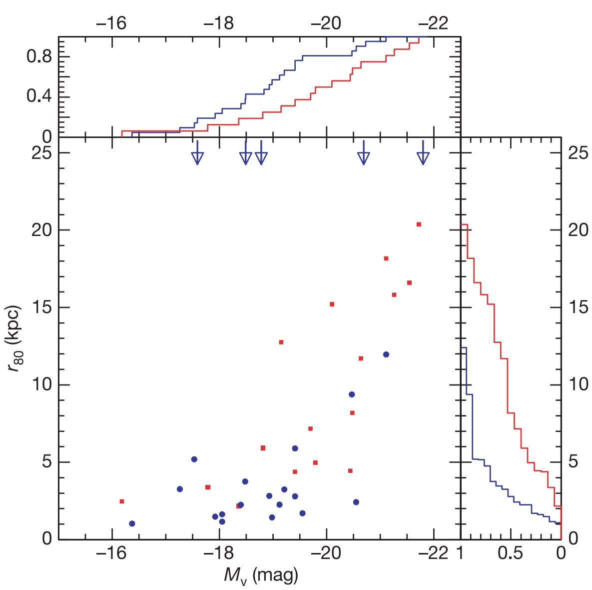

Figure 4 | A comparison of the absolute magnitude and size distributions of the GRB and supernova hosts. In the main panel, the core-collapse supernova hosts are represented as red squares, and the LGRB hosts as blue circles. The absolute magnitudes of the hosts are shown on the x axis, and the lengths of the semi-major axes of the hosts on the y axis. The plot is then projected onto the two side panels where a histogram is displayed for each host population in each of the dimensions—absolute magnitude and semi-major axis. Shown as blue arrows are the absolute magnitudes of GRB hosts with $z < 1.2$ that have been detected from the ground but have not yet been observed by HST. These hosts are only included in the absolute magnitude histogram. The hosts of GRBs are both smaller and fainter than those of supernovae.

Discussion

Although the evidence is now overwhelming that both core-collapse supernovae and LGRBs are formed by the collapse of massive stars, our observations show that the distribution of these objects on their hosts, and the nature of the hosts themselves, are substantially different. How then can this be? We propose here that these surprising findings are the result of the dependence of the probability of GRB formation on the state of the chemical evolution of massive stars in a galaxy.

Even before the association of LGRBs with massive stars had been established, a number of theorists had suggested that these objects could be formed by the collapse of massive stars, which would leave behind rapidly spinning black holes. An accretion disk about the black hole would power the GRB jet. These models, sometimes referred to as 'hypernovae' or 'collapsar' models, implicitly require very massive stars, as only stars greater than about 18 solar masses form black holes. But in fact it was widely suspected that even more massive stars would be required—if only to provide the required large energies, and to limit the numbers of supernovae progressing to GRBs.

We conclude that LGRBs do indeed form from the most massive stars and that this is the reason that they are even more concentrated on the blue light of their hosts than the light itself. The most massive stars (O stars) are frequently found in large associations. These associations can be extremely bright, and can indeed provide the peak of the light of a galaxy—particularly if that galaxy is a faint, blue irregular, as are the GRB hosts in general. Indeed, a connection of LGRBs with O stars (and perhaps Wolf-Rayet stars) is a natural one—given the strong emission lines (including Ne [III]) seen in many of these hosts[12,13] and the evidence for possible strong winds off the progenitors of the GRBs seen in absorption in some LGRB spectra[34,35].

However, O stars are found in galaxies of all sizes. Indeed, studies of the Magellanic clouds suggest that the initial distribution of masses of stars at formation in these dwarf galaxies is essentially identical to that in our much larger spiral, the Milky Way[36]. Therefore, a difference in the initial mass function of stars is unlikely to be responsible for the differences between the hosts. We propose that the fundamental differences between the LGRB and supernova host populations is not their size or luminosity, but rather their metallicity, or chemical evolution. Some evidence of this already exists. The hosts of seven LGRBs (GRBs 980425 (P.M.V., personal communication), 990712[13], 020903[37], 030323[38], 030329[17], 031203[39] and 050730[40]) have measurements of, or limits on, their metallicity, and in all cases the metallicity is less than one-third solar. The small size and low luminosity of the GRB hosts is then a result of the well known correlation between galaxy mass and metallicity (see ref. 41 and references therein).

But why do LGRBs occur in low-metallicity galaxies? This may be a direct result of the evolution of the most massive stars. It has recently been proposed that metal-rich stars with masses of tens of solar masses have such large winds off their surfaces (due to the photon pressure on their metal-rich atmospheres) that they lose most of their mass before they collapse and produce supernovae[4]. As a result they leave behind neutron stars, not the black holes necessary for LGRB formation. Ironically, stars of 15–30 solar masses may still form black holes, as they do not possess radiation pressure sufficient to drive off their outer envelopes. Direct evidence for this scenario comes from recent work showing that the Galactic soft γ-ray repeater, SGR 1820−06, is in a cluster of extremely young stars of which the most massive have only started to collapse[42]—yet the progenitor of SGR 1820−06 collapsed to a neutron star, not a black hole. Recent observations of winds from very massive (Wolf-Rayet) stars provide further support for this scenario: outflows from the low-metallicity stars in the Large Magellanic Cloud are substantially smaller than those seen from more metal-rich Galactic stars[43]. The possible importance of metallicity in LGRB formation has therefore not escaped the notice of theorists[44,45].

A preference for low metallicity may also explain one of the most puzzling results of GRB host studies. None of the LGRB hosts is a red, sub-millimetre bright galaxy. These highly dust-enshrouded galaxies at redshifts of ~1–3 are believed to be the sites of a large fraction of the star formation in the distant Universe[46]. And although some LGRB hosts do show sub-millimetre emission, none have the red colours characteristic of the majority of this population. However, it is likely that these red dusty galaxies have substantial metallicities at all redshifts. The low metallicity of hosts may also help explain the fact that a substantial fraction of high-redshift LGRB hosts display strong Lyman-α emission[47].

All well-classified supernovae associated with LGRBs are of type Ic, presumably because the presence of a hydrogen envelope about the collapsing core can block the emergence of a GRB jet[24]. Thus only those supernovae whose progenitors have lost some, but not too much, mass appear to be candidates for the formation of a GRB. Given the large numbers of type Ic supernovae in comparison to the estimated numbers of LGRBs, however, it is likely that only a small fraction of type Ic supernovae produce LGRBs. Indeed, even the number of unusually energetic type Ib/Ic supernovae appears to dwarf the LGRB population[48]. Another process, perhaps the spin-up of the progenitor in a binary[27], may decide which type Ic supernovae produce LGRBs. Interestingly, it was the similar distribution of supernovae on their hosts, and particularly the fact that type Ib/Ic were no more correlated than type II with the UV bright regions of their hosts, that led ref. 25 to the conclusion that type Ib/Ic supernovae form from binaries. LGRBs clearly track light differently from the general type Ic population. However, the samples used by refs 25 and 26 were from supernovae largely discovered on nearby massive galaxies—dwarf irregular hosts are underrepresented in these samples. It will be particularly interesting to see whether large unbiased supernova surveys at present underway produce similar locations for their supernovae.

We do not know, however, what separates the small fraction of low-metallicity type Ic supernovae that turn into LGRBs from the rest of the population. Potentially, the answer is the amount of angular momentum available in the core to form the jet. In this case, the preference for low metallicity may indicate that single star evolution dominates over binary interaction in forming LGRBs. Deep, high-spectral-resolution studies of LGRB afterglows may provide insight here, by allowing studies of the winds off the progenitor and any binary companion.

Only a small fraction of LGRBs are found in spiral galaxies, even for LGRBs with redshifts $z < 1$ where spirals are much more common. However, 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 to violate the trend that we have seen for the general LGRB population, and avoid the bright central regions of their hosts. The present number of LGRBs known in spirals is still too small to test this prediction. But a sample size a few times larger should begin to allow such a test. Additionally, a survey of the metallicity of the hosts of the GOODS supernovae should find a higher average metallicity than that seen in GRB hosts. Finally, if low metallicity is indeed the primary variable in determining whether LGRBs are produced, then as we observe higher redshifts, where metallicities are lower than in most local galaxies, LGRBs should be more uniformly distributed among star-forming galaxies. Indeed, some evidence of this may already be present in the data[32]. LGRBs, however, are potentially visible to redshifts as high as $z \approx 10$. At significant redshifts, where the metallicities of even relatively large galaxies are expected to be low, we may find that LGRBs do become nearly unbiased tracers of star formation.

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